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Results from the CUORE experiment

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Summary. — Neutrinoless double beta decay ($0\nu\beta\beta$) is a rare, second-order nuclear transition that occurs only if neutrinos are massive Majorana particles or through new physics beyond Standard Model. This process explicitly violates the lepton number (L) by two units and, therefore, the observation of $0\nu\beta\beta$ would demonstrate that L is not a symmetry of nature. Combined with flavour mixing and cosmological measurements, it can provide unique contraints on neutrino mass scale and establish whether neutrinos are Dirac or Majorana particles. The Cryogenic Underground Observatory for Rare Events (CUORE) is an experiment located at the LNGS searching for $0\nu\beta\beta$ decay of ^{130}Te. CUORE exploits the bolometric technique to reach high resolution around the Q-value (2527.5 keV). It consists of an array of 988 natural TeO_2 cubic crystals grouped into 19 towers. With a total active mass of 742 kg (∼206 kg of ^{130}Te), CUORE is operated at very low temperature with a new ^{3}He/^{4}He refrigerator. Data taking started at the beginning of 2017. After a brief introduction on the detector and the way data analysis is performed, I describe CUORE first results for the search of the $0\nu\beta\beta$ decay that were published in March 2018.

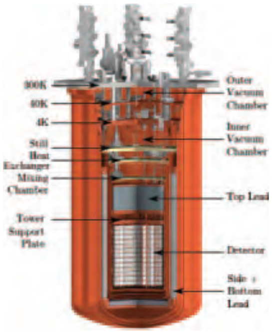

Fig. 1. – Rendering of the CUORE cryostat.

1. – Introduction

Neutrinoless double beta decay represents one of the most powerful ways to probe experimentally the existence of lepton flavour violation and determine missing neutrino properties. The decay rate can be expressed as $\Gamma_{0\nu\beta\beta} = G_{0\nu}\ |M_{0\nu}|^2\ \frac{m_{\beta\beta}}{m_e}$, where $m_{\beta\beta}$ is $|\sum_{i=1,2,3}\ U_{ei}^2\ m_i|$ if the $0\nu\beta\beta$ decay is mediated by light Majorana neutrino exchange.

A measurement of the decay rate gives the possibility to constrain the value of the effective Majorana mass. If it occurs, the $0\nu\beta\beta$ decay will have a robust experimental signature: a sharp peak at the Q-value of the decay in the summed energy spectrum of the final state electrons. To maximize the sensitivity [1] an experiment must have a large source mass (in CUORE $\sim$742 kg), a very low backround rate near $Q_{\beta\beta}$ (our goal is 0.01 counts/keV/kg/yr) and a good energy resolution (CUORE aims at 5 keV). Also the choice of the isotope has a strong impact: among candidates for $0\nu\beta\beta$, ^{130}Te has the highest natural abundance (34.17%) and large $Q_{\beta\beta}$ of (2527.515 ± 0.013) keV.

The Cryogenic Underground Observatory for Rare Events (CUORE) [2] applies the innovative bolometric technique at an unprecedent scale to the search for the $0\nu\beta\beta$ decay of tellurium isotopes. Located at the Laboratori Nazionali del Gran Sasso, CUORE is composed of a segmented array of 988 TeO_2 detectors arranged into 19 towers and operated at extremely low temperatures. The total active mass of 742 kg, ^{130}Te is 206 kg.

2. – CUORE detector

A bolometer is a sensitive calorimeter that measures the energy deposited after a particle interaction thanks to the increase in the base temperature of the medium. Each bolometer in CUORE has three primary components: an energy absorber (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 frame that acts both as the structural support and the thermal bath to restore the reference temperature. Measuring the signal amplitude we can find the amount of energy released in the process. At the operating temperature of 10 mK, the typical heat capacity corresponds to $\Delta T/\Delta E \sim 100\,\mu$K/MeV and a voltage increase of $\sim$1 V.

CUORE towers are arranged in a close-packed array and thermally connected to the mixing chamber of a ^{3}He/^{4}He refrigerator [3] as shown in fig. 1. Precooling to maintain the dilution cycle is realized by five two-stage ($\sim$40 K and $\sim$4 K) pulse tube cryocoolers, whereas the base temperature is reached through the ^{3}He/^{4}He mixture. The operating temperature is a compromise between maximizing thermal gain and optimizing the signal bandwidth. The dimensions, experimental volume and mass ($\sim$1 m^3 and $\sim$15 tons, respectively), make CUORE cryostat the largest and most powerful cryogen-free dilution cryostat in operation. Its realization followed strict experimental requirements, such as mechanical insulation and extremely low levels of radioactivity for the materials used. In order to suppress external γ-ray background, neutrons and environmental contributions two lead shields are integrated into the cryogenic volume and two external shields surround the detector. Thanks to the analysis of CUORE-0 [4] data and the radio assay of the materials used for CUORE detector, it was possible to identify the main background sources [5] in the region of interest and to make a Monte Carlo simulation to find an estimate of the background index. Alpha decays from the surface of the copper frame give the main contribution, the total B.I. is $[1.00 \pm 0.03 \text{ (stat.) } ^{+0.23}_{-0.10} \text{ (syst.)}]10^{-2}$ counts/keV/kg/yr.

3. – Analysis techniques and first CUORE results

The first result on $0\nu\beta\beta$ of ^{130}Te was obtained with two datasets, the first including May and June acquisition, the last made of August and September data. Both datasets include initial and final calibration phases, used to identify the detector response to signals of known energy and to check if it is stable over the period considered. We use data collected between calibrations for the $0\nu\beta\beta$ decay search. A single event is made of a 10 s window (3 s before and 7 after the trigger): the pretrigger gives a measurement of the bolometer temperature before the interaction. We also analyze waveforms that do not contain visible pulses to monitor and model our detector noise behaviour.

A total of 984 of 988 channels are working properly and we found an overall average event rate of $\sim$50 mHz in calibration data and $\sim$6 mHz in physics data. The exposure for the two dataset is 86.3 kg $\cdot$ yr for TeO$_2$ and 24.0 kg $\cdot$ yr for ^{130}Te. Data analysis proceeds through several steps. First, the amplitude of each pulse is estimated, by means of a filter that maximizes the SNR. The signal amplitude is stabilized against thermal drifts and calibration coefficients are determined using 6 γ lines from ^{232}Th. Then data are blinded: we produce an artificial peak at $Q_{\beta\beta}$ and the fit procedure to measure $\Gamma_{0\nu\beta\beta}$ is fixed without knowing the real spectrum in the ROI. As we expect any $0\nu\beta\beta$ decay event to release the whole energy in the same crystal in which it took place (88% probability), we remove all events that occurred in different bolometers within 10 ms. The detector response function is determined using high statistics ^{208}Tl 2615 keV γ line from calibration data and includes three Gaussian components. The energetic resolution (FWHM) is (8.3 ± 0.4) keV for the first dataset and (7.4 ± 0.7) keV for the second one.

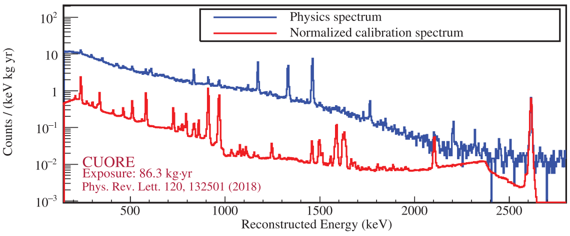

Fig. 2. – Energy spectra of phsyics (blue) and calibration (red) data. The calibration spectrum is normalized to the physics data at the 2615 keV line. Figure taken from ref. [6].

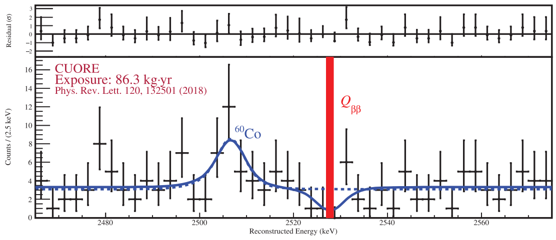

Fig. 3. – Bottom: best-fit model (solid blue line) overlaid on the spectrum of $0\nu\beta\beta$ decay candidates. The vertical band is centered at $Q_{\beta\beta}$. Top: normalized residuals. Figure taken from ref. [6].

Calibration and unblinded phsysics spectra are shown in fig. 2. The fit model for the ROI (2465–2575 keV) includes the $0\nu\beta\beta$ decay peak, a peak for the ^{60}Co coincident gamma rays (1173 and 1332 keV) and a flat background. The observed background index in the ROI is (0.014 ± 0.002) counts/keV/kg/yr, in line with our expectations. The 155 candidate events together with the result of the fit are shown in fig. 3.

The best fit $\Gamma_{0\nu\beta\beta}$ is $(-1.0\ ^{+0.4}_{-0.3}$ (stat.) $\pm$ 0.1 (syst.)) 10^{-25} yr^{-1}. We conclude that there is no evidence for the $0\nu\beta\beta$ decay and set a limit on the ^{130}Te half-life $\tau^{0\nu}_{1/2} > 1.3 \cdot 10^{25}$ yr (90% C.L.) [6]. Combining the first CUORE result with the estimates obtained from its two predecessors, CUORE-0 and Cuoricino, we place the most stringent limit to date on the half-life of ^{130}Te for the $0\nu\beta\beta$ decay: $\tau^{0\nu}_{1/2} > 1.5 \cdot 10^{25}$ yr (90% C.L.). Interpreting this result in the framework in which $0\nu\beta\beta$ is mediated by light Majorana neutrino exchange, we can translate it into a limit on the effective Majorana mass: $m_{\beta\beta} < (140\text{–}400)$ meV.

In conclusion, CUORE is the first ton-scale cryogenic detector for the search for $0\nu\beta\beta$. The successful operation paves the way to the use of large-mass bolometer arrays for rare-event searches. Even if further optimization is needed, the results we gained with two datasets show that our purposes are within the reach of 5 years data taking.

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