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Status and prospects of discovery of $0\nu\beta\beta$ decay with the CUORE detector

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Summary. — In this contribution we present the achievements of the CUORE experiment so far. It is the first tonne-scale bolometric detector and it is in stable data taking since 2018. We reached to collect about 1800 kg×yr of exposure of which more than 1 ton×year have been analysed. The CUORE detector is meant to search for the neutrinoless double β decay ($0\nu\beta\beta$) of the ^{130}Te isotope. This is a beyond Standard Model process which could establish the nature of the neutrino to be Dirac or a Majorana particle. It is an alternative mode of the two-neutrinos double β decay, a rare decay which have been precisely measured by CUORE in the ^{130}Te. We found no evidence of the $0\nu\beta\beta$ and we set a Bayesian lower limit of 2.2×10^{25}yr on its half-life. The expertise achieved by CUORE set a milestone for any future bolometric detector, including CUPID, which is the planned next generation experiment searching for $0\nu\beta\beta$ with scintillating bolometers.

1. – Introduction

Since the discovery of neutrino flavour oscillation, we learned that this elusive particle is massive. This was not predicted by the Standard Model of particle physics, and it opens the possibility for different scenarios. Indeed, we don't know yet the value of the neutrino mass neither its origin. Being a neutral fermion, there is the possibility to describe such a particle with a model different from the Dirac one, which rules all the other fermions. It is the case of a theory elaborated by E. Majorana in 1937 [1]. In this picture the neutrino would coincide with its own antiparticle, giving rise to processes in which the total lepton number is violated. It is the case of the neutrinoless double β decay ($0\nu\beta\beta$), which predict the simultaneous conversion of 2 neutrons into protons with the emission of only 2 electrons in the final state, thus violating the lepton number of 2 units [2]. Beside the discovery of the true origin of the mass of the neutrino, the importance of the search for this process relies in the possibility to explain the asymmetry of matter and antimatter in our universe starting from the lepton number violation. Such a symmetry violation has never been observed, so the observation of the $0\nu\beta\beta$ would be the first hint for such explanation.

This process is an alternative mode of the two-neutrinos double β decay ($2\nu\beta\beta$) which is a rare process although it is predicted in the Standard Model. It has been observed in about 11 nuclei in which the single β decay is energetically forbidden. This, happens in particular in nuclei with the same number of protons and neutrons, which are also the candidates for the $0\nu\beta\beta$. The half-life of the $2\nu\beta\beta$ has been precisely measured by several experiments and ranges from 10^{18} to 10^{24} yr.

Differently from the $0\nu\beta\beta$ it provides the emission of 2 electrons and 2 antineutrinos in the final state, giving rise to a continuous energy spectrum, due to the sum of electrons energies, ending at the Q-value of the given isotope. The $0\nu\beta\beta$ instead has a clear signature given by a monochromatic peak at the Q-value of the isotope. The actual half-life best limits on this decay ranges between 10^{24}–10^{26} yr depending on the isotope. This limit can be translated into an upper limit on the so called effective majorana mass ($m_{\beta\beta}$) which is a quantity directly related to the lepton number violation, and thus it is proportional to the amplitude of the process through the following formula:

$$(t^{0\nu}_{1/2})^{-1} = G^{0\nu}\,|M^{0\nu}|^2\,\frac{|\langle m_{\beta\beta}\rangle|^2}{m_e^2} \tag{1}$$

where $t^{0\nu}_{1/2}$ is the $0\nu\beta\beta$ half-life, $G^{0\nu}$ is the phase space factor, $M^{0\nu}$ is the nuclear matrix element and m_e is the electron mass as a energy scale reference to $m_{\beta\beta}$. The use of $m_{\beta\beta}$, which ranges between about 60 and 600 meV in the current experiments best limits, allows a direct comparison of the results on different isotopes [3].

The sensitivity on the $0\nu\beta\beta$ half-life is described by the following formula:

$$S_0\nu \propto \epsilon\sqrt{\frac{M\,T}{\Delta\,B}} \tag{2}$$

where ϵ is the efficiency, M is the active mass, T the livetime, Δ the energy resolution and B the background level in the Region Of Interest (ROI) for the $0\nu\beta\beta$. Cryogenic calorimeters, also called bolometers, are the particle detectors exploited by the CUORE (Cryogenic Underground Observatory for Rare Events) as well as by the CUPID-0 and CUPID-Mo medium mass demonstrators for the next generation experiment CUPID

(CUORE Upgrade with Particle IDentification) for the search of the $0\nu\beta\beta$. The peculiar features of this technology perfectly suit the requirements of Eq. 2 to increase the half-life sensitivity on this process [4, 5]. These are made with crystals containing the candidate isotope and kept at very low temperatures (of the order of 10 mK) by dedicated cryogenic facilities. As a particle interact with the crystal it increases its temperature producing thermal phonons. The temperature (ΔT) increase follows the formula $\Delta T = \Delta E/C$ where ΔE is the energy released in the crystal and C is the thermal capacity. Since for the crystal $C \sim T^3$, it is possible to detect the temperature increase due to an energy release thanks to the very low operation temperature. The thermal phonons are converted into an electric signal by a cryogenic sensor, which is a Neutron Doped Transmutation germanium (NTD-Ge) thermistor in the case of CUORE. This detection mechanism guarantees an excellent energy resolution (of the order of 0.2-0.3% FWHM at the ROI). Moreover, cryogenic calorimeters present a very high efficiency since the absorber, *i.e.*, the crystal, coincide with the source of the decay. These detectors have also a large flexibility in the choice of the materials, both of the experimental setup and of the absorber, which presents manifold advantages. First of all it is possible to build the detector using radiopure materials to reduce the background level due to natural radioactivity from contamination. Then it is possible to choice the crystal compound according to the needs of the experiment (*e.g.*, scintillating crystals can be used as done by CUPID-0 and CUPID-Mo). Finally, this technology allows to accurately choose the candidate isotope, which is a crucial aspect of the experiment. Indeed, an isotope characterized by an high Q-value for the double β decay will have a lower background index in the ROI because of a reduced contribution from natural radioactivity. In particular, the endpoint of the γ natural radioactivity is the 2615 keV line from the ^{208}Tl, present in the ^{232}Th decay chain. The isotope chosen for CUORE, the ^{130}Te, has a Q-value in a low background region between the 2615 keV Compton edge and the photo-peak, *i.e.* (2527.515 ± 0.013) keV. The other great advantage offered by the ^{130}Te is that it has the largest isotopic abundance (34%) among the possible candidates, which improves the active mass exposure and allows a cost-effective use of natural tellurium. Typically, these detectors are operated in underground laboratories, such as the Laboratori Nazionali del Gran Sasso (LNGS) to shield the experiment against cosmic rays which represent a potential background. Last, cryogenic calorimeters technology can be implemented in large scale detectors array, as demonstrated by the CUORE experiment.

2. – The CUORE detector

The CUORE detector (fig. 1) represent a milestone for the development of the bolometric technology and for the large scale cryogenic experiments [6]. It is made of 988 5 $\times$ 5 $\times$ 5 cm^3 natural crystals of TeO$_2$, arranged in 19 towers packed inside a multistage cryogen-free cryostat, uniquely designed for this application. It is equipped with 5 pulse tubes cryocoolers to maintain an high duty cycle by avoiding the cryogen refill. The CUORE cryostat is the key element for the success of the experiment. It reached to cool down 15 tons of material below 4 K, 3 tons of which below 50 mK. 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 tubes relative phases to minimize their contribution to low frequencies noise [7]. Moreover, a Si heater is glued on crystals for thermal gain correction. In particular, it injects periodically a fixed energy thermal pulse in each crystal to correct the pulse amplitude dependence by the cryostat thermal instabilities.

CUORE is located underground at the LNGS in Italy, under a rock overburden equivalent to approximately 3600 m of water, which shields from hadronic cosmic rays and reduces the muon flux by six orders of magnitude.

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.

Since 2019 CUORE is in stable data taking, with less than 8% of down time. We collected up to now about $\sim$1800 kg×yr of exposure (fig. 2), of which more than 1 ton×yr have been analysed.

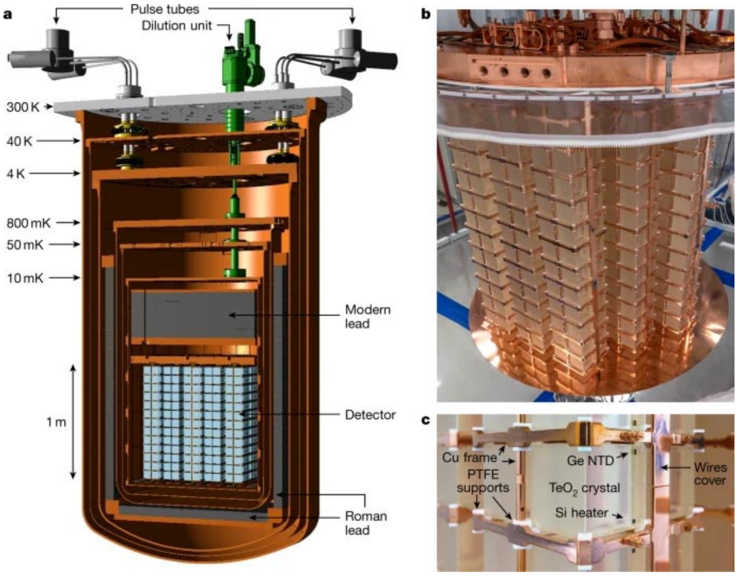

Fig. 1. – On the left, rendering of the millikelvin facility of CUORE. A picture of the detector is shown in the top right panel while the bottom right panel depicts a single bolometer in the CUORE detector.

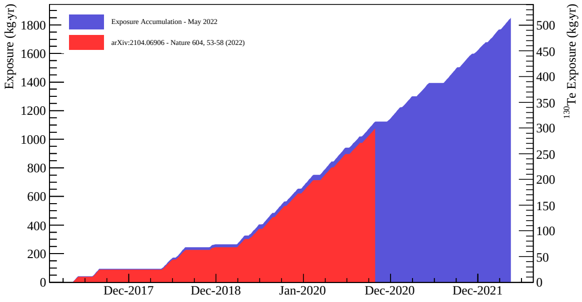

Fig. 2. – CUORE data taking from the beginning to May 2022. The plateaus are due to cryogenic maintenance.

3. – Data 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 [8], 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. [9]).

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.

After the optimization of the analysis procedure, we could proceed with the fit of the energy spectrum to search for $0\nu\beta\beta$ events. The ROI we selected ranges from 2490 to 2575 keV, and it includes, together with the $0\nu\beta\beta$ peak at the ^{130}Te Q-value, the peak from the ^{60}Co at 2505.7 keV. We performed an unbinned fit using a Bayesian approach. In particular the likelihood model includes two peaks, modelled with the detector response function, due to the $0\nu\beta\beta$ and the ^{60}Co, and a linear background. All the priors were uniform and non–negative. Thus the free parameters of the fit were the rate of the signal and of the ^{60}Co, and the background index and slope. We sampled the posteriors by means of the BAT (Bayesian Analysis Toolkit) software. The results are shown in fig. 3. The resulting signal rate is of $(0.9 \pm 1.4) \times 10^{-26}$ yr^{-1}, thus we

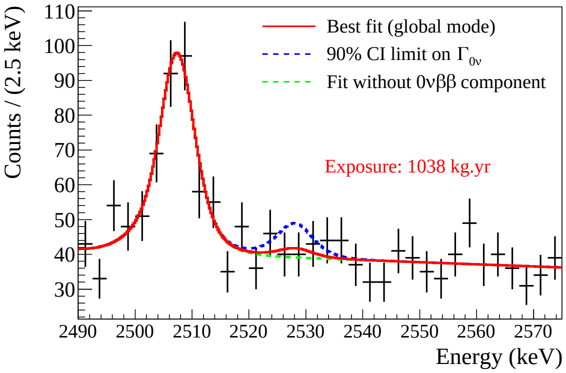

Fig. 3. – Energy spectrum in the ROI of the ^{130}Te $0\nu\beta\beta$. The best fit is shown with the solid red curve while the dotted blue and green curves represent the fit with the signal rate fixed at its 90% C.I. limit and at 0, respectively.

concluded that no evidence of $0\nu\beta\beta$ was observed. Thus we could set an upper limit from the signal rate posterior which, converted into half–life lower limit, corresponds to 2.2×10^{25}yr [11, 12]. This can be converted into an upper limit on the effective majorana mass of $m_{\beta\beta}$ <90-305 meV, whose spread is due to different models adopted to compute the nuclear matrix elements. The background index we found is $(1.49 \pm 0.04) \times 10^{-2}$ counts/(kg keV yr) which we estimate to arise mainly (∼90%) from degraded α particles from surfaces contamination, and from multi–Compton scattering of the 2615 keV γ–peak events (∼10%) [10, 13]. The expected exclusion sensitivity, which we evaluated from toy experiments in background only hypothesis, using real data fit results, is 2.8×10^{25}yr, which means we had 72% of chance to obtain a stronger limit.

4. – Future of CUORE

The CUORE final goal is to collect 3 tons×yr of exposure and reach a sensititivity on the effective majorana mass of $m_{\beta\beta} < 50 - 130$ meV. Moreover, with the CUORE data we could to perform several important studies on other physical processes. We provided an extremely precise measurement of the ^{130}Te $2\nu\beta\beta$ half-life, $[7.71^{+0.08}_{-0.06}(\mathrm{stat})^{+0.12}_{-0.15}(\mathrm{syst})] \times 10^{20}$ yr , which is the dominant component of the spectrum of events with multiplicity 1 [10]. We also searched for both $2\nu\beta\beta$ and $0\nu\beta\beta$ decay of ^{130}Te to excited states of ^{130}Xe. This decay provides a multi-site signature of γs in coincidence with the emitted electrons. We found a lower limit of 1.3×10^{24} yr and 5.9×10^{24} yr for the half-life of the $2\nu\beta\beta$ and $0\nu\beta\beta$ respectively ,to the 0_2^+ state of the ^{130}Xe [14].

We recently searched for $2\nu\beta\beta$ and $0\nu\beta\beta$ of the ^{128}Te isotope, which presents a lower Q-value (866.7 ± 0.7 keV) and a lower isotopic abundance (31.75%) [15].

We also investigated the decay modes of the ^{120}Te isotope, which is also present in the CUORE detector with an abundance of 0.09%. It could decay via positron–emitting electron capture without neutrinos in the final states ($0\nu\beta^+$EC), which would provide a clear signature given by positron–electron annihilation and the daughter nucleus (^{120}Sn) de–excitation via X-rays/Auger electron emission [16].

The CUORE detector also allows to search for beyond standard Model processes in the lower energy region (tens of keV or below) which could be affected by Dark Matter or Solar Axions interactions [17, 18]. Finally, an intense program of denoising techniques develompent is ongoing in the CUORE detector [7]. The characterization of the noise of CUORE is supported by a detailed study of its thermal response which is described in [19].

When CUORE will end its data taking, it will be substituted by its upgrade CUPID (CUORE Upgrade with Particle IDentification) [20]. It will use the same cryogenic facility and it will benefit from the expertise achieved along many years of CUORE operation. The main innovation of CUPID will be the use of scintillating crystals as bolometers. By coupling light detectors to the bolometers it will be possible to detect scintillation photons simultaneously to the heat. This feature allows to reject α particles because these have a quenched light yield. Indeed α particles from surfaces contamination release only a fraction of their energy in the crystal, producing events falling in the ROI which, as mentioned above, represent the dominant background for the $0\nu\beta\beta$ search in CUORE [13]. Indeed CUPID aims to reach a "background-free" environment by suppressing the α background by a factor 100, in order to push the $0\nu\beta\beta$ half-life sensitivity to about 10^{27}yr. Moreover, CUPID will study the candidate isotope ^{100}Mo, which present a Q-value (3034.40 ± 0.17 keV) above the endpoint of the γ natural radioactivity (about 2615 keV), further improving the background level in the ROI. The heat–light dual read–out technique has been first proved by the CUPID-0 experiment [21] which used ZnSe cylindrical crystals, and then by the CUPID-Mo experiment [22], which first tested the performance achieved by Li_2MoO_4 cylindrical crystals enriched in the ^{100}Mo isotope. Indeed, CUPID provides to use this compound for cubic shaped crystals, which were first tested in a measurement performed at the LNGS [23]. Also the light detectors will exploit the bolometric technology. These will be made with a wafer of Ge coated with SiO to increase the light absorption and shaped to match the crystals faces [24]. The technology developed for CUPID has been tested and optimized in several R&D measurements at the LNGS [23-25] and at the Canfranc Laboratories [26]. The good results obtained paved the way to the construction and test of the first prototype tower of CUPID, which is planned for the first half of 2022.

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