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CALDER: High-sensitivity cryogenic light detectors

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Summary. — The current bolometric experiments searching for rare processes such as neutrinoless double-beta decay or dark matter interaction demand for cryogenic light detectors with high sensitivity, large active area and excellent scalability and radio-purity in order to reduce their background budget. The CALDER project aims to develop such kind of light detectors implementing phonon-mediated Kinetic Inductance Detectors (KIDs). The goal for this project is the realization of a $5 \times 5\,\text{cm}^2$ light detector working between 10 and 100 mK with a baseline resolution RMS below 20 eV. In this work the characteristics and the performances of the prototype detectors developed in the first project phase will be shown.

1. – Introduction

The most sensitive bolometric experiment searching for neutrinoless double-beta decay (0νDBD) will be CUORE [1]. Operating 988 cubic crystals (edge = 5 cm) of TeO_2 as bolometers, CUORE will study the 0νDBD of ^{130}Te. The signal produced by this reaction are two electrons with a total kinetic energy of about 2.5 MeV. Unfortunately the α background events, produced by the radioactive contamination located on the surfaces of the detector components will limit the performances of the experiment: the sensitivity on

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the effective Majorana mass ($m_{\beta\beta}$) is expected to reach the level of 0.05–0.13 eV, *i.e.* the beginning of the inverted hierarchy region of the neutrino masses. The CUPID (CUORE Upgrade with Particle IDentification) interest group [2] aims to develop a CUORE-sized bolometric detector able to reach a sensitivity on $m_{\beta\beta}$ of the order of 0.01 eV, *i.e.* the end of the inverted hierarchy region. This ambitious goal can be reached by increasing the source mass and reducing the background in the region of interest. To increase the number of 0νDBD emitters, crystals grown with enriched material are needed. The background suppression can be achieved by discriminating β/γ against α events by means of the different light yield produced in the interactions within a scintillating bolometer like ZnSe [3] (^{82}Se), $ZnMoO_4$ [4] (^{100}Mo), $LiMoO_4$ [5] (^{100}Mo) and many others. Up to now, the scintillating crystals were coupled to light detectors made by thin germanium disks equipped with Neutron Transmutation Doped germanium sensors, that show a typical intrinsic energy resolution of about 80 eV RMS [6].

Unfortunately, TeO_2 crystals do not scintillate. However, many advantages offered by TeO_2 crystal, as the superior bolometric performances, the lower enrichment costs in ^{130}Te, and the huge expertise in its growth, have provided a strong motivation to pursue another, very challenging, option. In fact, an active background rejection can be applied to the TeO_2 bolometers by exploiting, instead of the scintillation light, the Cherenkov radiation. Indeed, as proposed in ref. [7] and demonstrated in ref. [8], detecting the Cherenkov radiation produced in the TeO_2 crystal only by electrons (at the low energies of the natural radioactivity) it is possible to disentangle the β/γ interactions from the α ones. The tiny amount of Cherenkov energy detectable at the 0νDBD of ^{130}Te (100 eV) sets strong requirements on the light detector that must be interfaced to TeO_2 crystal:

- large active surface ($5 \times 5\,\text{cm}^2$) in order to maximize the Cherenkov photons collection
- very high sensitivity (< 20 eV) because of the low signal associated to the 0νDBD of ^{130}Te
- high scalability and ease in fabricating/operating up to 1000 channels in order to be easy integrated in pre-existing cryogenic facilities.

For these reasons, the CALDER (Cryogenic wide-Area Light Detectors with Excellent Resolution [9]) project proposes a new technique, based on Kinetic Inductance Detectors. As explained in the next section, the natural multiplexing of KIDs in the frequency domain provides an unprecedented scalability for this kind of experiments, ensuring the easily and low cost operation and installation of a 1000 channels size detector.

2. – Phonon-mediated kinetic inductance detectors

A superconductor biased with high frequency AC current ($\nu \sim$ GHz) exhibits the so-called kinetic inductance (L_k) of the Cooper pairs: a change in electromotive force is opposed by the inertia of them (Cooper pairs) since, because of their mass, they prefer to travel at constant velocity and therefore it takes a finite time to accelerate the charge carriers. The resulting phase lag in voltage is identical to the one produced by an inductor making them indistinguishable in a normal circuit. By coupling the superconductor with a capacitor a LC circuit can be realized. This acts like a resonator with a resonant frequency $f_0 = \frac{1}{2\pi\sqrt{LC}}$ (see fig. 1(a)). The properties of superconductors allow to fabricate resonators with typical quality factor (Q) of the order of 10^4–10^5. When

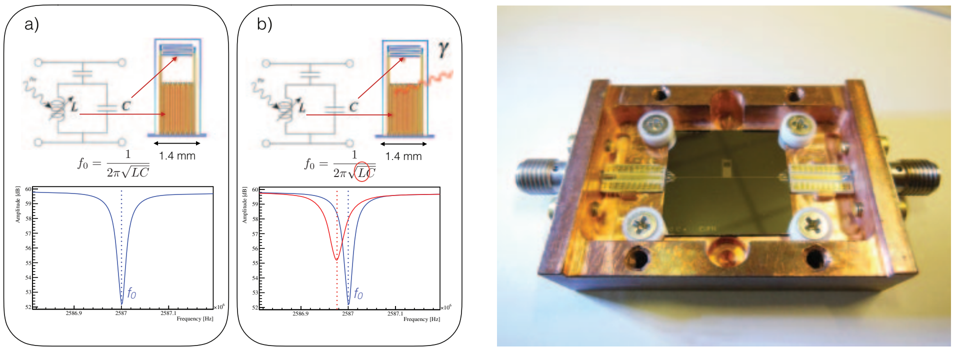

Fig. 1. – (a) Top: comparison between the finite element equivalent representation and a real design of a KID. Bottom: a typical resonance produced by such a circuit. (b) Bottom: resonance shape change after a particle interaction within the KID. Right: a single Al KID deposited on a 2×2 cm^2 Si substrate. The chip was assembled in a copper structure using four teflon (PTFE) elements.

a photon interacts in the superconductor it breaks Cooper pairs increasing the average momentum per Cooper pair and, as a consequence, increasing L_k. Moreover, the breaking of Cooper pairs into quasiparticles increases the dissipation of the resonator, thus reducing Q as shown in fig. 1(b). Monitoring the changes in the resonance parameters (amplitude and phase) it is possible to infer the energy that was deposited by the photon interaction [10]. The main advantage offered by these detectors, besides an excellent energy resolution (few eV), is their suitability for frequency-domain multiplexing. Indeed, each KID can be designed to resonate at a proper frequency, so that hundreds of KIDs can be coupled to a single read-out feed-line and excited with a frequencies combination, each one tuned on the own resonant frequency of the KID. Such property decreases the number of electronic channels, as well as the heat-load on the cryogenic system, needed for the detector's readout.

The main limit of this technology is that KIDs can feature a maximum active area of a few mm^2, while next-generation experiments demand for light detectors with a sensitive surface of tens of cm^2. To get around this limitation an indirect detection of the photon interactions was proposed: KIDs are evaporated on a large (cm^2) insulating substrate (Si or Ge) that mediates the photon interactions converting them into phonons. These phonons travel in the substrate until a portion of them is absorbed by the KIDs; the remaining is lost in the substrate supports or absorbed in substrate defects. This approach, known as phonon-mediated approach gives rise, on the one hand, to the possibility of monitoring a large active surface using few KIDs but, on the other, to the problem of the phonon collection efficiency.

The goal of the CALDER project is proving that this approach, proposed by Swenson *et al.* [11] and Moore *et al.* [12] for other applications, allows to realize a light detector with all the characteristics required by next-generation experiments. The project is divided in three main phases:

- the first one is focused on the development of all the necessary acquisition and analysis tools and on the optimization of the detector geometry. For this phase we decided to work with a well known material for KIDs applications, Aluminum, that will allow to reach an RMS energy resolution of about 80 eV;

- the second one is devoted to the test of more sensitive superconductors, such as TiN, Ti+TiN, or TiAl, in order to lower the energy resolution below 20 eV
- in the last one, the optimized light detectors will be coupled to an array of TeO_2 bolometers to prove the potential of this technology.

The results obtained in the first phase are summarized below.

3. – Aluminum resonator

The first light detectors developed by the CALDER project consist of a $2 \times 2\,\text{cm}^2$ Si substrate, $275\,\mu$m thick, read by 40 nm thick and $4.0\,\text{mm}^2$ Al film lumped-element resonator as the one shown in fig. 1, right. Details on the detectors fabrication can be found in ref. [13]. The detectors are cooled below the critical temperature using a ^{3}He/^{4}He dilution refrigerator with base temperature of about 10 mK. The output signal is fed into a CITLF4 SiGe low noise amplifier [14], which is thermally anchored to the 4 K plate of the cryostat. The rest of the electronics is located at room temperature and its features, together with the description of the cryogenic facility and the acquisition software, can be found in refs. [9,15,16]. The detectors are operated in the most sensitive point, where the signal-to-noise ratio (S/N) in the phase direction is maximum (see ref. [17]).

The detector performance in terms of phonons collection efficiency and energy resolution are evaluated by exploiting optical pulses fired by a 400 nm led pulser and driven to the substrate face opposite to the KIDs by means of an optical fiber. The energy of these optical pulses can be adjusted from 310 eV up to 30 keV. The calibration of the optical apparatus, indeed, is made with a photomultiplier at room temperature and is corrected using a Monte Carlo that accounts for the geometry of the set-up and for the optical properties of Si. As a cross-check, the detectors have been exposed also to X-ray sources of ^{57}Co (6.4 and 14.4 keV) or ^{55}Fe (5.9 and 6.4 keV). When an interaction occurs in the substrate the energy absorbed by the resonator is just a fraction of the deposited one

$$E_{abs} = \epsilon E_{dep}, \tag{1}$$

where ϵ represents the detector efficiency. Since the binding energy of the Cooper pairs is $2\Delta_0$ (for Al $\Delta_0 = 197 \pm 5\,\mu$eV) the number of quasiparticles created by the energy release in the resonator is $N_{qp} = \frac{2\epsilon E_{dep}}{2\Delta_0}$. This variation in the quasiparticles number gives rise to a phase shift ($\delta\phi$) of the resonator. Exploiting the principles of superconductivity it is possible to convert $\delta\phi$ into an energy deposition inside the detector, as described in ref. [18]:

$$\delta\phi = \frac{\alpha S_2(\omega, T)}{N_0 \Delta_0^2} \cdot \frac{Q}{V} \cdot \epsilon E_{dep} \tag{2}$$

where α is the fraction of the detector inductance due to the kinetic inductance (of the order of 4–15% for Al), $S_2(\omega, T)$ is a slow function of the temperature (about 2.3–2.6 for our detectors), N_0 is a parameter that depends on the superconductor (for Al $1.72 \times 10^{10}\,\text{eV}^{-1}\mu\text{m}^{-3}$). The second term, containing the resonator quality factor Q and active volume V, depends mostly on the geometry of the device. Up to now several KIDs

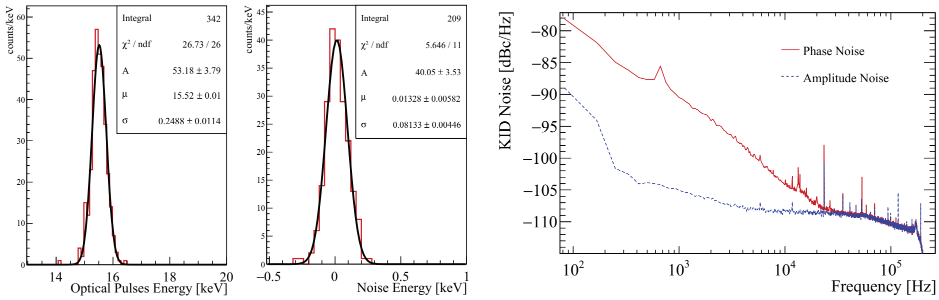

Fig. 2. – Left: energy resolution on light pulses with energy of 15.5 keV. The corresponding baseline resolution evaluated on acquired windows without pulse results 81 eV. Right: noise power spectrum in both amplitude and phase response; the first one is compatible with the expected noise contribution (see ref. [18]), the phase one presents an additional contribution starting from 2×10^4 Hz down to lower frequency.

geometry have been tested changing some of the parameter of eq. (2) (as for example Q and V that can be easily varied up to an order of magnitude). As expected the efficiency is proportional to V as described in ref. [19]. The average performances in terms of noise resolution results between 150 and 100 eV. The best result was obtained using an aluminum deposition with an active surface of 4 mm^2 and a thickness of 60 nm: a noise resolution of 80 eV and an efficiency of about 10% was obtained. With the production of this detector the first phase of the CALDER project was accomplished. Nevertheless, the energy resolution of all the tested resonators was worsened by a low-frequency noise (see fig. 2, right), whose origin is still under investigation. Understanding and suppressing this noise source will allow to further improve the performance of aluminum KIDs.

4. – Conclusion and prospective

The CALDER project aims to develop a light detector able to satisfy all the requirements for a next generation neutrino-less double beta decay experiment exploiting KIDs. The phase one of the project is now ultimated since an Al light detector with 80 eV RMS resolution was successfully tested. The next step is to start the production of chips based on other, more sensitive superconductors. The resolution, indeed, scales as

$$\delta E \propto \frac{T_C}{\epsilon\sqrt{QL_k}}, \qquad (3)$$

thus, superconductors with lower critical temperature and higher inductance would allow to further enhance the sensitivity. Possible candidates are sub-stoichiometric titanium nitride (TiN), or composite superconductors such as Ti+TiN or Ti+Al.

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