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Latest results from the CUORE experiment

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The CUORE experiment is searching for the neutrinoless double β decay of the ^{130}Te using cryogenic calorimeters. The CUORE detector consists of 988 TeO_2 crystals packed in 19 towers and placed in a cryogenic facility with a base temperature of 10 mK. Crystals are enriched in the isotope ^{130}Te which is the candidate for the neutrinoless double β decay. It is taking data since 2017 at the Laboratori Nazionali del Gran Sasso in Italy. Such a long operation of a bolometric experiment in stable condition has no precedent: by reaching 1 tonne-year of exposure CUORE set a fundamental milestone for any future experiment using this technology. The CUORE collaboration investigated the neutrinoless double β decay of ^{130}Te exploiting the updated 1 tonne-year of statistics, setting a limit of 2.2×10^{25} yr at the 90% of credibility interval on the half-life, with a median sensitivity of 2.8×10^{25} yr.

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1. Introduction

Despite the discovery of the neutrino oscillations established that the neutrino is a massive particle, the origin of its mass still needs investigations. Being a neutral and massive particle, there is an open possibility that the neutrno is a Majorana particle; in this case neutrino and anti-neutrino would be the same particle [1]. This hypothesis is so promising since it would give rise to processes in which the total lepton number is violated, which would be an important hint for the explanation of the lack of antimatter in our universe.

The neutrinoless double β decay ($0\nu\beta\beta$) is one of the lepton number violating processes consequent to the Majorana nature of the neutrino [2]: it is an alternative mode of the double β decay ($2\nu\beta\beta$), which have been observed and studied in 12 nuclei. This is one of the processes with the longest lifetime in the universe, which ranges from 10^{18} to 10^{24} yr, depending on the isotope. Despite the knowledge acquired on this process keeps rising, the neutrinoless mode has not yet been found. To search for this decay, it is sufficient to look for a peak of events at the Q-value of the double β decay. Thanks to the efforts of several experiments, we know that its half-life has to be longer that 10^{24}-10^{26} yr, depending on the isotope.

Cryogenic calorimeters, also called bolometers, are one of the most promising detectors for the search of very rare processes such as the $0\nu\beta\beta$ [3]. Indeed, these detectors present an excellent energy resolution, of the order of 0.3% FWHM in the region of interest for the $0\nu\beta\beta$, and a very good containment efficiency, of about 80-90%. These are two of the fundamental characteristics needed by any experiment which aim to push at limits the sensitivity on the $0\nu\beta\beta$ half-life. Cryogenic calorimeters consist of crystals, enriched in the isotope of interest, and equipped with a cryogenic sensor to convert a temperature variation into an electric signal. A particle interacting in the crystals releases energy, which is converted into heat an detected as a temperature increase. The detection of such a small temperature variation, which is about 100 μK/MeV, is possible thanks to the very low temperature (of the order of 10 mK) reached in the cryogenic facilities where bolometers are operated.

Another fundamental properties that experiments searching for the $0\nu\beta\beta$ have to take care of is the background level, which has to be as low as possible. For this reason these kind of experiments are operated in deep underground laboratories to shield the detector against cosmic rays. Moreover, the materials to build the detector have to be radiopure to reduce as much as possible the contamination from natural radioactivity. The CUORE (Cryogenic Underground Observatory for Rare Events) experiment represent the state of art of this technology [4].

2. The CUORE Experiment

CUORE is the result of almost 30 years of $0\nu\beta\beta$ studies and development of bolometric detectors [5]. It is made of 988 $5 \times 5 \times 5$ cm^3 crystals of TeO$_2$ enriched in ^{130}Te. Among the isotopes candidate for the $0\nu\beta\beta$, the ^{130}Te has a very high natural isotopic abundance, about 34%, which allows a cost-effective use of natural tellurium. Moreover, the Q-value of the ^{130}Te double β decay, which is (2527.515 ± 0.013) keV, lies above most of the natural radioactivity γ background. The TeO$_2$ crystals are arranged in 19 towers packed inside a multistage cryogen-free cryostat, uniquely designed for this application. It is equipped with 5 pulse tube cryocoolers to maintain an

high duty cycle by avoiding the cryogen refill. The experimental volume, about 1 m^3, is mechanically decoupled from the cryostat to reduce the noise induced by the vibrations. Moreover, we optimize periodically the pulse tube relative phases to minimize their contribution to low frequencies noise. Each TeO_2 crystal is equipped with an NTD-Ge thermistor which convert a temperature variation into an electrical pulse. Moreover, an heater injects periodically a fixed energy thermal pulse in each crystal to correct the pulse amplitude dependence by the cryostat thermal instabilities.
Finally, in order to suppress as much as possible any radioactive contamination, we applied a strong material selection and cleaning and we exploited three lead shields, two inside the cryostat and one outside, against external γ radioactivity.

3. Analysis and Results

We amplified and filtered the electrical pulses produced by the NTD-Ge thermistors through a 6-pole Bessel anti-aliasing filter. By saving continuous waveforms, we triggered the pulses offline applying an algorithm to suppress the low signal-to-noise ratio frequencies. The pulses window had a total lenght of 10 s, including a pre-trigger of 3 s. CUORE data are divided in one/two months long datasets; at the end, and at the beginning of each dataset, we collected calibration data in presence of an external ^{232}Th-^{60}Co source.
We maximized the signal-to-noise ratio by applying a matched filter, called optimum filter [6], whose transfer function is based on the average pulse and noise waveform power spectrum for each dataset and each crystal. The ^{232}Th-^{60}Co source provided several γ lines which allowed to build a calibration curve to turn the amplitude into energy. We applied some cuts on data to remove noisy or spurious events and to ensure a high data quality for the analysis. Then, we applied a pulse shape discrimination which employs the PCA algorithm (see Ref. [7]).
We studied the detector response function from calibration datasets on the 2615 keV peak from ^{208}Tl, present in the ^{232}Th decay chain, which is the closest to the $0\nu\beta\beta$ Q-value: we modelled it with the superposition of three Gaussians with the same width. Finally, we blinded the data by shifting a portion of events from the 2615 keV γ line to the $0\nu\beta\beta$ Q-value, and viceversa.
We defined the region of interest (ROI) for the $0\nu\beta\beta$ as a window around the Q-value, namely between 2490 and 2575 keV. By fitting the energy spectrum of the ROI it is possible to identify the contribution due to the $0\nu\beta\beta$. The fit model consisted of the detector response function and a linear function for the background. The ROI also included the peak due to the ^{60}Co, as shown in Fig. 1, whose rate was one of the free parameters of the fit. The other free parameters were the rate of the signal and the background index and slope. We treated the systematics of this analysis as nuisance parameters. In particular these were the efficiencies (of containment and of the analysis cuts), the energy scale, the Q-value, the energy resolution and the ^{130}Te isotopic abundance. We performed the fit by means of the BAT (Bayesian Analysis Toolkit) software.
We didn't find any evidence for the $0\nu\beta\beta$, thus we set a lower limit from the signal rate posterior. In terms of $0\nu\beta\beta$ half-life it resulted to be 2.2 $\times 10^{25}$ yr at 90% of credibility interval. We evaluated the median sensitivity from toy experiments, in background only hypothesis, by using the real data fit results: it resulted to be 2.8 $\times 10^{25}$ yr and the probability to obtain a limit stronger than the measured one is 72% [8].
The background index arising from the ROI fit is $1.49(4) \times 10^{-2}$ counts / (keV kg yr) and, as showed

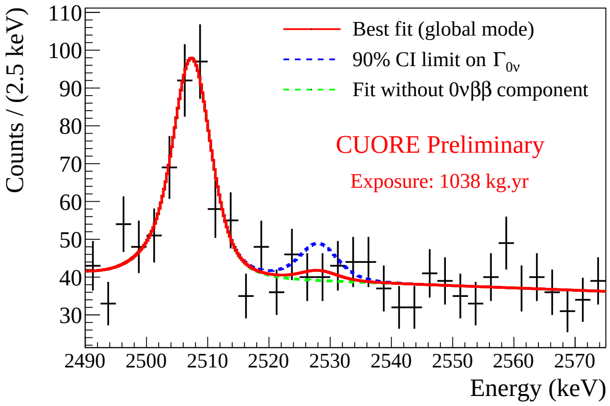

Figure 1: Energy spectrum in the ROI of the ^{130}Te $0\nu\beta\beta$. The best fit is shown with the solid red curve while the dotted blue and green curves represent the fit with the signal rate fixed at its 90% C.I. limit and at 0, respectively.

in [9] it is mostly due to degraded α particles. This is a fundamental input for CUPID (CUORE Upgrade with Particle IDentification) which will be the successor of CUORE, taking its place in the same cryogenic facility. Indeed, CUPID will reject the dominant α background by means of scintillating crystals and light detectors, aiming to search for the $0\nu\beta\beta$ in a background free environment [10].

We achieved these results thanks to the high statistics collected by the CUORE detector. Such a long detector operation has no precedent in a bolometric experiment, making CUORE the first and only able to collect 1 tonne-year of data in stable condition. This consideration establish the success of the CUORE experiment, which set a milestone for CUPID and any other future bolometric experiment.

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