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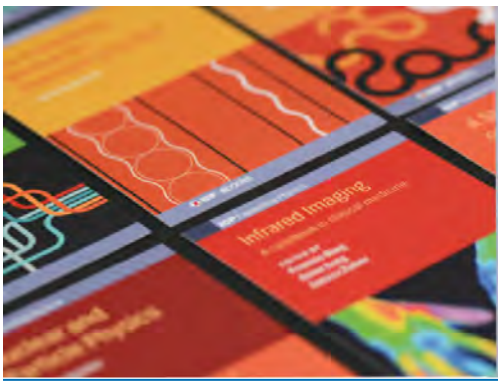

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CALDER - Neutrinoless double-beta decay identification in TeO_2 bolometers with kinetic inductance detectors

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Abstract. Next-generation experiments searching for neutrinoless double-beta decay must be sensitive to a Majorana neutrino mass as low as 10 meV. CUORE, an array of 988 TeO2 bolometers being commissioned at Laboratori Nazionali del Gran Sasso in Italy, features an expected sensitivity of 50-130 meV at 90% C.L, that can be improved by removing the background from α radioactivity. This is possible if, in coincidence with the heat release in a bolometer, the Cherenkov light emitted by the β signal is detected. The amount of light detected is so far limited to only 100 eV, requiring low-noise cryogenic light detectors. The CALDER project (Cryogenic wide-Area Light Detectors with Excellent Resolution) aims at developing a small prototype experiment consisting of TeO_2 bolometers coupled to new light detectors based on kinetic inductance detectors. The present R&D is focused on the light detectors. We present the latest results and the perspectives of the project.

1. Introduction

Bolometers proved to be good detectors to search for neutrinoless double-beta decay ($0\nu\beta\beta$), thanks to the possibility of studying different isotopes, the excellent energy resolution, and the low background they can achieve [1]. The CUORE experiment [2] will search for the $0\nu\beta\beta$ of ^{130}Te using an array of 988 TeO_2 bolometers operated at a temperature around 10 mK. Each bolometer weighs 750 g, for a total active mass of 741 kg, 206 kg of which are ^{130}Te (34.2% natural abundance in tellurium [3]). The energy resolution and the background at the Q-value of the decay ($Q_{\beta\beta}$=2528 keV [4]), are expected to be 5 keV FWHM and 10^{-2} counts/(keV kg y), respectively [5]. CUORE is in construction at Laboratori Nazionali del Gran Sasso (LNGS) in Italy, and is expected to start operations within one year. The 90% C.L. sensitivity of CUORE to the $0\nu\beta\beta$ half-life is predicted to be 10^{26} years in 5 years of data taking [5].

The sensitivity of CUORE could be further improved by increasing the amount of isotope and by reducing the background level, which is expected to be dominated by α radioactivity. To this end a new experiment to be run after CUORE is being designed, CUPID [6, 7]. The technology of CUPID is not yet defined. One possibility is to use scintillating crystals enriched in high-$Q_{\beta\beta}$ isotopes, such as $Zn^{82}Se$ [8] or $Zn^{100}MoO_4$ [9]. The scintillation light is detected in coincidence with the heat release in the bolometer and is used to discriminate the β signal from the αs. The other option is to use again TeO_2 bolometers, enriched in ^{130}Te. Since TeO_2 is not a scintillator, the βs can be tagged only by detecting the small amount of Cherenkov light that is emitted by particles absorbed in the crystal [10].

The Cherenkov light detected from β particles interacting in a CUORE amounts to 100 eV at $Q_{\beta\beta}$ [11], . The light detector consisted in a germanium disk read by a Neutron Transmutation Doped (NTD) germanium thermistor [12], which was originally developed to detect the much larger amount of light emitted by scintillating crystals (several keVs). The light detector noise amounted to 70 eV RMS, a level too high to allow an event by event discrimination. It was computed that, to reject the α background, one needs new light detectors featuring a noise smaller than 20 eV RMS. It has to be noted that high-sensitivity light detectors, even if not strictly required, could also be applied to scintillating bolometers. In the case of ZnSe, for example, they would allow to discriminate nuclear recoils from electron recoils at low energies and thus enable the search for direct Dark Matter interactions [13].

The light detector technology implemented in CUPID, aside the achievement of the noise goal, must prove to be reproducible, scalable to a thousand light detectors, and easily implementable in the CUORE infrastructure [6]. The CALDER project [14] is developing new sensors based on Kinetic Inductance Detectors (KIDs) [15], a technology invented in 2003 that is expected to match the CUPID requirements. In this paper we describe the detector concept and report the latest results.

2. Light detector description

KIDs base their working principle on the kinetic inductance, a property of superconductors cooled below the critical temperature. When an AC bias is applied to a superconductor, the Cooper pairs, because of their mass, exhibit a kinetic inertia to the field variation. This inertia acts as an inductance and depends on the number of Cooper pairs, which can be modified by energy releases in the metal. A KID is obtained by including the superconductor in a high quality factor circuit excited at the resonant frequency $f_0 = 1/\sqrt{LC}$. When radiation is absorbed and a fraction of Cooper pairs is broken into quasiparticles, the inductance, and so the transfer function of the circuit, change. The signal is extracted by monitoring the phase and amplitude modulation of the wave traveling through the circuit.

The key feature of KIDs is that different sensors can be coupled to the same line by making them resonate at slightly different frequencies. The resonant frequency of each sensor can be easily tuned by means of small modifications of the layout of the capacitor and/or inductor of the circuit. With this technique, multiplexing factors of the order of thousands have been already demonstrated [16].

The maximum active area that can be obtained with a KID is of few mm^2, a value that is small compared to the 5×5 cm^2 area of a CUORE bolometer face. Covering the entire area of a single light detector with hundreds of pixels is unreasonable, since a thousand light detectors is needed. For this reason we are implementing phonon-mediated devices, using the substrate on which the pixels are deposited as mediator (the same concept implemented in the CRESST experiment but with TES sensors [17]). Photons hitting on the substrate can convert to athermal phonons, scatter in the substrate itself, reach the sensors and generate a signal. In this way a single KID can monitor areas much larger than its dimensions.

The CALDER detectors are fabricated at CNR IFN on high quality, 300 μm thick, high

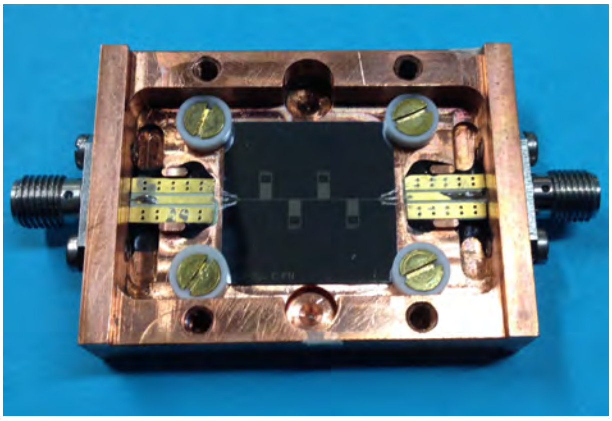


Figure 1. The 4-pixel 2×2 cm^2 detector in its copper holder. The detector is suspended by PTFE supports and illuminated on the back by an optical fiber couple to a room-temperature LED and by a ^{57}Co source.

resistivity Si(100) substrates. In this phase of the project the resonators are patterned by electron beam lithography on a single 40 nm thick aluminum film deposited using electron-gun evaporator [18]. The single pixel consists of an inductive meander with an active area of ~ 2 mm^2, and a capacitor that ensures the uniformity of the current across the resonator and allows to vary the resonant frequency [14] .

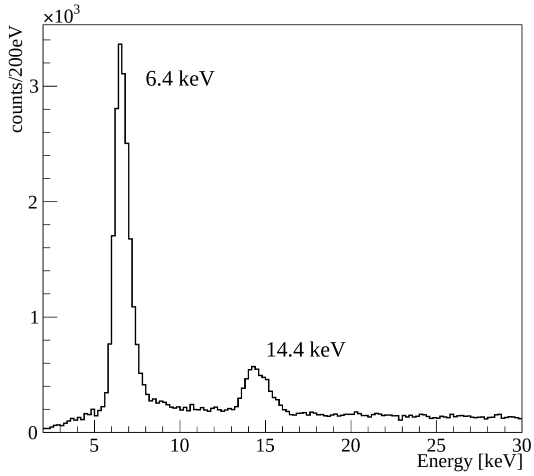
The chip we present is composed of 4 pixels deposited on a 2x2 cm^2 substrate, assembled in a copper structure using PTFE supports (Fig. 1). The other side of the holder (not shown) is covered with a copper collimator hosting a ^{57}Co calibration source (peaks at 6.4 and 14.4 keV) and an optical fiber coupled to a room-temperature LED, that produces pulses at 400 nm. The detector is operated in a ^{3}He/^{4}He dilution refrigerator with base temperature of 10 mK. The output signal is fed into a CITLF4 SiGe cryogenic low noise amplifier operated at 4K. A detailed description of the chip design, the cryogenic setup of our laboratory at Sapienza University, the room-temperature electronics and the acquisition software can be found in references [14, 19, 20].

3. Results

The 4 KIDs are excited simultaneously at their resonant frequency. The microwave power of each resonator is chosen as to optimize the signal to noise ratio of the phase readout [21], that is found to be 3-4 times more sensitive than the amplitude readout. Depending on the resonator the input power ranges from -63 to -72 dBm. The rise time of the signals ranges from 15 to 30 μs while the decay time is around 230 μs and is attributed to the recombination time of quasiparticles (τ_{qp}) into Cooper pairs. The waveforms are processed offline with the optimal filter [22], to further increase the signal to noise ratio.

The total energy spectrum of the ^{57}Co calibration source obtained combining the signals from the four pixels (see more details in Ref. [23]) is shown in Fig. 2 (left). The energy resolution on the 6.4 keV X-rays and on the 14.4 keV γ-rays is found to be 350 and 600 eV, respectively. The baseline noise amounts to 154 ± 6 eV and is so far the best value in literature obtained with phonon mediated KIDs (Fig. 2 right).

After calibrating the detector, we performed a scan with the optical fiber in the energy region between 0.7 and 25 keV. The energy of the optical pulses was previously calibrated with a PMT at room temperature, and corrected for the PMT quantum efficiency, for the reflectivity of



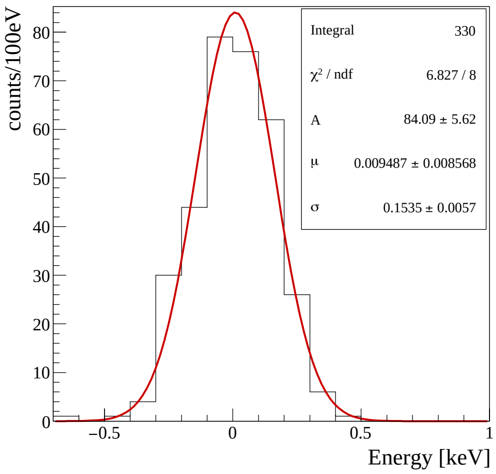


Figure 2. Combined energy spectrum of the 4 KIDs. The 6.4 keV X-rays and the 14.4 keV γ-rays generated by the ^{57}Co source (left) and the baseline noise (right).

silicon, and for the geometrical efficiency, evaluated through a Monte Carlo simulation based on the Litrani software [24]. The energy detected is found consistent within 5% with the expected one, proving the reliability of our calibration and the overall understanding of the detector behavior.

4. Perspectives

The energy resolution in the limit in which the amplifier noise dominates is expected to improve with the increase of the quality factor of the resonators (Q), the increase of the phonon collection efficiency (η), the increase of the fraction (α) of kinetic inductance over the total inductance and the decrease of the superconductor gap $2\Delta_0$. In this test with aluminum resonators Q ranged from 6×10^3 to 35×10^3 depending on the resonator, η was estimated as 18%, $\alpha = 6\%$ and $\Delta_0 = 200$ μeV [23]. Unfortunately the KIDs with higher Q did not feature a better signal to noise ratio, because an extra low frequency noise, increasing with Q was observed (Fig. 3). The source of this noise is not yet understood. One possibility is that the electronics generating the excitation tones introduces a random phase jitter that is amplified by the resonators.

Aside understanding the noise source, we are designing new detectors to increase the sensitivity. We have designed a new pixel geometry with a 70% larger active area, that is expected to increase η, and with a smaller geometric inductance, that is expected to increase α above 10%. At the same time we are developing a system to deposit films of titanium nitride, a superconductor that features a kinetic inductance an order of magnitude greater than aluminum and a 2-3 times lower gap. The combination of these improvements is expected to bring the baseline resolution of the light detectors from 154 eV below the goal of 20 eV.

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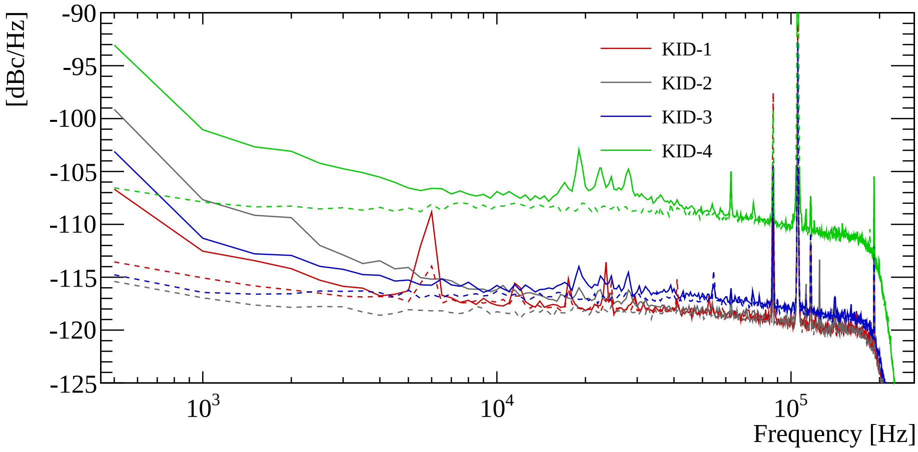

Figure 3. Phase (solid) and amplitude (dotted) noise of the 4 KIDs. The amplitude noise is consistent with the white noise from the cyogenic amplifier ($T_N = 7$ K). The phase noise exhibits an extra contribution at low-frequency, increasing with the Q of the resonator, possibly due to random jitters in the excitation tones of the resonators.

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