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Latest results from the CUORE experiment

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Summary. — The Cryogenic Underground Observatory for Rare Events (CUORE) is a tonne-scale experiment located at the Laboratori Nazionali del Gran Sasso that exploits the bolometric technique to search for neutrinoless double beta ($0\nu\beta\beta$) decay of ^{130}Te. Its detector consists of an array of 988 natural TeO_2 crystals grouped into 19 towers. With a total active mass of 742 kg (∼206 kg of ^{130}Te), CUORE is kept at a very low temperature (∼10 mK) by means of a powerful custom made dilution refrigerator. Data taking started at the beginning of 2017. Following several optimization campaigns in 2018 and early 2019, CUORE is currently in stable operating mode. After a brief introduction on the $0\nu\beta\beta$ decay mechanism and the CUORE detector, we focus on the second CUORE $0\nu\beta\beta$ result attained with an accumulated exposure of 372.5 kg · yr and a median exclusion sensitivity of $1.7 \cdot 10^{25}$ yr. No evidence of $0\nu\beta\beta$ signal was observed and a lower limit of $3.2 \cdot 10^{25}$ yr at the 90% Credibility Interval (C.I.) on the ^{130}Te half-life for this process was set. Finally, we discuss a new measurement of the ^{130}Te $2\nu\beta\beta$ half-life obtained with an improved model of CUORE background and present the CUORE future perspectives.

1. – Introduction

Neutrinoless double beta decay is a rare, second-order nuclear transition in which an initial nucleus (A, Z) decays to a member $(A, Z + 2)$ of the same isobaric multiplet with the simultaneous emission of two electrons [1].

In the attempt to investigate the nature of the $0\nu\beta\beta$ transition various theoretical possibilities were considered; however, the general interest has remained focused on the neutrino mass mechanism [2]. The decay rate can be expressed as

$$\Gamma_{0\nu\beta\beta} = G_{0\nu}|M_{0\nu}|^2 \frac{|m_{\beta\beta}|^2}{m_e^2}, \tag{1}$$

where $m_{\beta\beta}$ is $\left|\sum_{j=1,2,3} U_{ej}^2 m_j\right|$ if the $0\nu\beta\beta$ decay is mediated by light Majorana neutrino exchange. This process explicitly violates the lepton number (L) by two units and therefore its discovery would demonstrate that L is not a symmetry of nature. Combined with flavour mixing and cosmological measurements, it can provide unique constraints on the neutrino mass scale and establish whether neutrinos are Dirac or Majorana particles. Furthermore, this observation could be linked to the cosmic asymmetry between matter and antimatter (baryogenesis via leptogenesis [3]).

The experimental signature of $0\nu\beta\beta$ is a monoenergetic peak at the Q-value of the decay, considering the summed energy spectrum of the two emitted electrons. The candidate isotopes that could undergo $0\nu\beta\beta$ are even-even nuclei for which single beta decay is energetically forbidden. To maximize the sensitivity [4] an experiment must have a large source mass (in CUORE $\sim$742 kg), a very low background rate near $Q_{\beta\beta}$ (we measured 1.38(7) counts/keV/kg/yr [5]) and a good energy resolution (7.0(4) keV FWHM). The choice of the isotope has a strong impact as well: among candidate emitter nuclei for $0\nu\beta\beta$, ^{130}Te has the highest natural isotopic abundance ($\sim$34.17%) and a Q-value of (2527.515 ± 0.013) keV, above most of the natural γ radioactivity. The Cryogenic Underground Observatory for Rare Events (CUORE) [6] is a running experiment located at the Laboratori Nazionali del Gran Sasso (LNGS) whose main scientific goal is the search for $0\nu\beta\beta$ decay of ^{130}Te.

2. – The CUORE detector

The detector consists of a close-packed array of 988 natural-TeO_2 cubic crystals, for a total active mass of 742 kg ($\sim$206 kg of ^{130}Te).

A *bolometer* is a sensitive calorimeter in which the particle energy release is measured via the temperature increase of the absorber material. In CUORE, each bolometric detector has an energy absorber, *i.e.*, the crystal itself; a temperature sensor, a neutron-transmutation-doped germanium thermistor that converts the temperature rise into a voltage pulse; and a weak thermal link to the copper support structure to restore the reference temperature. By measuring the pulse amplitude, we can reconstruct the amount of energy released in particle events. At an operating temperature of roughly 10 mK, the typical TeO_2 heat capacity is such that 1 MeV corresponds to a temperature increase of $\sim$100 μK.

CUORE is cooled to cryogenic temperatures thanks to a powerful multistage custom-made ^{3}He/^{4}He dilution refrigerator [7]. After the first cooling step from room temperature is performed by the so called *fast cooling system*, 5 cryogen-free pulse tubes let us reach 4 K while maintaining a high duty cycle. Base temperature is reached with the final stage, *i.e.* the dilution unit. The dimensions, namely an experimental volume of $\sim$1 m^3 and a mass of about 17 tonnes (12.7 of which below 4 K), make the CUORE cryostat the largest dilution refrigeration in operation and the coldest cubic meter in the known universe. The cryostat design and construction had to respect very stringent experimental requirements in terms of temperature, mechanical stability, in order to keep extremely low vibrations levels, and materials radio-purity. In particular, besides the natural shielding provided by the LNGS from cosmic rays (3600 m.w.e. rock overburden), in order to suppress the γ and neutron background, two lead shields have been integrated into the cryogenic volume and a lead + polyethylene shield surround the whole cryostat. Internal shields are made of lead: the one surrounding and below CUORE detector is made of ancient Roman lead, whose radioactive emission is less than 4 mBq/kg of ^{210}Po.

CUORE detector assembly began in 2012 and data taking started in early 2017. As it was the first time such a huge solid-state cryogenic detector was ever operated, several optimization campaigns followed. Among them, we find a study of the vibrational noise induced by the pulse tubes that ended up with the development of an active noise cancellation system to properly tune their relative phases [8], a temperature scan to identify the optimal condition in terms of resolution and signal amplitude (current T is 11.8 mK) and an upgrade of our calibration setup in order to shorten calibration periods and avoid frequent data taking interruptions.

After the latest operation of maintenance of the cryogenic system performed in 2019, data taking is proceeding smoothly with an average rate of ~ 50 kg $\cdot$ yr. We group our data into datasets covering one to two months each, bookended by calibrations at the beginning and at the end. We use the data between calibration periods for the $0\nu\beta\beta$ decay search and refer to them collectively as *physics data*.

Data processing starts with the continuous acquisition of the voltage crossing the thermistor of each bolometer: the sampling frequency is 1 kHz. A single event is contained in a 10-s window: a 3-s pretrigger gives a proxy of the bolometer temperature, while the 7 s-pulse gives the amount of energy released, since this is proportional to its amplitude. We analyze waveforms that do not contain visible pulses to monitor and model our detector noise behavior. During the online data acquisition, we save continuous detector waveforms and separately trigger them with a software derivative trigger. This has the aim of monitoring the overall detector performance. In parallel to this, we developed an optimum trigger (OT) algorithm based on the optimum filter technique [9]. We retrigger all the collected data using OT in order to lower the energy thresholds of our detectors.

3. – Analysis techniques and search for neutrinoless double beta decay

The CUORE data analysis consists of a series of following steps that are performed by using a modular software specifically designed for the experiment. Once signal events are properly identified, we extract their amplitude by means of the matched filter technique as the maximum value of the filtered waveform. We then stabilize the signal amplitude against thermal drifts. For this purpose, we employ the silicon heaters placed on all the crystals to periodically inject stable voltage pulses with precise and fixed energy. For each channel, we determine the calibration coefficients referring to γ lines from ^{232}Th and ^{60}Co sources. Once the energy of physical events is reconstructed data are blinded: we produce an artificial peak at $Q_{\beta\beta}$ and we completely define our fit procedure to measure the signal rate $\Gamma_{0\nu\beta\beta}$ without knowing the real spectrum in the region of interest (ROI).

Then a series of cut is applied to them in order to reliably identify $0\nu\beta\beta$ candidate events. We remove noisy periods of data taking from the final data selection for $0\nu\beta\beta$ search. Since we expect from Monte Carlo (MC) simulations that most of $0\nu\beta\beta$ events ($\sim$88%) will fully release their energy in a single crystal, we also apply an anti-coincidence cut to minimize background contribution in the ROI. This is mainly due to α particles and multiple-Compton scatterings from the ^{208}Tl line at 2615 keV. Finally, we discard all pulses whose shape is not consistent with a true particle interaction. The signal efficiency is calculated as the product of the containment efficiency, the reconstruction efficiency, the anticoincidence efficiency, and the pulse shape analysis (PSA) efficiency. The former is evaluated by means of MC simulations, the latters referring to the specific set of datasets included in the analysis. We model our detector response function using the high statistics calibration spectrum around the ^{208}Tl line at 2615 keV. We employ the extracted function to fit the most prominent γ lines in physics data. In this way we extrapolate the energy resolution at the Q-value and quantify any possible shift in the position of the signal peak.

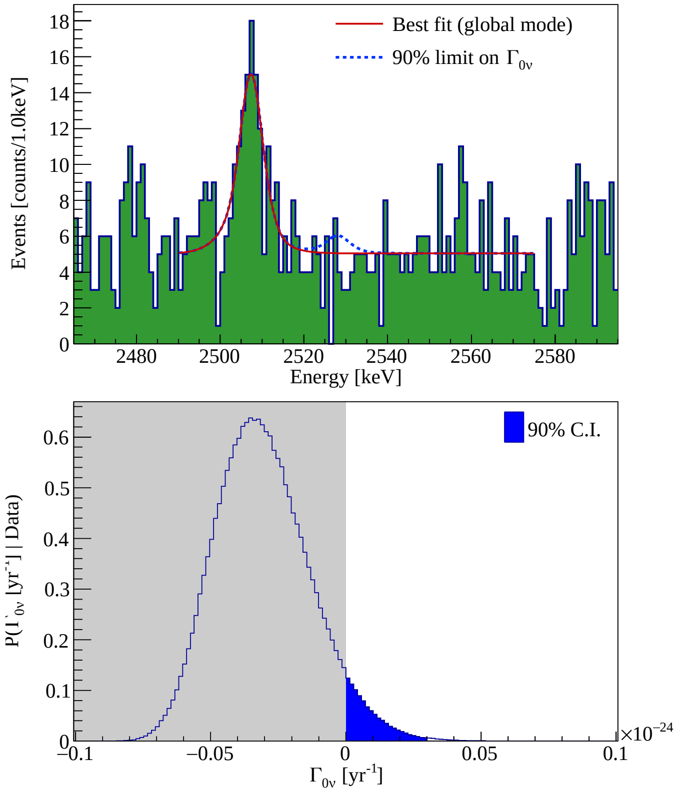

Fig. 1. – Top: ROI spectrum with the best-fit curve (solid red) and the best fit-curve with the $0\nu\beta\beta$ decay component fixed to the 90% C.I. limit (dashed blue) Bottom: Posterior on $\Gamma_{0\nu\beta\beta}$ with all systematics included for the fit on the physical range ($\Gamma_{0\nu}$) and on the full range. The 90% C.I. is shown in blue. Figures from ref. [5].

The $0\nu\beta\beta$ decay search presented here is based on an accumulated TeO_2 exposure of $372.5\ \mathrm{kg}\cdot\mathrm{yr}$, corresponding to the first 7 datasets acquired from 2017 to 2019. We model the physics spectrum in the ROI (2490,2575) keV with a flat background continuum, a posited signal peak and the ^{60}Co sum peak at 2505.7 keV. The latter contribution accounts for two parameters in the minimal fit, one for the peak amplitude and a second one for the position. We perform a Bayesian unbinned fit to the maximum posterior probability combined over all calorimeters and datasets, imposing a uniform prior on positive values of the signal rate $\Gamma_{0\nu\beta\beta}$. We find no evidence of $0\nu\beta\beta$ decay and set a lower limit on the ^{130}Te half-life for this process $T^{0\nu}_{1/2} > 3.2 \cdot 10^{25}$ yr (90% C.I) [5]. If one assumes that $0\nu\beta\beta$ decay is mediated by the light Majorana neutrino exchange, this result corresponds to a range of upper limits on the effective Majorana mass of $m_{\beta\beta} < 75 - 350$ meV, depending on the nuclear matrix elements calculations considered. We use a fully Bayesian approach to evaluate how the systematics, included as additional nuisance parameters in the fit, affect our estimate of the signal rate. Since we observe a background under-fluctuation removing the physical constraint on $\Gamma_{0\nu\beta\beta}$, we artificially release it allowing for negative rate values in order to quantify its change when systematics are activated. The impact on the best fit value is $< 0.04\%$, while the effect on the half-life (extracted when $\Gamma_{0\nu\beta\beta} > 0$ holds) is smaller than 0.4%. With a median limit setting sensitivity of $S^{0\nu}_{1/2} = 1.7 \cdot 10^{25}$ yr, the probability to obtain a stronger limit than the measured one is about 3%.

4. – The CUORE background model: Measurement of the $2\nu\beta\beta$ half life

In order to systematically study the CUORE radioactive contamination, a background model was developed based on the results from CUORE predecessor, *i.e.* CUORE-0 experiment, and radio-assays directly performed on the CUORE detector materials [10]. Such model includes 9 geometric elements: the crystals, the towers copper structure, the copper vessel, the cryostat thermal shields, the lead shields and the lead suspension system as described in [11]. They account for a total of 60 β/γ contaminants and the SM allowed counterpart of the decay of interest, *i.e.* ^{130}Te $2\nu\beta\beta$ transition. An additional contribution for the residual muon flux at the detectors is also included in the model. Simulations of the CUORE events are produced with GEANT4 and three spectra are considered to perform an MCMC binned fit to real data. The first is the spectrum of single bolometer events whereby $2\nu\beta\beta$ should give the maximum contribution, the second is the one produced by simultaneous events on two crystals and the third is obtained considering the sum energy of the former. A flat prior is set on all the fit parameters except the muon contribution for which a Gaussian probability density function is assumed. Including all the possible systematic effects, a new measurement of the $2\nu\beta\beta$ ^{130}Te half-life was extracted and yielded the world's most precise measurement for this isotope [11]:

$$T^{2\nu\beta\beta}_{1/2} = \left[7.71^{+0.08}_{-0.06}\,(\text{stat.})^{+0.12}_{-0.15}\,(\text{syst.})\right] \cdot 10^{20} \ \text{yr} \ . \tag{2}$$

5. – Conclusion and future perspectives

The CUORE data taking is currently proceeding smoothly towards the goal of a 5 years live time. Other rare decay searches are possible with CUORE data. The analysis of the ^{130}Te double beta decay to the first excited states based on the most significant signatures is among them [12]. Given the previous results we can assess that CUORE proved the scalability of the bolometric technique and paved the way to rare processes bolometric searches. The experience of CUORE will be the starting point of the future CUPID (CUORE Upgrade with Particle IDentification) project [13].

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