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Dark Matter search with CUORE-0 and CUORE

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Abstract

The Cryogenic Underground Observatory for Rare Events (CUORE) is a ton-scale experiment made of TeO_2 bolometers that will probe the neutrinoless double beta decay of ^{130}Te. Excellent energy resolution, low threshold and low background make CUORE sensitive to nuclear recoils, allowing a search for dark matter interactions. With a total mass of 741 kg of TeO_2, CUORE can search for an annual modulation of the counting rate at low energies. We present data obtained with CUORE-like detectors and the prospects for a dark matter search in CUORE-0, a 40-kg prototype, and CUORE.

Selection and peer review is the responsibility of the Conference lead organizers, Frank Avignone, University of South Carolina, and Wick Haxton, University of California, Berkeley, and Lawrence Berkeley Laboratory

Keywords: dark matter, tellurium, CUORE, low threshold

1. Introduction: the CUORE experiment

The CUORE [1] experiment is the result of more than twenty years of development of the bolometric technique applied to the physics of rare events. Mainly conceived for the search for neutrinoless double beta decay [2], its detector performance and unique features give it the potential for a much wider range of applications in the rare events particle and nuclear physics field.

CUORE detectors (often referred to as *thermal detectors*) are based on the bolometric technique, which represents the theoretically simplest approach to a calorimetric measurement of a particle's energy. An *absorber* is kept at a constant temperature until a particle interacts in it, releasing its kinetic energy via the standard radiation-matter interactions (depending on the particle energy and nature). After a time lag, the duration of which depends on many factors but is usually short enough to fit the time requirements of a low-rate particle detector, the deposited energy, independent of the processes responsible for the deposition itself, is converted to heat. This heat produces a rise in the temperature of the absorber that depends on the total energy originally deposited by the radiation. An electrical signal proportional to the energy is then generated by means of a temperature-dependent resistor, or *thermistor*, that is thermally coupled to the absorber.

In CUORE, 988 independent detectors are assembled in a compact and modular array of 19 towers whose structure is made of copper, selected and cleaned in order to fulfil strict purity requirements and provide the thermal bath needed for the bolometers to work. Each detector is a 750 g TeO_2 crystal instrumented with a NTD (*Neutron Transmutation Doped*) Ge thermistor and a Si heater that can release a known amount of power into the absorber. Both the thermistor and heater are glued to the crystal with epoxy glue spots that ensure mechanical and thermal contact [3].

The total mass of the active part of the detector is 741 kg, while the energy resolution is expected to be around 5 keV. This estimate is based on extensive previous experience with TeO_2 bolometers, including CUORE-0, a single CUORE tower presently running in Hall A at Laboratori Nazionali del Gran Sasso (LNGS) as a double beta decay experiment and a demonstration of the construction technology that is being used for CUORE.

CUORE has two important features that enable its use for a variety of applications. Its highly modular design allows background suppression with anti-coincidence techniques, and its superior energy resolution (that, at low energy, is dominated by electronic and thermal noise) allows it to acquire data with a low energy threshold. Software tools that implement online filtering and pulse shape discrimination can then further improve the data. As a result, CUORE is a powerful tool for the study of other phenomena in addition to double beta decay, in particular physics with low energy signature in the detector, such as dark matter [4], solar axions [5], supernova neutrinos and artificial source neutrinos.

2. CUORE and CUORE-0 status

The CUORE detectors are being assembled underground in the CUORE clean room in Hall A at LNGS in Italy. More than half of the crystals are already equipped with sensors and readout wiring and are assembled into towers, ready for installation in the cryostat. The cryostat, a complex and unique machine that will cool several tons of material, including the detectors and the innermost lead and copper shields, to 10 mK and will keep them at this stable temperature for several years, is also in an advanced commissioning phase. The different cooling stages have been tested separately, and they are now assembled in the final configuration and are undergoing performance characterisation. The detector construction will be completed by the end of 2014, while the first cool down is planned for 2015.

CUORE-0, the first tower built with the same materials and technology that have been developed for CUORE, has been running and taking data in the former CUORICINO [6] cryostat since March 2013. After the detector performance was optimised for data-taking in the high-energy region, the first results on the background in the double beta decay region were released [7]. Although the main goal of CUORE-0 is proving the performance of CUORE-like detectors and reaching a good sensitivity for the double beta decay half-life, the detector will soon be optimised for the study of the lower end of the energy spectrum as well. This is of great interest in order to fully understand the potential of CUORE as an observatory for low-energy particle physics processes.

3. Towards Dark Matter detection in CUORE

The CUORE research program includes a search for evidence of dark matter (DM) through the direct detection of galactic halo WIMPs.
The detection mechanism is the same as that used in most direct detection experiments: a WIMP from the galactic halo coherently scatters off a target nucleus (Te or O in CUORE crystals), mediated by the weak interaction. In this interaction, the WIMP transfers to the nucleus a fraction of its momentum. The nucleus recoils with a kinetic energy that depends on the kinematics of the interaction, mainly on the transferred momentum and the WIMP and nucleus masses (see Figure 1). The signal in the detector is generated by the conversion of the recoil energy into heat that increases the temperature of the absorber.
Since the CUORE detectors are made of a composite material, both tellurium and oxygen can be the target for the WIMP detection. The very different mass of the two elements allows a wider range of favourable kinematic conditions for the detection. Tellurium nuclei are very heavy, so the recoil energy is generally very small unless the mass of the WIMP is also large (of the order of 100 GeV); furthermore, a nuclear form factor suppresses the interaction for large momentum transfer, leading to a recoil spectrum for Te nuclei that is typically shifted towards the low energy end of the spectrum (below about 25 keV). The cross section, however, is large as it scales approximately as the number of nucleons squared.
The much lighter oxygen nuclei are more favourable targets for light WIMPs (below 10 GeV), but have smaller cross sections. Spin dependent cross sections on both oxygen and tellurium are highly suppressed; TeO_2 is thus only sensitive to spin independent interactions.

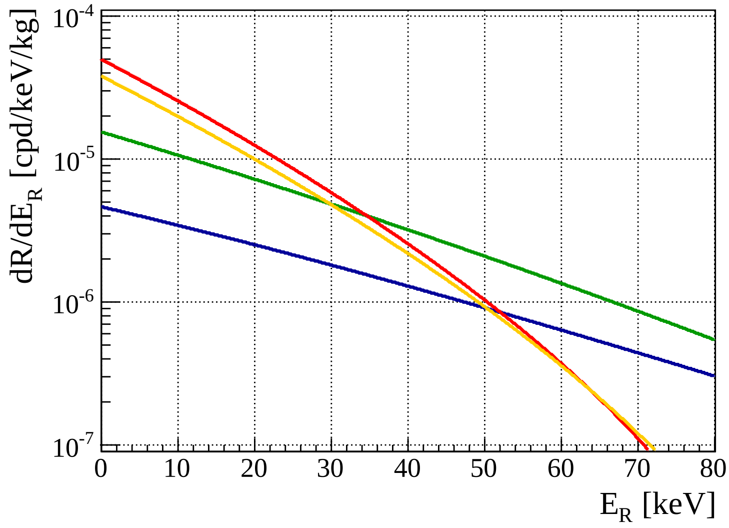
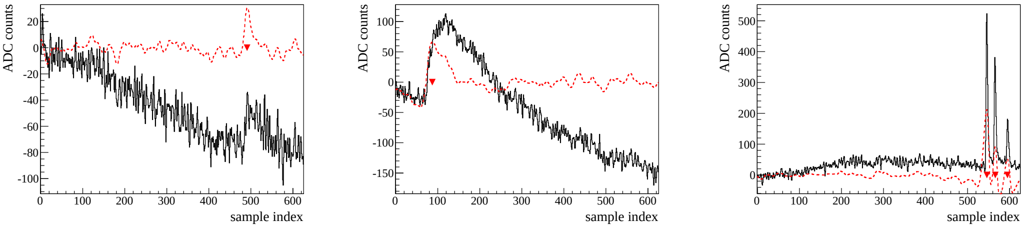


Fig. 1: Recoil spectra for some elements (or compounds), assuming a WIMP mass of 100 GeV and a spin independent cross section of 10^{-45} cm^2. Yellow = TeO_2, red = Xe, green = Ge, blue = Ar. Helm [12] form factors and an isotropic Maxwellian halo with ρ_W = 0.3 GeV c^{-2} cm^{-3}, v_0 = 220 km/s and v_{esc} = 600 km/s are used.

Bolometers are good instruments for the detection of nuclear recoils induced by DM interactions; the mass of the absorber can be large (up to ∼1 kg with the present technology) without spoiling the energy resolution of approximately 5 keV, comparable with that of semiconductor detectors. Moreover, since double beta decay experiments require high statistics, the detector stability is guaranteed for long time periods. Large mass, high energy resolution and long term stability make CUORE a powerful tool for the study of an energy dependent annual modulation of the signal event rate, considered one of the smoking guns of WIMP discovery. Moreover, the quenching factor for nuclear and electron recoils is expected to be 1 (and has been measured to be compatible with 1 down to 100 keV). This should remove the high uncertainty introduced in the interpretation of data from other direct detection experiments, due to the lack of a precise knowledge of the quenching factor for the used materials.

Two potential limits can be identified that could reduce the sensitivity of CUORE to a DM signal. First, CUORE is designed mainly for the detection of double beta decay events in the 2.5 MeV energy region, while the typical nuclear recoil energy is below 25 keV. In the standard DAQ system, continuous data stream is recorded together with triggered data samples based on a threshold trigger applied to the electrical signal produced by the thermistors; when a temperature variation larger than the threshold is detected, the temperature values in a time window are recorded. The information about the energy deposited by a particle is extracted from the temperature pulses by means of a software tool, the Optimum Filter (OF, or matched filter [8]).

The OF, based on the expected pulse shape generated by a particle and the average thermal and electrical noise power spectrum of the detectors, maximises the signal-to-noise ratio, giving the most accurate evaluation of the original particle energy. This technique, however, is applied only to those signals that were triggered. Therefore the detector threshold (of the order of some tens of keV) is usually much higher than the



(a) Particle releasing about 3 keV (b) Mechanical heating (c) Electronic interference

Fig. 2: Examples of the output of the Optimum Trigger in some typical cases. The black line is the raw signal while the red dashed line represents the corresponding output of the OT.

minimum energy that could be measured by applying the OF, which is of the order of the energy resolution.

In order to effectively reduce the energy threshold, the Optimum Trigger (OT) has been developed [9]. The stream of data coming from the thermistors is continuously analysed (presently offline, but an online version of the same technique is being tested) by applying the matched filter to overlapping time windows. A trigger fires when the filter continuous output, which achieves the maximum theoretical signal-to-noise ratio, becomes larger than the threshold, which can be set as low as the irreducible magnitude of the noise at the OF output.

In Figure 2 an additional feature of the Optimum Filter and Optimum Trigger can be appreciated: by comparing the shape of the signal with the expected shape of a pulse generated by a particle interaction, it is possible to associate each event a shape quality parameter. This parameter allows the discrimination of particle events from thermal or mechanical fluctuations or electronic interference that may be large enough to be triggered at the output of the filter.

A second complication in the search for low energy phenomena is the fact that TeO_2 bolometers aren't, with the present technology, able to identify the nature of the particles that are interacting in the absorber. Recoiling nuclei, alpha particles, beta particles, and gamma rays that release the same energy in a crystal are expected to generate the same signals. Irrespective of the original mechanism of interaction, which can be substantially different for different particles, all the energy is quickly converted into heat, and the shape of the signal depends much more on the thermal parameters of the detector, such as the heat capacity and conductances among the different elements, than on the original phonon spectrum.

This lack of information on the particle type is a problem both in the double beta decay region of interest (ROI), where the electron-type expected signal can be emulated by a alpha particle with degraded energy, and in the low energy region, where nuclear recoils cannot be discriminated from the dominating background of low energy X-rays, beta and gamma radiation.

Since no technology for particle discrimination in TeO_2 has been successfully implemented, only a passive background reduction approach is available, consisting in the identification and mitigation of all the possible sources of radiation that can contribute to the background in the different ROIs.

A large effort has been made in the last decade to implement procedures and technologies that are able to reduce the background in the double beta decay ROI in CUORE. Since this approach aims to eliminate any sources located near the detector and to shield any sources far from the detector, it is expected to positively affect also the background at all energies.

All materials used in the construction of every part of the experimental setup, from the cryostat to the copper structures that hold the detector, are carefully selected. The detector parts are then cleaned with rigorous procedures that have been developed and tested specifically to remove the most dangerous known contaminants in each material. Finally, the assembly and storage procedures have been studied in order to minimise the probability of detector recontamination.

These strategies have been successfully applied and tested in CUORE-0, where the desired reduction of the background level in the double beta decay ROI has been achieved. Data on the background in the low energy ROI will be released as soon as the detector is optimised for such measurements.

4. CCVR2: the low energy demonstrator

A CCVR (CUORE Crystal Validation Run) is a test run of four crystals randomly chosen from each production batch of CUORE to measure the bolometric performance and the purity of the materials [10]. During the second of these runs, CCVR2, the Optimum Trigger was tested and a study of the performance of TeO_2 bolometers at low energy was performed [4]. Three out of four detectors reached a threshold of 3 keV. The background between the threshold and 25 keV was studied and can be fitted with a double exponential plus a Gaussian peak at ~4.7 keV, whose origin is still under study (see Figure 3).

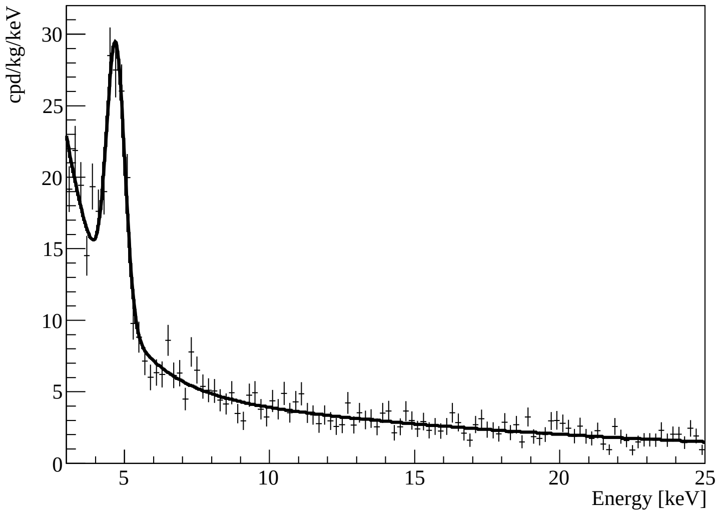


Fig. 3: CCVR2 background between the threshold (3 keV) and 25 keV. The spectrum corresponds to an exposure of 43.64 kg*day, i.e. 19.4 days of data taking with three CUORE-like detectors. The data are fit to a double exponential model, plus a gaussian peak at 4.7 keV whose origin is still under study.

The integrated background rate was measured to be 15.3±1.5 counts/kg/day (cpd/kg) with a total exposure of about 40 kg·day. Until CUORE- 0 is optimised for low energy data acquisition, CCVR2 will be considered the CUORE low energy background and threshold demonstrator.

5. Sensitivity evaluation

In order to understand the real potential of CUORE as a DM detector, a dedicated Monte Carlo simulation has been developed. The DM signature in CUORE is an annual modulation of the number of counts in the energy region where the WIMP-induced nuclear recoils are expected, i.e. between the low energy threshold and 25 keV.

The simulation is based on two external inputs: the background of the detector, measured in CCVR2 and extrapolated to CUORE (and CUORE-0), and the expected modulation function, which depends on the theoretical models that describe the WIMP velocity distribution, Earth's motion in the halo, the WIMP number density, and other factors [11]. In the expected rate calculation we have considered Helm [12] form factors and an isotropic Maxwellian halo with ρ_W = 0.3 GeV c^{-2} cm^{-3}, v_0 = 220 km/s and v_{esc} = 600 km/s.

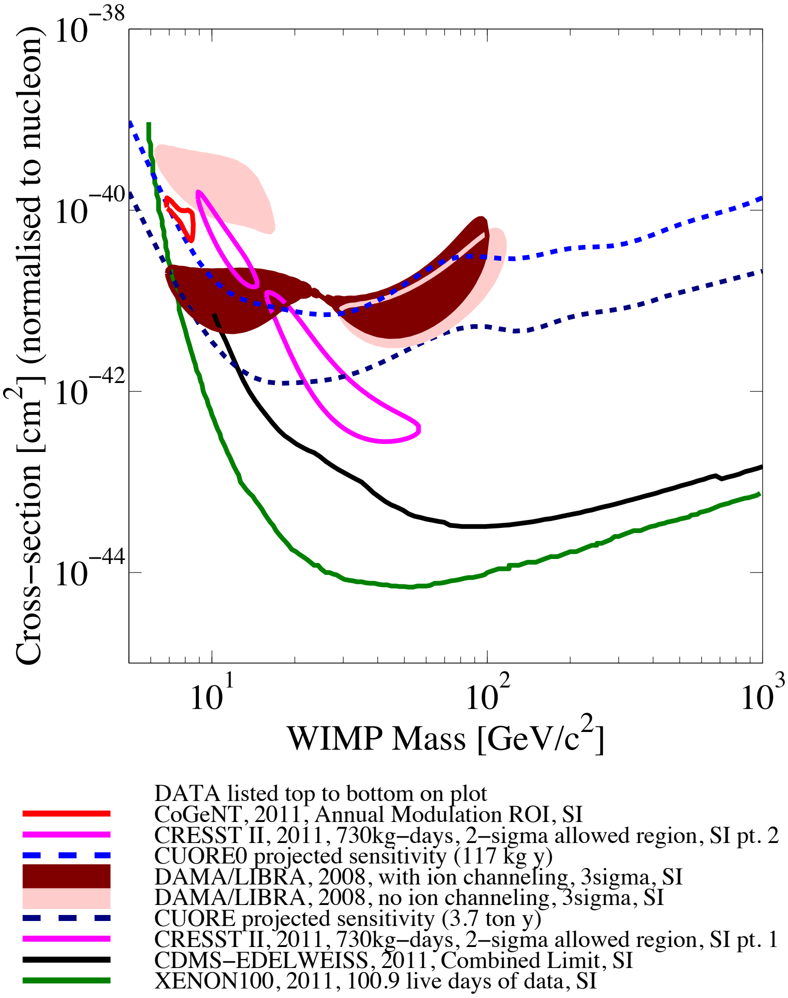


Fig. 4: 90% C.L. sensitivity to the cross-section for spin independent interactions normalised to nucleon. For CUORE-0 the 3 years projected sensitivity is shown, while CUORE line corresponds to 5 years projected sensitivity (*http://cedar.berkeley.edu/plotter/*).

An expected spectrum of nuclear recoils is then generated for a specific point in the WIMP mass versus cross-section parameter space at a specific time of the year. The simplest approach is the generation of two spectra, one for the winter and one for the summer months; i.e., with a time difference of half a modulation period. The difference between the two spectra is then fit with the same model that has been used to generate the data. The same fit is also performed with a null model, where the cross section has been forced to zero and no annual modulation is expected.

A spectrum is generated N times for each pair of values in the WIMP mass - cross section plane. Both the signal and null models are fit to the N spectra for each pair of values. The probability of detecting the signal is calculated, for each point in the parameter space, as the number of times when the likelihood of the model with the signal is larger than the likelihood of the null model.

Both the spectra generation and the likelihood calculations are performed with ROOFIT tools. With this software, a WIMP sensitivity plot is created for CUORE and CUORE-0, assuming CCVR2 background levels and 3 keV energy threshold in both cases. In Figure 4, the 90% C.L. sensitivity on spin-independent WIMP-nucleon cross section is compared with that of other experiments for the spin-independent model.

The particular shape of the exclusion curves, with two local minima, is due to the fact that what is studied here is the sensitivity to the annual modulation, that is based on the difference in rate between summer and winter. For Te this difference is maximum at ∼20 GeV and then changes sign around 60 GeV, producing a second minimum at ∼100 GeV. The presence of oxygen in the target allows for the detection of lower mass WIMPs.

6. Conclusions: CUORE's contribution to the dark matter search

CUORE is an upcoming ton-scale experiment with very low background and excellent energy resolution. CUORE is currently under construction at LNGS and will begin operation in early 2015. CUORE-0, the first CUORE tower, is currently taking data in the same location and will measure the potential of CUORE as an observatory for low energy physics in the next few months. Until then, CCVR2 is the benchmark for the low energy performance of large mass TeO_2 bolometers.

CUORE will be one of the few solid-state detectors in the 1 ton mass range and will run in the same location as most competing experiments based on inorganic scintillators and noble gas detectors. This offers a valuable source of complementary information in the DM direct detection field. Thanks to its large mass and low energy threshold, CUORE will be sensitive to energy-dependent annual modulation signals in a non-negligible fraction of the parameter space, allowing it to test with an alternative technique some of the present hints and claims of WIMPs detection.

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