Recent progresses on BSM and Dark Matter searches with CUORE

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Abstract

The Cryogenic Underground Observatory for Rare Events (CUORE) is the first bolometric $0\nu\beta\beta$ experiment to reach the one-tonne mass scale. The detector, located underground at the Laboratori Nazionali del Gran Sasso in Italy, consists of 988 TeO_2 crystals arranged in a compact cylindrical structure of 19 towers, operating at a base temperature of about 10 mK. After beginning its first physics data run in 2017, CUORE has since collected the largest amount of data ever acquired with a solid state detector and provided the most sensitive measurement of $0\nu\beta\beta$ decay in ^{130}Te ever conducted. The large exposure, sharp energy resolution, segmented structure and radio-pure environment make CUORE an ideal instrument for a wide array of searches for rare events and symmetry violations. New searches for low mass dark matter, solar axions, CPT and Lorenz violations, and refined measurements of the $2\nu\beta\beta$ spectrum in CUORE have the potential to provide new insight and constraints on extensions to the standard model complementary to other particle physics searches. In this contribution, the recent progress on BSM and dark matter searches in CUORE are discussed.

1 Introduction

The CUORE experiment, thanks to the large mass, low background budget and low energy thresholds, has the capability to carry out different BSM and Dark Matter searches. In the following, before going into the details of these seaches, the CUORE experimental technique and setup are outlined. The current status of data-taking and detector stability are also discussed, giving a brief overview on the outstanding result achieved in the $0\nu\beta\beta$ decay search, thanks to the good performance of the detector. The focus of the discussion is then moved on the tools and analysis techniques developed to search for BSM and Dark Matter with CUORE, and the results achieved so far in these topics.

2 The CUORE experiment

CUORE (Cryogenic Underground Observatory for Rare Events) [1] is the first cryogenic detector exploiting the bolometric technique at the tonne-scale, with the detector core working at temperatures around 10 mK. The experimental setup is running in Hall A at the Laboratori Nazionali del Gran Sasso (LNGS) labs, in Italy, at a depth of 3600 mwe. Built with the primary goal to test the lepton number violation through $0\nu\beta\beta$ decay, it is also a powerful tool to go beyond, and search for BSM and Dark Matter events.

The bolometric detectors are 5×5×5 cm^3, 750 g TeO_2 crystals in thermal equilibrium, through PTFE holders, with a copper frame acting as heat sink at T∼10 mK. The milli-Kelvin temperatures allow to get an heat capacity as low as $C\sim 10^{-9}$ J/K, such that an energy deposition of 1 MeV causes an increase in temperature of a crystal of 100 μK. The rise in temperature is readout through Neutron Transmutation Doped (NTD) Ge thermistors. The full detector consists of 988 crystals arranged in 19 copper frame towers, each with 13 floors and 4 crystals per floor. A total TeO_2 mass of 742 kg (206 kg of ^{130}Te, 189 kg of ^{128}Te and 0.5 kg of ^{120}Te) is achieved. A closely packed detector array, with high granularity and minimized material facing the crystals, is functional for the reduction and tagging of the radioactive backgrounds.

The cryogenic system is a challenge by itself [2], consisting in a multistage cryogen-free cryostat (5 pulse-tubes and a custom dilution-unit) with high duty cycle. The detector is mechanically decoupled from the cryostat and outside environment to mitigate energy dissipation from vibrations. Radioactive backgrounds are reduced exploiting different approaches: material screening and accurate selection, cleaning of copper surfaces facing crystals, modern and Roman lead shieldings and strict protocols for crystal growing. Moreover, deep underground installation and neutron shielding prevent cosmic ray muons and muon induced backgrounds.

3 Data-taking, stability and $0\nu\beta\beta$ result

CUORE started data-taking in Spring 2017, and a series of commissioning, optimisation and operations campaigns went on during the next months. Continuous data-taking since 2019 is now ongoing. As of May 2022, a total uptime of ∼90% and more than 1.8 tonne·year of exposure has been collected. As an example, a very good temperature stability, with temperature variations less than 1% over a one year data-taking period, is achieved.

Recently, the CUORE Collaboration achieved the most sensitive ^{130}Te $0\nu\beta\beta$ decay result with 1 tonne · year exposure [3]. No evidence for the $0\nu\beta\beta$ decay has been found and a lower bound of $T^{0\nu}_{1/2} > 2.2\times10^{25}$ yr on the half-life of the process has been set at 90% credibility interval. This is converted to an upper limit on the effective Majorana mass of $m_{\beta\beta} < 90-305$ meV. The background index in the region of interest is $\sim 1.49(4)\times10^{-2}$ counts/keV/kg/yr and the energy resolution at the process Q-value is 7.8 ± 0.5 keV FWHM.

4 Tools for beyond Standard Model searches

Beyond Standard Model processes produce very low energy deposits in the CUORE crystals. The ability to identify the corresponding pulses with a good efficiency is mandatory to perform searches with good sensitivity. During online data-taking a derivative trigger (DT) is used for on-the-fly data quality monitoring. Offline data undergo a re-triggering procedure with an optimal trigger (OT) algorithm, based on the optimum filter technique [4], and the identified pulses are analyzed to produce all physics searches. The advantage of the OT is that the values for the energy thresholds are about ∼4-5 keV, whereas for the DT they are about ∼40 keV, for a trigger efficiency of 90% [5].

A denoising procedure is also being developed to remove the vibrational noise leaking into the bolometric channels. The idea is to exploit accelerometers, antennae and microphones installed in the experimental site to identify and measure the source of noise, the information is then used in the denoising procedure.

In order to build a low energy spectrum (E<100 keV), used in particular for Dark Matter and axion searches, a further cleaning of the OT triggered data is needed. Non-physical events near trigger threshold leaking into the spectrum need to be discarded. Such noise events are due to tower vibrations, electronic noise, energy deposits in the NTDs, and can mimic signal pulses. A pulse-shape discrimination variable, OT_{χ^2}, is exploited [6]: it is defined as the χ^2 from the fit of the pulse under test with a template drawn from the average pulse of the considered channel. The distribution of OT_{χ^2} as a function of the event energy shows that real signal events lay in a band around $\mathrm{OT}_{\chi^2} \sim 1$, whereas noise events populate an oblique band starting from $\mathrm{OT}_{\chi^2} \sim 1$ at low energies and extending to larger OT_{χ^2} values at higher energies. In CUORE0 a Kolmogorov-Smirnov (KS) algorithm based on the OT_{χ^2} shape was developed to search for the best energy thresholds above which only signal events are selected. A new approach has been developed for CUORE [7], in order to face the problem of building the OT_{χ^2} shape within the KS algorithm computation. In fact, thanks to the reduction of the background budget, CUORE experiences a lower event rate with respect to CUORE0. The ballpark of the analysis energy thresholds computed with this new method is around 20 keV, and do not include the denoising procedure yet.

5 BSM and Dark Matter searches

5.1 BSM in $2\nu\beta\beta$ spectral shape distortion

CPT violation and Majoron emission processes affect the spectral shape of the $2\nu\beta\beta$ decay spectrum. Thus, searches for these BSM physiscs processes in CUORE are based on finding very small distortions of the $2\nu\beta\beta$ decay spectrum.

The Standard Model invariance under Lorentz transformation implies invariance under CPT. Observation of a violation of these symmetries would imply existence of BSM physics. The Standard Model Extension (SME) effective theory includes Lorentz violating operators, a subset of which also violates CPT (countershaded operators). The effect of CPT breaking operator is a modification of the phase-space properties in $2\nu\beta\beta$, implying a modification of the form of the decay spectrum. In particular, the spectral index of the $2\nu\beta\beta$ spectrum is 5, while that of the CPT violation term is 4. The scale factor of this last term, $\dot{a}^{(3)}_{0f}$, is the parameter of interest of the CPT violation search. The following analysis strategy has been developed and tested. A background model for CUORE is built from the fit of the simulated spectra from different contributions to the measured energy spectrum (Bayesian fit with JAGS) [8], and the CPT violating term is included as an additional component of the background model fit. A sensitivity study is carried on: for each given exposure, a set of toy-MC spectra are generated according to background only hypothesis; a fit with the signal plus background model is performed on each toy-MC. The likelihood is marginalised over all nuisance parameters, and the posterior for the decay rate related to the CPT violating term is evaluated. A 90% confidence interval is computed from the posterior, from which an exclusion sensitivity is obtained for the parameter of interest. The distribution of the computed limits from the set of toy-MC allows to obtain a median sensitivity, together with 1 and 2 σ bands. An analysis of physics data is then performed, by a Bayesian fit to the spectrum from data with the signal plus background model, and an upper limit on the parameter of interest is set. The systematics are not included yet: in the near future they will be worked out and taken into account in the analysis. Only 86.3 kg·yr of exposure is used for the development and validation of the analysis procedure. Details about the developed analysis can be found here [9]. An update of the results with the full available statistics is ongoing.

The $0\nu\beta\beta$ decay process with only electrons in the final state is not the only decay mode possible. Proposed models predict the emission of 1 or 2 neutral bosons, Majorons, together with the two electrons in the $0\nu\beta\beta$ decay final state. The experimental signature, like in the CPT violation case, is a continuous energy spectrum of the total energy from the two emitted electrons, with spectral index value depending on the considered model (possible values for the spectral index are 1, 2, 3 and 7). As for the CPT violation analysis, the background model for CUORE is an essential ingredient for the Majoron analysis. The component with given spectral index from a Majoron emission model is included in the background model fit and a similar procedure to that of CPT violation is adopted for the signal search in the data. Analysis of physics data is performed with a Bayesian fit to the spectrum from data with the signal plus background model and an upper limit on the half-life of each Majoron model is set, which is interpreted as an upper limit on the models coupling constant. An exposure of 387.5 kg·yr is used to develop and validate the analysis procedure, and also in this case an update with the full statistics is ongoing. Details about the developed analysis can be found here [10].

As discussed above, these analyses strongly rely on a good understanding of the background of the CUORE experiment. The Collaboration already developed a reliable and solid background model, nonetheless the model keeps improving. A larger statistics of 1 tonne·yr is being used to refine the background model, including even more components spread across the cryostat. The improved background model will certainly be beneficial to boost the sensitivity of the analyses based on the spectral shape distortions that have been discussed.

5.2 Solar axions and WIMPs

Dark Matter searches are focused on solar axions and WIPMs analyses. Solar axions are emitted by the de-excitation of the first ^{57}Fe level, thermally populated in the core of the Sun. The detection in the TeO_2 crystals is based on the axio-electric effect, with a signature characterized by a peak in the energy spectrum at 14.4 keV. The analysis was developed and validated in past CUORE crystal validation runs [11], and is sensitive to the $g_{Ae} \times g_{AN}^{eff}$ coupling constant. Work is in progress to implement the analysis with CUORE data. Another detection technique is based on the inverse-coherent Bragg-Primakov conversion in the bolometric crystals: the axion couples to the crystal lattice charge through a virtual photon and the interaction produces a photon only if Bragg's condition is satisfied (dependence given by the Sun-CUORE detector angle). The strategy is to look at the counting rate as a function of time over a single day and analyze it with a time-correlation method [12]. In this case, the analysis is sensitive to the $g_{A\gamma\gamma} \times g_{AN}^{eff}$ coupling constant, and is now being developed for the CUORE data.

WIMPs analysis technique is based on the recoil rate annual modulation due to the motion of Earth around Sun. TeO_2 crystals are good targets, since they combine heavy Te nucleus and light O nucleus, which helps enhancing the sensitivity to low WIMP masses. The CUORE0 data have been exploited to estimate the CUORE sensitivity [6], assuming the same background rate and analysis thresholds. The low energy spectrum of CUORE0 features a peak like structure between about 30-45 keV, present in all crystals. The physical origin might be due to contamination in the material facing the detectors, and is under investigation in CUORE. The chosen region of interest for the sensitivity study is between 10-28 keV, excluding the peak structure. The strategy to extract the sensitivity is as follows: for each point of the parameter space (m_W, σ_{SI}) a fit to the time integrated energy spectrum with signal plus background model is done, to extract best fit background coefficients; obtained background parameters are used to generate 100 toy-MC experiments; for each toy-MC the annual modulation likelohood, $\mathcal{L}_{AM}$, and the null hypotesys likelihood, $\mathcal{L}_{null}$, are maximised and the maximum likelihood ratio is computed; the experimental sensitivity is computed as the parameter space points for which at least 90% experiments prefer annual modulation hypothesis with respect to the null one.

The projection to 5 years CUORE data (75% duty cicle) with thresholds between 10-28 keV shows that most of the DAMA positive signal region can be exluded. Now CUORE, being in continuous data-taking since 2019, has the data to compute the actual sensitivity and perform the search. The work is in progress in such direction.

5.3 Barion number violation

Violation of barion number is essential to explain matter-antimatter asymmetry in the universe. In CUORE a search for the barion number violating process $^{130}\mathrm{Te} \rightarrow {}^{127}\mathrm{In} + e^+ + \pi^+ + \pi^+$ is being developed. The subsequent β^- and γ decay chain of ^{127}In involves a prompt and a delayed signal, which can be tagged in two crystals. A broad-cut, accounting for both γs and βs, and a narrow-cut, accounting only for γs, are being explored. A sample of 10^6 ^{127}In has been simulated with the full CUORE Geant4 simulation, including also the detector response. A preliminary study shows that the searched signals can be well identified. Dedicated studies for background rejection, from accidental coincidences, neutron and muon spallation, are being performed.

6 Conclusion

The CUORE experiment is running in stable conditions. Data-taking started in Spring 2017, alternating periods of commissioning, optimization and operations. Continuous data-taking is ongoing since early 2019. A set of tools needed for BSM and Dark Matter searches are in place, moreover a new approach to cancel the background not originated from particles and leaking into the bolometric channels, dubbed as denoising, is being developed and tested. A set of BSM and Dark matter analyses have been developed and validated with a subset of the available data: CPT violation, $0\nu\beta\beta$ with Majoron emission, solar axions and WIMPs. A barion number violation analysis, tri-nucleon decay, is being developed. Work is in progress to perform the analyses on the full available statistics acquired by CUORE.

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