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Development of kinetic inductance detectors for CUORE and LUCIFER

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Summary. — The purpose of the CALDER project (Cryogenic wide-Area Light Detector with Excellent Resolution) is to develop new cryogenic light detectors to be used in CUORE and LUCIFER to improve the sensitivity in the search of neutrinoless double beta decay ($0\nu\beta\beta$) and dark matter. The sensitivity of CUORE can be increased by a factor of 3, thanks to the reduction of the α background, obtained by detecting the Cherenkov light ($\sim 100\,\text{eV}$) emitted by βs events and not by the α-background. In LUCIFER the ability to discriminate β/γ events ($\sim 100\,\text{eV}$ of scintillation light) from nuclear recoils (no light) in the low-energy region opens the way to search for dark matter interactions. This detectors must have an active area of $25\,\text{cm}^2$, a baseline energy resolution of $\sim 20\,\text{eV}$ RMS and a working temperature of 10 mK. The technology chosen is based on the phonon-mediated kinetic inductance detectors (KIDs). This paper presents the results of the first prototypes tested.

PACS `95.55.Vj` – Neutrino, muon, pion, and other elementary particle detectors; cosmic ray detectors.
PACS `95.55.Rg` – Photoconductors and bolometers.
PACS `95.30.Cq` – Elementary particle processes.
PACS `95.35.+d` – Dark matter (stellar, interstellar, galactic, and cosmological).

1. – Introduction

The experiments searching for rare events, such as $0\nu\beta\beta$ [1] and dark matter interactions [2], need to operate in low-noise conditions. The bolometers are among the best detectors in this field, because they have a good resolution and the modular design allows for very high masses; they are limited only by the lack of an active background rejection tool. A very effective background suppression could be obtained by identifying the interacting particles through the simultaneous measurement of the bolometric signal (heat) and the particle light yield. In scintillating crystals the nature of the interacting particles is discriminated using the different yield of scintillation; however, as shown in [3], for not scintillating crystals the background can be reduced detecting the

Table I. – *Main features of the experiments in question. Total mass of crystals (M), resolution in the region of interest (σ), background in the region of interest (B) and sensitivity to the half-life of the $0\nu\beta\beta$ decay.*

Experiment	M [kg]	σ [keV]	B [count/keV $\cdot$ kg $\cdot$ y]	$T^{0\nu}_{1/2}$ [y]	Ref.
Cuoricino (TeO_2)	40.7	6.3	0.153 ± 0.006	$2.8\ \times 10^{24}$	[8]
CUORE-0 (TeO_2)	39	5.1	0.071 ± 0.011	2.8×10^{24}	[9]
CUORE (TeO_2)	741	5	~ 1–2×10^{-2}	0.95×10^{26}	[6]
LUCIFER (ZnSe)	17	13.4	$\sim 10^{-3}$	0.8×10^{26}	[10]
LUCIFER ($ZnMoO_4$)	14	7	$\sim 10^{-3}$	0.6×10^{26}	[11]

Cherenkov light produced by electrons and not by α-particles. For this reason, next generation experiments needs cryogenic light detectors with excellent sensitivity, that could operate in a wide range of temperatures. The CALDER project [4] aims at developing cryogenic light detectors with high sensitivity to UV and visible light, to be used for particle tagging in massive bolometers. In the next sections we present the CUORE and LUCIFER experiments, focusing on the requirement of new cryogenic light detectors. In sect. **3** we describe the new light detectors development process and the features of the KID sensors [5]. Finally, in sect. **4**, we detail the results of the first prototypes tested.

2. – Dual read-out technique in CUORE and LUCIFER

CUORE [6] and LUCIFER [7] are bolometric experiments, designed to search for the $0\nu\beta\beta$ decay, which will begin taking data in 2015 at the Laboratori Nazionali del Gran Sasso (LNGS). The principal features of CUORE, LUCIFER and their demonstrators are reported in table I.

The CUORE experiment is designed to search for the $0\nu\beta\beta$ decay of the ^{130}Te ($Q = 2528\,\text{keV}$ [6]). For this process we expect a monochromatic line at the Q-value of the decay in the sum spectrum of the two electrons, as neutrinos do not subtract energy. A detector with high resolution and efficiency is required to separate the $0\nu\beta\beta$ signal from the $2\nu\beta\beta$ background, for this reason in CUORE we use crystals grown by tellurium as bolometers. The detector of CUORE consists of 988 crystals of tellurium dioxide (TeO_2) in which 34% of Tellurium is ^{130}Te; each crystal is a 0.75 kg cube with 5 cm of side, the total mass is 741 kg (208 kg of ^{130}Te). The expected sensitivity on the half-life of the $0\nu\beta\beta$ decay of ^{130}Te is about 10^{26} years in 5 years of data taking.

The Cuoricino experiment [8] searched for the $0\nu\beta\beta$ decay of ^{130}Te using 40.7 kg of TeO_2 as bolometers, demonstrating also that the background in the region of interest is dominated by radioactive contaminations on the surfaces facing the detectors. α-particles produced by these impurities can lose a variable fraction of their energy in the host material and the rest in the detector, thus producing a flat background from the energy of the decay ($\sim 5\,\text{MeV}$) down to the region of interest of $0\nu\beta\beta$. The simulations show that this contribution will largely dominate the expected background of CUORE experiment in the region of interest.

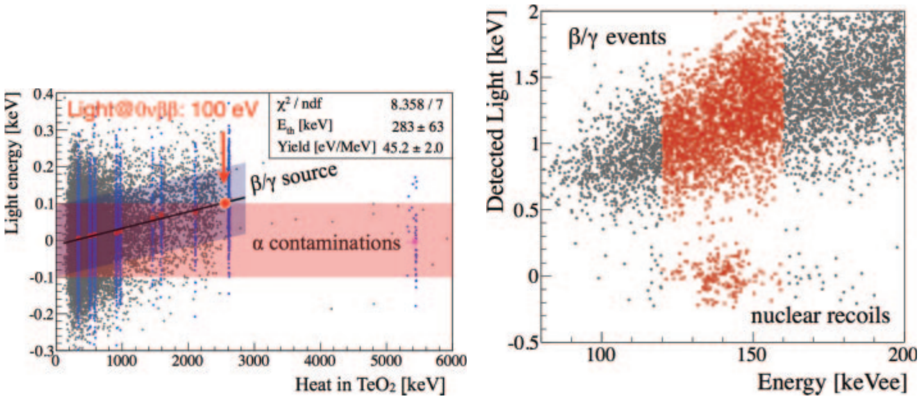

Fig. 1. – Left: Detected Cherenkov light *vs.* the heat signal in the TeO_2 bolometer for all the acquired events (gray dots) and for the events belonging to the γ-peaks (blue dots); the light collected for the γ-events is clearly energy dependent (red dots below 3 MeV) and compatible with zero for the α-decay of the ^{210}Po (pink dot at 5.4 MeV); the separation among the β/γ band (in blue) and the α band (in red) is not effective using the Germanium light detector developed in LUCIFER, figure adapted from [3]. Right: Scintillation light *vs.* the heat signal in the region around the nuclear recoils from the ^{210}Po decay in the LUCIFER ZnSe crystals; the recoils are selected applying the cut to detected light lower than 0.3 keV; the Gaussian distribution of the light emitted from the nuclear recoils has $\sigma_{LD} = 100\,\text{eV}$, this value can be taken as rough estimation of the sensitivity of the light detector; figure reprinted from [10].

The CUORE-0 experiment [9], a CUORE-like tower currently in taking data, has provided a reduction of the α background by a factor 6 respect to Cuoricino (as shown in table I). The new cryostat of CUORE, built by radio-pure materials, will produce a further reduction of γ contaminations but the α-particles still continue to dominate the background. Therefore it is clear that a new idea is required to achieve an effective background suppression. This can be done in CUORE by measuring the Cherenkov light emitted by electrons, which are above the threshold ($\sim 50\,\text{keV}$), in contrast to α-particles [3]. The tests were carried out to verify the effectiveness of this technique, by applying the light detectors developed in LUCIFER to the crystals of CUORE: of the total energy produced by Cherenkov effect ($\sim 900\,\text{eV}$) only 100 eV come out of the crystal, since most of the light is re-absorbed by the crystal. As shown in fig. 1 the separation of β/γ from α-background is not satisfactory due to the light detectors noise ($\sim 100\,\text{eV}$ RMS). Therefore we require a low noise (10–20 eV) light detector which allow to tighten the α-band and separate the signal from the background. Figure 2 shows the sensitivity of CUORE as a function of the signal-to-noise ratio in the light detector. The α-background would be reduced to a negligible level if the light detectors had a signal to noise ratio of at least five, that corresponds to a baseline resolution better than 20 eV RMS.

The LUCIFER project explores the possibility to build a scintillating bolometer experiment to search for $0\nu\beta\beta$ decay of isotopes with Q-values higher than 2615 keV (end of natural radioactivity). There are three main possibilities for this kind of detectors: ZnSe crystals [10] enriched in ^{82}Se ($Q = 2997\,\text{keV}$), $ZnMoO_4$ crystals [11] enriched in ^{100}Mo ($Q = 3034\,\text{keV}$) and $CdWO_4$ crystals [12] enriched in ^{116}Cd ($Q = 2814\,\text{keV}$). The β/γ background will decrease with respect to CUORE because the Q-values are above the bulk of the environmental γ radioactivity. On the other hand the use of scintillating

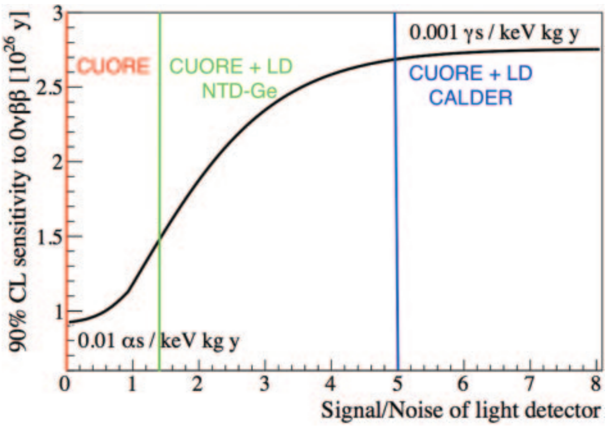

Fig. 2. – CUORE sensitivity to the ^{130}Te $0\nu\beta\beta$ decay half-life as a function of signal to noise ratio of the light detector. The three marked configuration are the CUORE current one (no light detectors), the CUORE with Neutron Transmutation Doped Germanium light detectors one and finally the hypothetical configuration given by application of CALDER light detectors; figure adapted from [3].

crystals will help to reject the α-background, because these particles have a different light yield than the one of β/γ. This technique, in principle, allows to eliminate all the α-background in LUCIFER and reach the so-called *zero background condition*. As a result in 5 years of data taking, LUCIFER is expected to get a sensitivity comparable to the CUORE one, but with a much smaller mass detector (36 bolometers with a total isotope mass of about 9.8 kg). LUCIFER could have a broader physics potential if equipped with sensitive light detectors. Scintillating bolometers are widely used for dark matter searches, as the simultaneous read-out of heat and light allows to disentangle the energy region where WIMPS interactions are expected from the background due to electrons and gamma. The light detectors with an energy resolution of 20 eV RMS, if used in LUCIFER, allow to achieve enough sensitivity to discriminate nuclear recoils (due to WIMP interactions) from β/γ background in the low energy region (see fig. 1 right).

3. – A new cryogenic light detectors with KID sensors

The discussion in the previous sections leads to demand a new cryogenic light detectors with the following specifications:

- an active area of $5 \times 5\,\text{cm}^2$ (area of the surfaces of the CUORE crystals);
- resolution below 20 eV RMS;
- operating temperature 10 mK;
- low concentration of radioactive material;
- reproducibility (1000 detectors).

The attempts to improve the NTD-Ge (Neutron Transmutation Doped Germanium) light detectors show that it is difficult to produce reproducible detectors with resolution

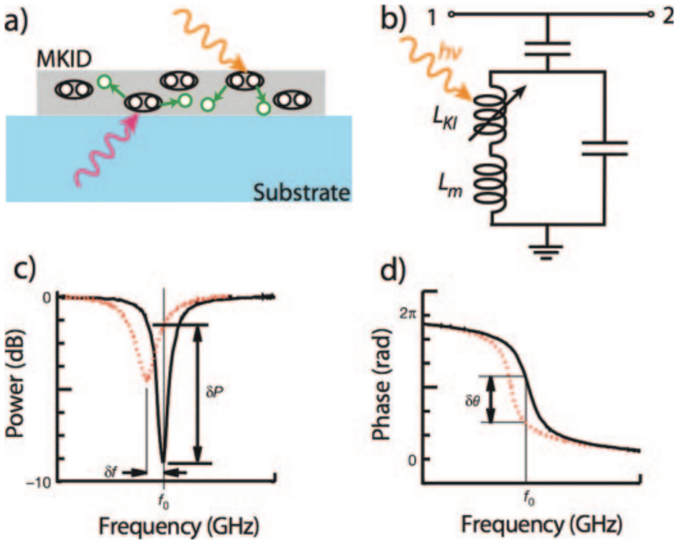

Fig. 3. – a) If a photon strikes the surface of a superconductor breaks some Cooper pairs, varying the kinetic component of the inductance (Energy required = fraction of meV). b) Using a thin-film superconductor we build an LC circuit with high-quality factor (resonance very narrow), along which is transmitted a fixed micro-wave. c) Driven by the incident radiation the circuit changes the frequency response. d) The phase and the amplitude of the micro-wave have a shift, that are the detected signal. Figure adapted from [15].

below 100 eV RMS, therefore it must adopt a different strategy. The first idea is to use TES (Transition Edge Sensors) based light detectors but they have problems of reproducibility and scalability. For this reason we decided to develop a phonon-mediated light detectors based on KID sensors, in which the interacting photons are converted in phonons that break the Cooper Pairs in a LC superconductor circuit as shown in detail in fig. 3.

They use read-out electronic at room temperature and their operation is quite simple, so they ensure good reliability. Furthermore, the possibility to tune each sensor to a different frequency is used to read from a single channel many detectors; this feature, called multiplexing, makes the KID very suitable for a large mass experiment, because the scalability to 1000 detectors is in principle linear, finally their introduction would require minimal changes to existing experimental apparatus.

The KIDs work only when excited by micro-wave signals, this limits their size to a few mm^2, then in order to achieve the required active area it needs a mediator, which in this case is given by the silicon substrate on which the KIDs are deposited. In this way the incoming photons are absorbed by a 300 μm thick silicon substrate, where they are converted into non-thermal phonons. Then the non-thermal phonons will be sampled by few lumped element KIDs deposited on the substrate. The starting point of the project is the Moore's work [13], who developed a similar detector to be used to search for dark matter. However, compared to Moore's work, it is not required to resolve the position of the interaction, this relaxes the constraints on the response time of the sensors, making it possible to increase their quality factor and thus improve the energy resolution.

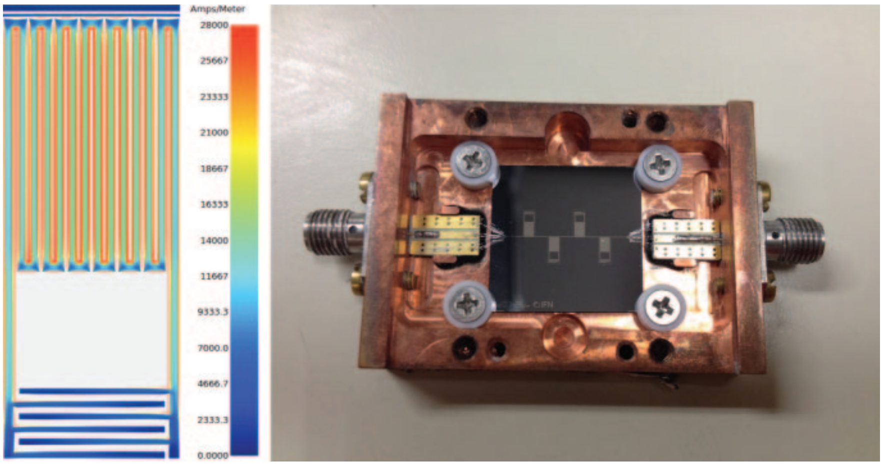

Fig. 4. – Left: Current density distribution in a single pixel; the power line is coupled to the inductive meander, that has a total area of about 2.3 mm^2, it is made of fourteen 2 mm long, 80 μm wide streps and the distance between two adjacent strips is 20 μm. Right: One of the first prototype of the light detector. Four Aluminium KID sensors are deposited on a 2×2 cm^2 silicon wafer; the detector is mounted in the copper holder that is used for the test measurements.

The research project for the next three years, has two phases: in the first one, currently in progress, single pixels are implemented and the performance of different superconducting materials are checked, developing in parallel a system of absolute calibration and the acquisition electronics; the read-out system is done starting from the electronic board used in NIKA [14]; in the second phase, the light detectors will be exposed to CUORE/LUCIFER bolometers at LNGS, in order to verify their performance and work at the same time on the electronics for a large-scale experiment.

4. – Status and future plans

In the first part of the project single pixel design (in fig. 4, left) has been optimized, also configuration of the cryostat and the electronics are tested. Currently we are testing the 4-pixels (see fig. 4, right) and 9-pixels detectors, characterising their response to a pulsed light source and an X-ray source of ^{55}Fe. Some results are reported in fig. 5,

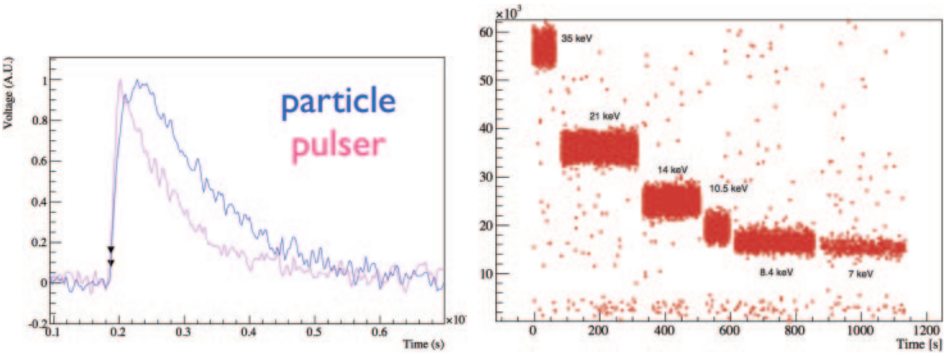

Fig. 5. – Left: Pulse phase variation of the micro-wave due to the light pulse of 35 keV. Right: Signal amplitude (in arbitrary unit) as a function of light pulse energy.

where we can see the variation of the phase of the micro-wave due to light interaction in the detector (left) and also an energy scan of the KID response (right). Thanks to this tests some of the critical parameters to work on are identified, such as the thickness of the ground plane and the width of the film. The main goal is to obtain a configuration that maximizes the quality factor of the resonators, the sensitive area, the sensitivity and reproducibility of the response. In the prototypes until now aluminium is used as a superconductor, since it is the most studied one in the literature; however, when the link between the geometry of the sensors and factors of merit will be clear, a prototypes will be realized using TiN (titanium nitride) as a superconductor, characterised by a kinetic inductance from ten to hundred times greater than aluminium; also their lower critical temperature contribute to improve the energy resolution of the detectors.

Moreover a study is ongoing to improve the geometry of the single pixel, so far never changed from the first prototype. In particular the new simulated sensor, compared to the previous, has an active area greater than 60% and fraction of the kinetic inductance (parameter defining the sensitivity) more than doubled [16].

In the coming months prototypes with this new geometry will be produced and tested, before in aluminium and after in TiN. Starting from next year, we will begin also testing at the Laboratori Nazionali de Gran Sasso (LNGS), in which the new light detectors will be expose to the CUORE and LUCIFER crystals to assess its performance.

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