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Cryogenic light detectors for background suppression: the CALDER project

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Background suppression plays a key role for experiments searching for rare events, like neutrinoless double beta decay and dark matter interactions. Next generation experiments based on the technology of cryogenic calorimeters can improve the background rejection exploiting the different light emission of different particles. Many R&D activities are now focussed on the development of sensitive light detectors that can be easily scaled up to ∼1000 devices without increasing the heat load for the cryogenic apparatus. The CALDER project proposes a new technology for light detection, that takes advantage from the superb energy resolution and natural multiplexed read-out provided by Kinetic Inductance Detectors (KIDs). The first project phase allowed to reach a baseline resolution of 80 eV using Aluminum sensors to sample a $2{\times}2\,\mathrm{cm}^2$ Silicon wafer. In this paper we present the most recent results and discuss the perspectives of the project.

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1. Introduction

Thanks to the excellent energy resolution, efficiency and intrinsic radio-purity, cryogenic calorimeters became very popular in the search for rare events such as neutrino-less double beta decay ($0\nu\beta\beta$) and dark matter interactions. Since these detectors are more or less equally sensitive to α's, electrons and nuclear recoils, they can not identify and reject interactions due to particles that are different from those of interest. To overcome this limit, cryogenic calorimeters can be equipped with a light detector, that allows to identify the nature of the interactions exploiting the different light yield of different particles. Next generation experiments [1, 2] demand for light detectors with excellent energy resolution (RMS better than 20 eV), high radio-purity and wide-active surface ($5{\times}5\,\mathrm{cm}^2$). Furthermore, since these experiments need a rather large number of detectors ($\sim$1000) to reach a competitive source mass (about 1 ton), the technology of light detectors should be simple, robust and easily scalable. In the following we discuss more specifically two physics cases in which sensitive light detectors could be the key for a breakthrough in the experimental sensitivity.

The most advanced calorimetric experiment for $0\nu\beta\beta$ searches, CUORE [3], is completing the commissioning phase at Laboratori Nazionali del Gran Sasso (Italy) and will start operations at the beginning of 2017. CUORE is searching for the $0\nu\beta\beta$ of ^{130}Te using 988 TeO_2 cryogenic calorimeters (for a total detector mass of about 740 kg) operated at 10 mK. The $0\nu\beta\beta$ signal consists of two electrons with total energy of about 2.5 MeV. The dominant background is expected to be due to α particles emitted by contaminants located in the inert materials that constitute the detector. Despite the state-of-the art technologies devised for the selection and cleaning of the materials, contaminations in α-emitting isotopes will dominate the background of CUORE, limiting the sensitivity of the experiment. The α background could be rejected on an event-by-event basis by exploiting the fact that electrons, in contrast to α particles, emit Cherenkov light. Nevertheless, at the energy of interest for $0\nu\beta\beta$, electrons crossing TeO_2 crystals emit only $\sim$100 eV of light [4]. This means that, to disentangle electrons from α particles, light detectors with energy resolution better than 20 eV are needed.

Another interesting application of sensitive light detectors concerns the CUPID-0 experiment, which is searching for the $0\nu\beta\beta$ of ^{82}Se using ZnSe cryogenic calorimeters [5]. Since ZnSe is a good scintillator at cryogenic temperatures, CUPID-0 can exploit the read-out of the scintillation light to identify and reject the α background. Given the much higher light output (a few keV, instead of $\sim$100 eV produced by Cherenkov effect), less performing light detectors are needed. Nevertheless, using a sensitive light detectors could be beneficial also for CUPID-0, as it would allow to perform particle identification also at much lower energies (below 30 keV), where the same detector could be exploited to search for nuclear recoils produced by dark matter interactions. A preliminary study allowed to establish that light detectors with RMS better than 20 eV would allow to achieve the sufficient sensitivity to reject interactions produced by electrons recoils, the dominant source of background in the ROI for dark matter searches [6].

Besides an excellent energy resolution and radio-purity, a next-generation light detector should provide (i) an active surface of the order of $5{\times}5\,\mathrm{cm}^2$ for an efficient coupling with macro-bolometers such as the TeO_2 crystals used by CUORE ($5{\times}5{\times}5\,\mathrm{cm}^2$ cubic crystals) or CUPID-0 (4.4 cm diameter and 5 cm height cylindrical crystals); (ii) reproducible and stable behavior in a rather wide temperature range (5-20 mK); (iii) simple read-out with low heat load for the cryogenic facility. Several technologies were proposed to devise such a light detector [7, 8, 9], but none of them has yet proved to be able to fulfill all the requirements.

2. The proposed technology: Kinetic Inductance Detectors

The CALDER project [10] proposes to realize a new light detector exploiting phonon-mediated Kinetic Inductance Detectors (KIDs [11]). KIDs are superconductors biased in AC. These devices act as inductors, as the AC biasing produces an oscillation of the Cooper pairs, that acquire kinetic inductance L_K. By inserting the superconductor into a high quality factor (Q$\sim$$10^4$-$10^5$) RLC circuit, we obtain a resonator which resonant frequency f_0 depend on the value of L_K. The absorption of energy breaks a fraction of the Cooper pairs, changing L_K and, as a consequence, the resonance parameters (frequency and amplitude). Monitoring the variations in phase and amplitude of the transmitted signal, we can reconstruct the energy of the incident photons (Fig. 1).

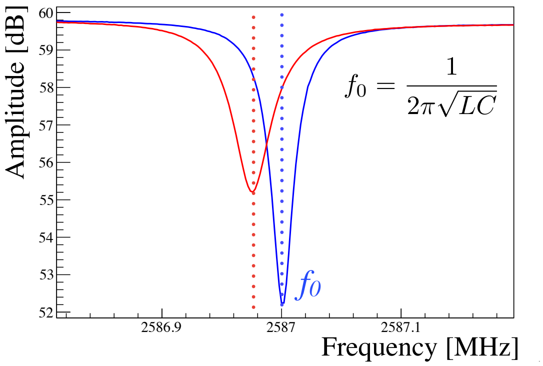

Figure 1: Typical transmission past a KID (blue). The total inductance L and capacitance C of the detector were designed in order to obtain a resonant frequency f_0 $\sim$2.6 GHz. When a fraction of Cooper pairs is broken into quasiparticles, the resonance shape and frequency change (red).

Besides an energy resolution of a few eV, KIDs bring two important advantages. First of all, they are easily multiplexable: each KID can be designed in order to resonate at a slightly different frequency, so that hundreds of resonators can be coupled to a single feed-line and a single cryogenic amplifier. Then, the response of KIDs is stable in a wide temperature range, provided that they are operated well below the critical temperature of the superconductor.

The main limit of KIDs is that their active surface is of a few mm^2, much smaller than the one required for new light detectors. For this reason, we use KIDs to sample a much wider substrate as proposed in Ref [12], rather than for direct detection. The insulating substrate (2$\times$2 cm^2, 300 μm thick Si wafers for the results described in this paper) is used to convert the impinging photons into phonons. Phonons travel in the substrate until they are absorbed by the KIDs, producing a signal. A typical implementation of this detector is shown in Figure 2.

The CALDER project begun in 2013 and foresees 3 main phases. The goal of the first phase is achieving an energy resolution of 80 eV RMS with KIDs made of Aluminum. Even if Aluminum is not a very sensitive superconductor, it is a very well known material and thus allows to work

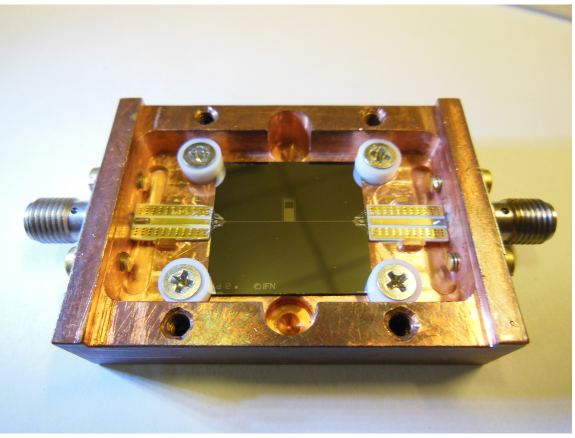

Figure 2: Single Aluminum KID deposited on a $2\times2\,\mathrm{cm}^2$, $300\,\mu$m thick Si substrate. The detector is assembled in a copper structure using four teflon PTFE elements with total contact area of about $3\,\mathrm{mm}^2$. The other side of the holder (not shown) is closed with a copper collimator hosting calibration sources consisting of X-rays and optical pulses produced by a fiber coupled to a room-temperature 400 nm LED.

on the optimization of the KID geometry. In the second phase we will move to more sensitive superconductors, such as Ti-Al, TiN, Ti-TiN to reach a baseline resolution lower than 20 eV. In the last phase, we will exploit the final light detector to read the tiny Cherenkov light emitted by TeO_2 macro-bolometers to prove the potential of this technology.

3. First project phase: Aluminum KIDs

All the phase-I CALDER prototypes were produced at Consiglio Nazionale delle Ricerche Istituto di Fotonica e Nanotecnologie (CNR IFN, Rome, Italy), using electron beam lithography.

The first light detector consisted of a Si substrate sampled by four 40 nm thick Al KIDs [13]. The active area of each pixel was made by an inductive meander of 14 connected strips of $80\,\mu\mathrm{m}\times2$ mm. The resonators were designed to be over-coupled, thus the total quality factors Q were dominated by the coupling quality factors Q_c, which in turn depend on the geometry of the resonator. For these KIDs we chose a rather conservative value of Q_c (from 6×10^3 to 35×10^3). Another parameter of interest to evaluate the detector performance is the internal quality factor Q_i, that is related to the quality of the superconductor. The higher Q_i, the longer the pulses relaxation time, the better the energy resolution. For the first prototypes Q_i was limited to a rather low value of $\sim150\times10^3$, resulting in a short relaxation time of 200-250 μs.

To evaluate the energy resolution, we calibrated the detectors using optical pulses with energy up to 30 keV. The optical system, consisting of a 400 nm room-temperature LED and an optical fiber, was energy calibrated at room temperature using a phototube and correcting for the geometrical efficiency of the set-up (including the materials reflectivity) using a Monte-Carlo simulation. The calibration was cross-checked using X-rays sources of ^{55}Fe and ^{57}Co.

The four resonators featured an efficiency ranging from 3.1% to 6.1% depending on the position with respect to the source. Summing the response of the KIDs on an event-by-event basis we obtained a total efficiency of 18±2 %, and a baseline resolution of 154±7 eV, about a factor 2 larger than the target of the first project phase. The detector performance was limited by a high noise level at low frequency, i.e. in the signal bandwidth, that spoiled the energy resolution. We tried to reduce this noise by modifying the room-temperature readout system: we used a Rubidium-referenced clock to drive the electronics, and we tested different groundings on the whole electronics and cryostat setup. These attempts were not successful, thus we inferred that the noise is produced by the chip itself. For this reason, we modified the geometry of the KID and we tried to increase as much as possible the signal height, in order to improve the signal-to-noise ratio. Since the signal height is proportional to the quality factors Q, we increased both Q_c and Q_i. Q_c was increased to 150×10^3 by design, while Q_i was increased of about one order of magnitude (up to 2×10^6) by depositing a thicker superconductor (60 nm instead of 40 nm). As expected, the much higher Q_i resulted also in a longer pulses relaxation time (of the order of 400 μs). Besides increasing the superconductor thickness, we enlarged the active surface from 2.4 to 4.0 mm^2 to improve the detection efficiency.

We performed a test by sampling a 2×2 cm^2 Si substrate similar to the one used for the first prototype, by using a single resonator with improved geometry [14]. The larger active volume allowed to reach a detection efficiency of (7.4±0.9)% with the optical source far from the KID, and (9.4±1.1)% with the source below the KID, to be compared with an efficiency ranging from 3.1% to 6.1% obtained with the old geometry.

We evaluated the energy resolution of this prototype using amplitude and phase signals separately for a comparison with the other prototypes, and then by combining the two estimators with the bi-dimensional matched filter to increase the sensitivity. The results reported in Fig. 3 were obtained illuminating the region far from the KID using photons bursts produced by the room-temperature LED with total energy ranging from 3 to 31 keV.

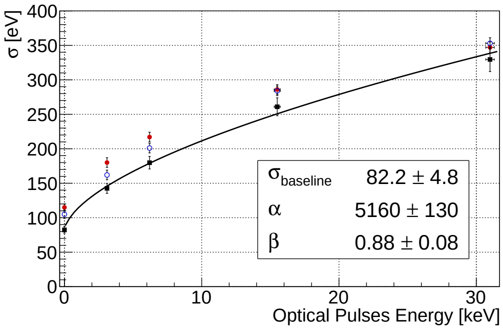

Figure 3: RMS energy resolution of phase (red circles), amplitude (blue empty circles) and their combination (black squares) as a function of the energy. The points at zero energy are the baseline resolutions $\sigma_{baseline}$, computed with a Gaussian fit on the amplitude of the noise windows after the matched filter. The combined RMS was fitted as function of the energy according to $\sigma(E)^2 = \sigma^2_{baseline} + \alpha E^{\beta}$.

The points at zero energy indicate the baseline resolution $\sigma_{baseline}$, which is the parameter of interest to quantify the detector sensitivity. The resulting baseline resolutions are 115 ± 7 eV in phase and 105 ± 6 eV in amplitude. The combination of the two estimator results in a baseline resolution of 82 ± 4 eV, about a factor 2 improvement with respect to the previous prototype. We believe that there is still room for improvement, and that a further design optimization and eventually the increase of the number of resonators will allow to improve the detector sensitivity even with Aluminum.

4. Second project phase: more sensitive superconductors

The achievement of an energy resolution of 80 eV RMS is within reach, so we begun to develop more sensitive superconductors. New materials can improve the energy resolution of KIDs as this parameter scales as $\Delta E \propto \frac{T_C}{\sqrt{QL}}$, where T_C and L are the critical temperature and the inductance of the superconductor.

Possible candidates are sub-stoichiometric Titanium Nitride (TiN), or multi-layers of superconductors such as Ti+TiN or Ti+Al, which characteristics are reported in Table 1. We already performed some measurements with Ti+Al resonators, obtaining an encouraging energy resolution of 50 eV (paper in preparation).

Table 1: Critical temperature T_C and inductance L of Aluminum, sub-stoichiometric TiN, multi-layers of Ti+TiN and multi-layers of Ti+Al. Measurements of Al and TiN (α state) were performed using a film thickness of 40 nm and 80 nm respectively. The values of Ti+Al were measured using a KID made of 10 nm of Ti and 25 nm of Al.

	Al	TiN sub-stoich.	Ti+TiN	Ti+Al
T_C	1.2	0.5	0.5-0.8	0.6-0.9
L [pH/square]	0.5	up to 50	6	1

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