Direct Dark Matter detection with CUORE

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Abstract. The Cryogenic Underground Observatory for Rare Events (CUORE) is an experiment to search for neutrinoless double beta decay in $^{130}$Te and other rare processes. CUORE is a bolometric detector composed of 988 TeO$_2$ crystals, with the total mass of about 1 tonne. The large detector mass, low backgrounds, and the low energy threshold of a few keV make the experiment well suited for direct detection of galactic dark matter particles and solar axions. We discuss the development of a novel low-energy trigger that enables such searches, and present the preliminary results from a test run with four CUORE-like crystals at Gran Sasso National Laboratory in Italy.

1. The CUORE experiment
The CUORE experiment is designed to search for the neutrinoless double beta decay ($0\nu$DBD) of $^{130}$Te [1]. CUORE will be made of 988 TeO$_2$ bolometers of 750 g each. Bolometers are detectors in which the energy from particle interactions is converted into heat and measured via the resulting rise in temperature. Operated at a temperature of about 10 mK, these detectors maintain an energy resolution of a few keV over their energy range, extending from a few keV up to several MeV. CUORE will be installed in the Gran Sasso National Laboratory (LNGS) and will start the data taking in about 3 years. The first CUORE tower, CUORE-0, composed by 52 bolometers, is under preparation and will start the data taking at the end of the year.

CUORE could also search for dark matter (DM) interactions, provided that the energy threshold is sufficiently low. DM candidates such as weak interacting massive particles (WIMPs) [2] are expected to produce signals at energies below $\sim$ 30 keV, and the interaction rate increases as the energy decreases. The energy threshold of CUORICINO bolometers, achieved using a trigger algorithm applied to the raw data samples, was of the order of tens of keV. If the threshold were of few keV, the CUORE experiment could be sensitive to DM interactions and thus play an important role in this growing research area. In the following we present a method we developed to lower the energy threshold, and the projected CUORE sensitivity to WIMP spin independent interactions.

2. Experimental setup
A CUORE bolometer is composed of two main parts, a TeO$_2$ crystal and a neutron transmutation doped Germanium (NTD-Ge) thermistor [3]. The crystal is cube-shaped ($5\times5\times5$ cm$^3$) and held by Teflon supports in copper frames. The frames are connected to the mixing chamber of a dilution refrigerator, which keeps the system at the temperature of $\sim$ 10 mK. The thermistor is glued on the crystal and acts as thermometer. When energy is released in the crystal, its temperature increases and changes the thermistor’s resistance. The thermistor is biased with
a constant current, and the voltage across it constitutes the signal [4]. The data presented in this paper comes from a four-bolometers array operated by the CUORE collaboration at LNGS in 2009. The main purpose of the detector was to check one of the first production batches of CUORE crystals [5]. Two Joule heaters were glued on two of the crystals and used to inject controlled amounts of energy, in order to emulate signals produced by particles [6, 7].

3. Lowering the energy threshold

At low energies the detection capability is limited by the detector noise. Electronics spikes, mechanical vibrations, and temperature fluctuations can produce pulses that, if not properly identified, generate nonphysical background. The lower the energy released in the bolometer, the more difficult it is to discriminate between physical and nonphysical pulses.

We developed a trigger and a pulse shape identification algorithm [8] that operate on data samples processed using the matched filter technique [9]. This filter is designed to estimate the amplitude of a signal, maximizing the signal to noise ratio. The transfer function is matched to the signal shape, and pulses with different shape are suppressed. The noise power spectrum of the detector, \( N(\omega_k) \), and the signal shape, \( s_i \), are needed to build the transfer function:

\[
H(\omega_k) = h \frac{s_i(\omega_k)}{N(\omega_k)} e^{-i\omega_k i_M},
\]

where \( s(\omega_k) \) is the Discrete Fourier Transform (DFT) of \( s_i \), \( i_M \) is the maximum position of \( s_i \) in the acquisition window, and \( h \) is a normalization constant that leaves unmodified the amplitude of the signal at the filter output. The estimation of \( N(\omega_k) \) is made by averaging the power spectrum of a large set of data windows acquired with a random trigger, while the signal shape \( s_i \) is obtained by averaging a set of high-energy particle signals in the 1-3 MeV range. Pulses are triggered when the data samples exceed a positive threshold, and a new trigger is possible when the data samples return below threshold, or after that a local maximum is found. The detection efficiency is estimated on pulses generated by the heater, performing an energy scan from about 1 keV up to 100 keV. In the case of bolometers without the heater, the estimation is made on simulated data. Three of the bolometers have a 3 keV energy threshold and a detection efficiency in excess of 80\%, while the fourth has a threshold of \( \sim 10 \) keV. To ease the analysis job we ignored this bolometer. To remove nonphysical pulses we fit the filtered pulses with the expected shape of the filtered signal. The \( \chi^2/\text{ndf} \) of the fit is used as shape parameter. We apply a cut on this variable to select signal events in the energy region below 30 keV. The probability of losing a signal event after this cut has been estimated to be less than 3\%.

4. Sensitivity to dark matter interactions

The four bolometers array took 19 days of data. The low energy spectrum obtained combining the three bolometers having 3 keV threshold, after cutting on the shape parameter and correcting for the detection efficiencies, is shown in Fig. 1. The data in the range 3-5 keV are not displayed, since they are still being studied; in place of the data we show their approximate behavior, that is an exponential decay. The counting rate ranges from \( \sim 20 \) cpd/keV/kg at 3 keV to \( \sim 2 \) cpd/keV/kg at 25 keV, and is well described by a double exponential decay. We estimate the CUORE sensitivity to WIMPs assuming that the background differential rate will be equal to the measured value in the four bolometers array, and that all bolometers will have a 3 keV threshold. It has to be stressed that CUORE bolometers, unlike many other detectors, cannot distinguish nuclear recoils from \( \beta/\gamma \) interactions. Nevertheless CUORE, by means of its mass and to the low background expected, could detect dark matter searching for an annual modulation of the counting rate at low energies.

We performed toy Monte Carlo simulations generating background events from the fit of the measured distribution in Fig. 1, and WIMP events from the theoretical distribution described in
Figure 1. On the left, differential rate at low energies obtained combining data from the three bolometers having the energy threshold at 3 keV. The region below 5 keV is still under study. The data are fitted with a double exponential decay, and the fit function is used as model of the CUORE background. On the right, CUORE(5y) (in red) and CUORE-0(3y) (in black) expected sensitivities compared to the actual limits on WIMP-nucleon elastic scattering cross section: DAMA/LIBRA $3\sigma$ evidence with ion channeling in dark red and without ion channeling in pink [12], Edelweiss II in green [13], XENON100 in blue [14], CDMS in magenta [15].

Ref. [10], using a quenching factor for nuclear recoils in TeO$_2$ equal to 1 [11]. We included the dependence of the WIMP interaction rate on the time in the year, and estimated the background+signal asymmetry subtracting the 3-months integrated spectrum across 2 December from the 3-months integrated spectrum across 2 June. The 90% C.L. sensitivity to the cross-section for spin independent interactions normalized to nucleon, as a function of the WIMP mass, for CUORE-0 in 3 years and CUORE in 5 years of data taking, is shown in Fig. 1 together with the present results of the leading experiments of the field. As it can be seen from the figure, CUORE-0 and CUORE will not be as sensitive as experiments able to discriminate nuclear recoils. CUORE, however, could investigate the same parameter space of the DAMA/LIBRA experiment, and could be the only experiment other than DAMA/LIBRA looking for an annual modulation of dark matter interactions.

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