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New results from the CUORE experiment

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The Cryogenic Underground Observatory for Rare Events (CUORE) is the first bolometric experiment searching for neutrino-less double-beta ($0\nu\beta\beta$) decay that has been able to reach the one-ton scale. The detector, located at the Laboratori Nazionali del Gran Sasso in Italy, consists of an array of 988 TeO_2 crystals arranged in a compact cylindrical structure of 19 towers. Following the completion of the detector construction in August 2016, CUORE began its first physics data run in 2017 at a base temperature of about 10 mK. Following multiple optimization campaigns in 2018, CUORE is currently in stable operating mode. In 2019, CUORE released its second result of the search for $0\nu\beta\beta$ corresponding to a TeO_2 exposure of 372.5 $\mathrm{kg} \cdot \mathrm{yr}$ and a median exclusion sensitivity to a ^{130}Te $0\nu\beta\beta$ decay half-life of $1.7 \cdot 10^{25}$ yr. We find no evidence for $0\nu\beta\beta$ decay and set a 90% C.I. Bayesian lower limit of $3.2 \cdot 10^{25}$ yr on the ^{130}Te $0\nu\beta\beta$ decay half-life. We present the current status of CUORE's search for $0\nu\beta\beta$. We give an update of the CUORE background model and the measurement of the ^{130}Te two neutrino double-beta

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($2\nu\beta\beta$) decay half-life. Eventually, we show the preliminary results on half-life limits from the analysis of ^{130}Te $0\nu\beta\beta$ and $2\nu\beta\beta$ decay to the first 0^+ excited state of ^{130}Xe.

Keywords: Neutrinoless double beta decay; two-neutrino double beta decay; background model; cryogenic detectors.

1. Double Beta Decay

Double beta decay is a rare nuclear process, in which a nucleus decays into its daughter isobar by emitting two electrons. Within the Standard Model framework, the two-neutrino double beta decay ($2\nu\beta\beta$) is a second-order process, in which the two electrons are accompanied by the emission of two electron anti-neutrinos; it has been observed for several nuclei (^{130}Te, ^{100}Mo, ^{76}Ge, ^{83}Se, ^{136}Xe, etc.) with half-lives $T^{1/2}_{2\nu\beta\beta} \sim 10^{18-24}$ yr. Extensions of the Standard Model predict another possible channel for this process, the neutrinoless double beta decay ($0\nu\beta\beta$), in which only the two electrons are emitted and it violates the leptonic number by two units.[1] The observation of $0\nu\beta\beta$ decay would imply a verification of the violation of the leptonic number in nature and the presence of a Majorana term for the neutrino mass. One of the favorite mechanisms for the $0\nu\beta\beta$ decay is the light Majorana neutrino exchange; from the $0\nu\beta\beta$ decay rate measurements one could infer the effective neutrino mass term. The experimental signature of the $0\nu\beta\beta$ decay is a peak at the Q-value ($Q_{\beta\beta}$) in the electrons' summed energy spectrum. The half-life sensitivity in $0\nu\beta\beta$ searches is given by $S_{0\nu} \propto \eta \cdot \epsilon \cdot \sqrt{\frac{M\cdot T}{\Delta\cdot B}}$, in case of finite background; η is the isotope abundance, ϵ is the detection efficiency, M is the active mass (kg), T is the live time (yr), B is the background index around $Q_{\beta\beta}$ expressed in counts/(keV $\cdot$ kg $\cdot$ yr) and Δ is the energy resolution at the Q-value. In order to maximize the sensitivity, an experiment for $0\nu\beta\beta$ search must have a large source mass, a very low background rate near the Q-value and a good energy resolution.[2]

2. The CUORE Experiment

The Cryogenic Underground Observatory for Rare Events (CUORE)[3–5] experiment is located at the Laboratori Nazionali del Gran Sasso (LNGS), Italy. It is among the international leading experiments for the search for $0\nu\beta\beta$ decay. The CUORE detector consists in a ∼1 tonne solid state cryogenic calorimeter made of 988 $^{(\mathrm{nat})}$TeO$_2$ crystals operated at ∼10 mK. This detector technology allows to profit of a large mass and a high granularity, for the investigation of rare events physics.

The choice of using $^{(\mathrm{nat})}$TeO$_2$ crystals for the CUORE experiment was driven by the several benefits these detectors can provide for the search of double beta decay of ^{130}Te.[6] The ^{130}Te isotope has the highest natural isotopic abundance (34.167%),[7] among the other $\beta\beta$ emitters; therefore there is no need for further enrichment. In the natural TeO$_2$ crystals, the $\beta\beta$ source is embedded into the detectors themselves, thus ensuring an high detection efficiency (∼90%). Moreover, the Q-value for the ^{130}Te $\beta\beta$ decay is $Q_{\beta\beta}$ (^{130}Te) = 2527 keV, above most of the natural radioactivity.

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After several decades of technology development and test demonstrators,[8] it was possible to proceed with a reproducible growth of large number of high quality and high purity crystals of ~1 kg each.[9] When the TeO_2 are operated as low-temperature detectors (10 mK), they show a very good energy resolution (~0.1–0.2% FWHM/E at $Q_{\beta\beta}$), which allows a better reconstruction of the background spectrum and a reduction of $2\nu\beta\beta$ decay irreducible background around $Q_{\beta\beta}$.

The CUORE TeO_2 detectors are operated as cryogenic bolometers sensitive to phonons.[10,11] An energy deposition in the crystal is converted into lattice excitations — phonons, which induce a slight temperature increase in the absorber. If the latter is operated at ~10 mK, the temperature variation is measurable via a sensor, a Neutron Transmutation-Doped (NTD) Germanium thermistor in case of the CUORE detectors, which converts the thermal signal into an electric signal by its resistance variation.[12,13] Each CUORE TeO_2 crystal is $5 \times 5 \times 5$ cm^3 in volume and 750 g in mass;[14] each of them is instrumented with one NTD thermistor and one Silicon heater (for thermal gain stabilization[15,16]). All the 988 detectors are arranged in an array of 19 towers, for a total mass of TeO_2 of 742 kg (206 kg of ^{130}Te), as reported in Fig. 1.

In order to operate all the TeO_2 detectors at ~10 mK, a dedicated cryogenic infrastructure was designed and built for CUORE.[17,18] CUORE makes use of a multistage cryogen-free cryostat, with two cooling systems: Pulse Tubes (PTs), lowering the temperature of the outer volumes down to 4 K, and a Dilution Unit (DU), cooling down the inner parts and the detectors to the base temperature of ~10 mK.

Fig. 1. The complete CUORE detector: The 19 towers hosting the 988 TeO_2 crystals.

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The CUORE ^{130}Te $0\nu\beta\beta$ projected sensitivity is $S_{0\nu} \sim 9 \cdot 10^{25}$ yr (90% C.L.) in 5 years, corresponding to a limit on the effective neutrino Majorana mass of $m_{\beta\beta} < 50$–130 meV. In order to reach this goal, a low background and low vibration environment is fundamental. The overburden of 1400 m calcareous rock (3600 m.w.e) provided by the LNGS underground location, allows to have a cosmic ray rate reduction of $\sim 10^{-6}$ relative to the surface. The materials for the detectors and the cryogenic infrastructure, as well as the assembly procedures underwent strict radio-purity controls to avoid re-contamination.[19] Passive lead shields protect the detector from external and cryostat radioactivity. The detector itself, given its high granularity, allows for some self-shielding. The CUORE background goal is 10^{-2} counts/(keV $\cdot$ kg $\cdot$ yr) in the Region Of Interest (ROI) around $Q_{\beta\beta}$. A mechanical-vibration isolation system acts by reducing the energy dissipation by vibrations coming from the cryogenic infrastructure, on the crystals.

3. CUORE Physics Data Taking

The CUORE data-taking started in Spring 2017, at a base temperature of almost 10 mK. After the initial data-taking phase, a significant effort was devoted in 2018 to understand the system and optimize the data-taking conditions.[20–22] Since March 2019, the data-taking is continuing smoothly with >90% uptime. See Fig. 2. CUORE acquired a total raw exposure (before analysis cuts) of almost 1 tonne · yr TeO_2 up to September 2020.

The CUORE data are grouped in data-sets, corresponding to 1 month of background/physics data with a few days of calibration (with ^{232}Th and ^{60}Co sources) at the start and end. In between two data-sets, we perform small maintenance activities, in order to ensure a stable and long-term operation of the system.

The signals from the CUORE detectors are read-out by a dedicated front-end electronics,[23–25] acting as a pre-amplification stage and an anti-aliasing filter. The

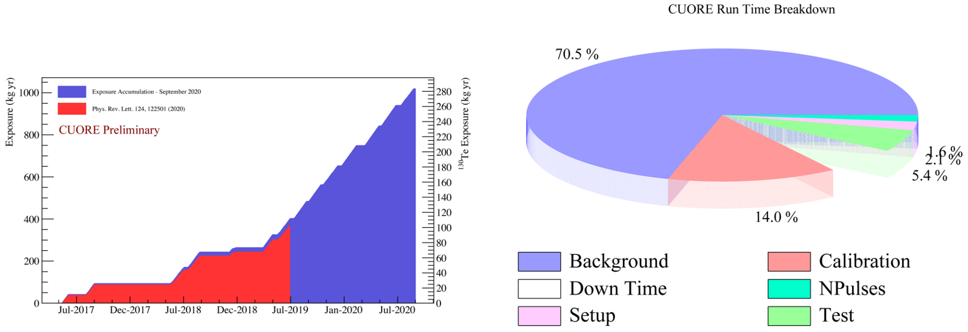

Fig. 2. (Color online) [Left] CUORE accumulated TeO_2 exposure since the initial cooldown in early 2017 up to early September 2020. [Right] CUORE run-type breakdown. The color bands indicate different periods of data-taking and activities: Energy calibration (red), physics data (blue), detector characterization and optimization (green, pink, light cyan), cryogenic maintenance and auxiliary interventions (blank).

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continuous data stream is digitized by a multi-reader DAQ system with 1 kHz sampling frequency.[26] The detector waveforms are separately triggered with a software trigger (online-derivative, offline-optimum trigger[27]); each single signal event is contained in a 10-s window: a 3s-pretrigger serving as a measurement of the detector base temperature, while the 7s-pulse allows to reconstruct the energy released in the process. The CUORE data undergo a series of sequential processing steps, using a modular software designed for the experiment.[28] We estimate the pulse amplitude using an optimum filter[29] that maximizes signal-to-noise ratio. We correct the signal amplitude against thermal drifts using tagged heater events with fixed energy. We identify a calibration function for each bolometer (a second-order polynomial with zero constant term), which we use to convert the amplitudes in energies. Once the energy of physical events is reconstructed, we discard time periods in which the detector conditions are not optimal. We define the signal shape corresponding to a true particle-interaction, by using γ lines from ^{40}K (1461 keV) and ^{60}Co (1173 and 1332 keV, respectively). Indeed, we build a signal-like event template with six pulse shape parameters; we discard all events with shape parameters not consistent with the reference. We profit the high granularity of the detectors by assigning to each event a value of multiplicity (M) to indicate the number of crystals interested by the same particle process within a certain time window (10 ms).

4. New Results from CUORE

The CUORE experiment released physics results from the unblinded data from 2017–2019. The first performed analysis consisted in the search of $0\nu\beta\beta$ decay of TeO_2[30,31] and afterwards the analysis was focused on the evaluation of the $2\nu\beta\beta$ half-life and background model reconstruction.[32] Studies of other rare processes,[33] such as the ^{130}Te $\beta\beta$ decay to the excited states of ^{130}Xe,[34] are ongoing profiting of the large amount of high-quality data from CUORE.

4.1. *$0\nu\beta\beta$ decay search*

The CUORE physics energy spectra, in which to look for a possible $0\nu\beta\beta$ signal of ^{130}Te, are obtained after applying basic quality cuts, rejection of spurious signals by pulse shape analysis and anti-coincidence ($M = 1$) selections to the raw data. The total exposure for the $0\nu\beta\beta$ search after the analysis selections was 372.4 kg · yr TeO_2 (103.6 kg · yr ^{130}Te).[30] The optimization of the event selections and of the analysis procedures is done on blinded energy spectra. The containment efficiency for a $0\nu\beta\beta$ decay to be single site event is evaluated via Monte Carlo simulation: $(88.350 \pm 0.090)\%$. The selection efficiencies (trigger, energy reconstruction, pile-up rejection, multiplicity, pulse-shape analysis) are evaluated on data: $(87.54 \pm 0.17)\%$. We build the detector response function on the 2615 keV calibration line; we then apply a scaling factor to obtain the correct energy resolution at $Q_{\beta\beta}$: (7.0 ± 0.4) keV FWHM.

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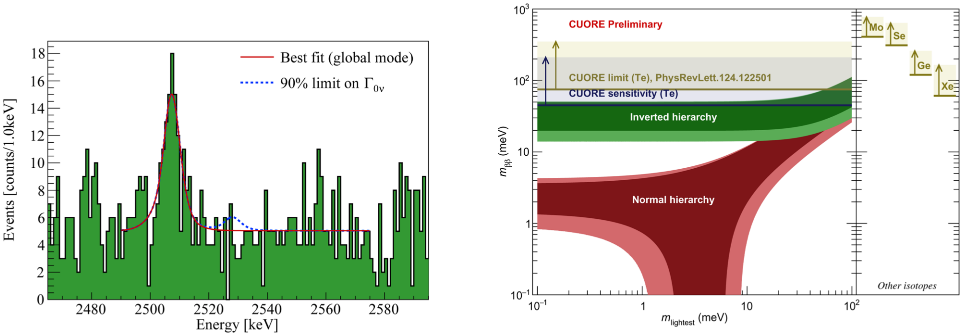

Fig. 3. [Left] Spectrum of the CUORE ROI for $0\nu\beta\beta$ and best-fit model result overlaid. [Right] Experimental limits on $m_{\beta\beta}$, including the results for ^{130}Te from CUORE. Figures from Ref. 30

The $0\nu\beta\beta$ peak search is performed on unblinded data. We utilize a Bayesian analysis (BAT[35]), with a likelihood model composed by: a flat continuum (B), a posited peak at $Q_{\beta\beta}$ (rate $\Gamma_{0\nu}$), a peak for the ^{60}Co sum peak. We proceed with an unbinned fit in the ROI [2490, 2575 keV] on physical range (rates non-negative), using a uniform prior on $\Gamma_{0\nu}$ (see Fig. 3). For the evaluation of the systematics, we repeat the fits with nuisance parameters, allowing negative rates; this has a <0.4% impact on the limit. We do not see evidence of signal; from the posterior of $\Gamma_{0\nu}$, we extract an upper limit of the decay rate, which we convert in a lower half-life limit for the $0\nu\beta\beta$ in ^{130}Te: $\mathrm{T}_{0\nu}^{1/2}$ $(^{130}\mathrm{Te}) > 3.2 \times 10^{25}$ yr (90% C.I. including systematics).

Repeating the fit in the ROI, without the $0\nu\beta\beta$ decay contribution, we can extract the ROI background index: $B = (1.38 \pm 0.07) \times 10^{-2}$ counts/(keV · kg · yr).

The exclusion sensitivity for the $0\nu\beta\beta$ decay is evaluated by generating pseudo-experiments with the background-only hypothesis and fitting the ROI with the background+signal hypothesis. The CUORE median exclusion sensitivity on ^{130}Te half-life, with the current data is: $\mathrm{S}_{0\nu}^{1/2}(^{130}\mathrm{Te}) = 1.7 \times 10^{25}$ yr; the probability to get a more stringent limit given the current sensitivity was 3.2%. The limit on $0\nu\beta\beta$ decay half-life can be converted in an upper limit of the effective neutrino mass term, in the context of light Majorana neutrino exchange: $\mathrm{m}_{\beta\beta} <$ 75–350 meV at 90% C.I. In Fig. 3, the current experimental limits on $m_{\beta\beta}$ are shown. 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.

4.2. *$2\nu\beta\beta$ decay measurement and background*

The reconstruction of the CUORE continuum profits of a Geant4[36, 37] dedicated Monte Carlo simulation of the detector, which convolves the physics events in the crystals with the measured detector response to produce the expected spectra.[38, 39] We consider 62 background sources in the simulation, a Bayesian Markov

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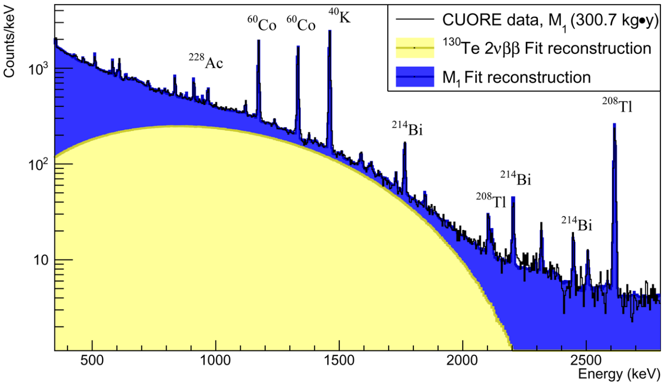

Fig. 4. (Color online) The CUORE observed spectrum (black) of multiplicity 1 events, with its reconstruction obtained by the background model. Figure from Ref. 32.

Chain–Monte Carlo fit with uniform priors is performed on the data utilizing the JAGS software.[40,41] We exploit coincidences and the detector self-shielding to constrain the location of the different background sources. The total exposure for the $2\nu\beta\beta$ analysis is 300.7 $\text{kg}\cdot\text{yr}$ of TeO_2. The background model is able to reproduce the major features of the observed spectra; the $2\nu\beta\beta$ decay is the dominant component of the observed single-site events' ($M = 1$) spectrum between ~1 MeV and 2 MeV, due to reduced γ backgrounds and self-shielding of outer TeO_2 towers (see Fig. 4). This allows us to provide a measurement of the ^{130}Te $2\nu\beta\beta$ half-life: $T^{1/2}_{2\nu}(^{130}\text{Te}) = 7.71^{+0.08}_{-0.06}(\text{stat})\ ^{+0.12}_{-0.15}(\text{syst}) \times 10^{20}$ yr.[32] The systematic uncertainties considered are related to data selection (geometric splitting, time splitting, fit range), choice of $2\nu\beta\beta$ spectral shape and unconstrained fallout products (^{90}Sr). This result is the most precise measurement of the $2\nu\beta\beta$ decay half-life of ^{130}Te to date, thanks to the strict radio-purity controls, the increased statistics, and the robust background model. It is consistent with the previous results (NEMO-3,[42] CUORE-0[43]).

4.3. $0\nu\beta\beta$ and $2\nu\beta\beta$ decays to excited states

Double beta decay can proceed also through transitions to the various excited states of the daughter nucleus.[44] The $2\nu\beta\beta$ decay to the 0^+ excited state has been observed in ^{100}Mo and ^{150}Nd, with half-lives of the order of few 10^{20} yr.

The signature of the decay is a cascade of de-excitation γs in coincidence with βs (see Fig. 5 [left]). We expect multi-site signatures ($M > 1$) and a background reduction with respect to the corresponding transitions to the ground state, especially in case of a high detector granularity. We performed the search of both $0\nu\beta\beta$ and $2\nu\beta\beta$ decays to the first 0^+ excited state of ^{130}Xe; both searches are based on a 372.5 $\text{kg}\cdot\text{yr}$ TeO_2 exposure. We considered only fully contained events for the analysis. We found no evidence of signal for both $0\nu\beta\beta$ and $2\nu\beta\beta$ decays of ^{130}Te to ^{130}Xe 0^+ excited state; an example of the unbinned Bayesian fit is reported in Fig. 5

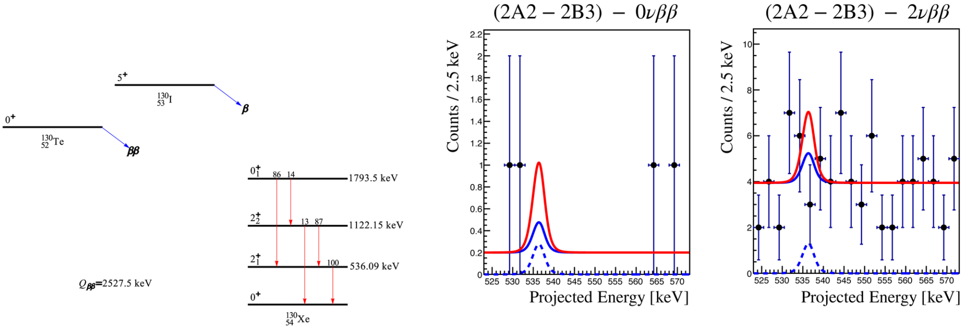

Fig. 5. (Color online) [Left] Decay scheme of ^{130}Te showing the energy levels of the daughter ^{130}Xe nucleus and the branching ratios and energies for the γ transition.[45] [Center] and [Right] Unbinned fit plotted on binned data for one of the signatures: Best fit curve (blue solid), its reconstructed signal component (blue dashed), and the 90 % C.I. marginalized limit on the decay rate (red solid). Figure from Ref.[34]

[center, right] for one of the signatures. From the combined analysis of the signatures which contribute the most to the discovery sensitivity in the $\beta\beta$ decay rate, we set the following limits on the decay half-lives: $T^{1/2}_{0\nu,0+}(^{130}\mathrm{Te}) > 5.9 \times 10^{24}$ yr (90% C.I.), $T^{1/2}_{2\nu,0+}(^{130}\mathrm{Te}) > 1.3 \times 10^{24}$ yr (90% C.I.).[34]

5. Conclusions

CUORE is the first tonne-scale operating bolometric $0\nu\beta\beta$ detector. We reported the new CUORE physics results of ^{130}Te $0\nu\beta\beta$ and $2\nu\beta\beta$ decays to ground and excited states with the physics data collected in 2017–2019.[30–32,34] A raw exposure of more than 1 tonne · yr has been achieved and data-taking is proceeding. Updated results for the 1 tonne · yr total exposure (after analysis cuts) will be released soon. The CUORE data taking is currently underway to collect 5 years of run time. The CUORE operations and data-taking give an important feedback for the future CUPID project (CUORE Upgrade with Particle IDentification).[46,47]

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