CUORE: first results and prospects

PROCEEDINGS OF SCIENCE

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CUORE is the first bolometric tonne-scale experiment aiming at the investigation of neutrinoless double-beta ($0\nu2\beta$) decay of ^{130}Te. The cryogenic commissioning followed by the detector installation and cool down took place during 2016. After the optimisation of all the detectors, the data-taking started in spring 2017. We report about the results of the first dataset acquired in May, which led to a limit on the $0\nu2\beta$ half-life of ^{130}Te of 6.6×10^{24} yr. An upgrade of CUORE, named CUPID, is planned to improve the $0\nu2\beta$-decay sensitivity via passive and active background reduction and crystal enrichment. Some technologies for CUPID are currently under study and two of them are presented here, involving the detection of Cherenkov and scintillation light emitted by enriched $^{130}TeO_2$ and $Li_2^{100}MoO_4$ crystals respectively. This will allow us to reject the currently dominant α background.

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1. Introduction

Neutrinoless double-beta ($0\nu2\beta$) decay [1] is a rare hypothetical nuclear transition, which consists in the transformation of two neutrons in two protons and two electrons with no neutrinos in the final state. This process is possible only if the neutrino is a Majorana particle, more in general its observation would demonstrate the non-conservation of the lepton number [1]. If mediated by the exchange of light Majorana neutrinos, the discovery of this process would fix the neutrino mass-scale, would contribute to the definition of the neutrino mass hierarchy, and in general to a deeper knowledge of the neutrino itself [1].

CUORE (*Cryogenic Underground Observatory for Rare Events*) experiment [2] is the first tonne-scale experiment based on bolometers searching the $0\nu2\beta$ decay of the ^{130}Te, whose expected signal is a peak at the Q-value of the transition (2527 keV). This isotope is a good candidate for $0\nu2\beta$ decay thanks to its high isotopic abundance (34.2%). It is embedded in the detectors themselves, which consist of 5-cm-side cubic TeO_2 crystals with a mass of 750 g. This well-known compound has been chosen because of its excellent bolometric performance ($\sim$5 keV FWHM energy resolution at the 2615 keV ^{208}Tl γ quanta [3]) and crystals radiopurity (^{232}Th < 0.8 μBq/kg, ^{238}U < 0.7 μBq/kg assuming secular equilibrium [4, 5]). CUORE is using 988 bolometers arranged in 19 towers constituted by 13 floors of 4 detectors each. Each crystal is equipped with a neutron-transmutation-doped germanium (NTD-Ge) thermistor for the read-out of the temperature signal and a silicon heater used for the thermal gain stabilisation. The experiment is hosted at LNGS (Laboratori Nazionali del Gran Sasso, Italy) in a liquid-helium-free cryostat, which can reach 10 mK temperature with the combined use of a diluition unit and four pulse tubes.

2. CUORE first results

After the cryogenic system commissioning, the CUORE detector was installed during summer 2016 and then cooled down to base temperature at the end of the same year. This work reports about the results obtained from the first dataset, corresponding to a 3-week measurement, acquired in May 2017 after a preliminary optimisation of the detector. 984 detectors are working and 90% of them have been used in this analysis, providing a total ^{130}Te exposure of 10.6 kg·yr. We considered a region of interest (ROI) between 2465 and 2575 keV and a total efficiency of 55.3$\pm$3% (including trigger and energy reconstruction, pulse shape discrimination, single-hit events and $0\nu2\beta$ containment). The recorded background, $9.8^{+1.7}_{-1.5}\times10^{-3}$ counts/(keV kg yr), showed a good agreement with the Monte Carlo simulations [6]. Fig. 1 shows the improvement in the backgound level from CUORE-0 to CUORE: the few events present in the ROI are mainly due to degraded-energy α particles emitted by detector surfaces [5]. Energy spectra show a good energy resolution: 10.6 keV FWHM at 2615 keV of ^{208}Tl γ quanta were obtained during the first calibration and they were then improved to 7.9 keV during the physics run thanks to the lower pile-up rate. Ongoing studies and optimisation are aiming to a further improvement of the energy resolution of the detector. Fig. 1 shows the background spectrum in the vicinity of the ROI and the fit used to obtain the $0\nu2\beta$ half-life limit: $T_{1/2}^{0\nu2\beta} > 4.5\times10^{24}$ yr at 90% C.L. This result, combined with the limits obtained by CUORICINO (19.75 kg·yr) and CUORE-0 (9.8 kg·yr), produces a more stringent limit of $T_{1/2}^{0\nu2\beta}$

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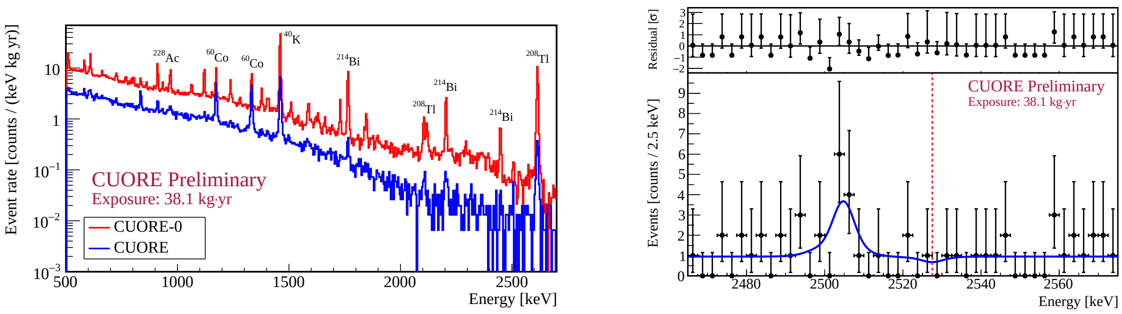

Figure 1: *Left*: Comparison of background spectra in the γ region for CUORE-0 and CUORE experiments. *Right*: Best fit in the ROI with residuals. The peak at (2504.8±1.2) keV is a sum γ line from ^{60}Co.

> 6.6×10^{24} yr at 90% C.L.[1]. CUORE will run for 5 years and its final sensitivity on $T_{1/2}^{0\nu2\beta}$ will be 9×10^{25} yr [8]. This new limit will start to probe the inverted hierarchy region of neutrino masses.

3. CUPID experiment

An upgrade of CUORE is foreseen at the end of its data taking. This new experiment is named CUPID (*CUORE Upgrade with Particle IDentification*) [9], and its purpose will be to investigate the entire inverted hierarchy region, reaching a sensitivity to the $0\nu2\beta$ half-life of the order of 10^{27}-10^{28} yr. This goal will be achieved by increasing the number of 2β-active nuclei (thanks to crystal enrichment) and by reducing the background. The CUORE main α background can be removed with the help of particle identification. One of the most promising active background rejection technique considered for CUPID [10] is the use of bolometric light detector to register the Cherenkov or scintillation radiation emitted by the main absorber. Some technologies are presently under test [11, 12, 13, 14, 15, 16, 17, 18, 19, 20] to find the best solution in view of CUPID. Two of them, based on $^{130}TeO_2$ and $Li_2^{100}MoO_4$ crystals, are illustrated below.

TeO_2 crystals emit a feeble light that can be used to tag $\beta(\gamma)$ events. The light has two origins: it is mainly produced by Cherenkov effect [21], but a non-negligible component of scintillation is also present [15]. The Cherenkov threshold is 50 keV for $\beta(\gamma)$ and 400 MeV for α, which can be rejected when their thermal energy populates the ROI. A β-like event in the $0\nu2\beta$ region corresponds to an energy of only 100 eV in terms of collected light and the related signal is difficult to observe with a standard light detector based on NTD-technology [11, 17]. This challenge can be faced by a light detector boosted by the Neganov-Luke effect [22, 23]: this kind of devices manage to amplify thermal signals thanks to an electric field, consequently improving the signal-to-noise ratio and lowering the threshold [12, 13, 14, 15]. Two Neganov-Luke-assisted light detectors, coupled to two enriched $^{130}TeO_2$ crystals (435 g) at LNGS, allowed us to separate $\beta(\gamma)$ from αs obtaining an α rejection factor of 98.21% and 99.99% with a $\beta(\gamma)$ acceptance of 95% [14]. Also, the two bolometers showed a high energy resolution (6.5 and 4.3 keV FWHM at the 2615 keV γ quanta of ^{208}Tl) and a high radiopurity (^{228}Th and ^{226}Ra < 3.1 μBq/kg).

An interesting alternative for the CUPID experiment is to change the $0\nu2\beta$-decay isotope: ^{100}Mo is a promising candidate thanks to its Q-value (3034 keV) higher than the natural γ ra-

[1] This dataset has been reprocessed and combined with a new physics run acquired in August 2017 [7].

dioactivity and its reasonably high isotopic abundance of 9.7% combined with the possibility of enrichment above 95%. A favorable compound containing ^{100}Mo is Li_2MoO_4, developed by the LUMINEU project [19, 20]. Detectors based on this crystal scintillator have a high energy resolution in the ROI (< 6 keV), are characterised by an excellent radiopurity (< 6 μBq/kg for ^{228}Th and < 11 μBq/kg for ^{226}Ra) and are able to fully separate αs (> 9σ) thanks to an adequate scintillation efficiency. Four enriched $Li_2^{100}MoO_4$ crystals have been tested underground at the LSM (Laboratoire Souterrain de Modane, France), showing a good reproducibility [20]. The next step will be the measurement of an array consisting of 20 $Li_2^{100}MoO_4$ bolometers that will start taking data in early 2018 at LSM. In view of CUPID, a capacity for crystal mass production, possibly multi-site, will be crucial: the present $Li_2^{100}MoO_4$ crystal growth has been performed at Nikolaev Institute of Inorganic Chemistry (NIIC, Novosibirsk, Russia) but new possibilities are under study in France (CLYMENE project [24]) and in China (CUPID-China).

4. Conclusions and acknowledgements

CUORE, the first tonne-scale cryogenic experiment based on TeO_2 bolometers, successfully accomplished the commissioning in 2016, the first dataset was acquired during May 2017 and was followed by the first data release in July 2017. A preliminary analysis of this first dataset, combined with the previous limits of CUORICINO and CUORE-0 experiments, set a limit on the $0\nu2\beta$ half-life to 6.6×10^{24} yr with a sensitivity of 9×10^{25} yr in 5 years of data-taking. The present performance and results of two technologies developed in view of the CUPID experiment have been reported. The feasibility to measure the tiny light emitted by enriched TeO_2 crystals, guaranteeing the rejection of the α background, has been demonstrated. Scintillating $Li_2^{100}MoO_4$ bolometers confirmed their performance reproducibility in terms of radiopurity, energy resolution and $\alpha/\beta(\gamma)$ separation. A 20-crystal pilot experiment (CUPID-Mo) with a significant isotope mass of about 2.5 kg will start taking data in 2018.

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