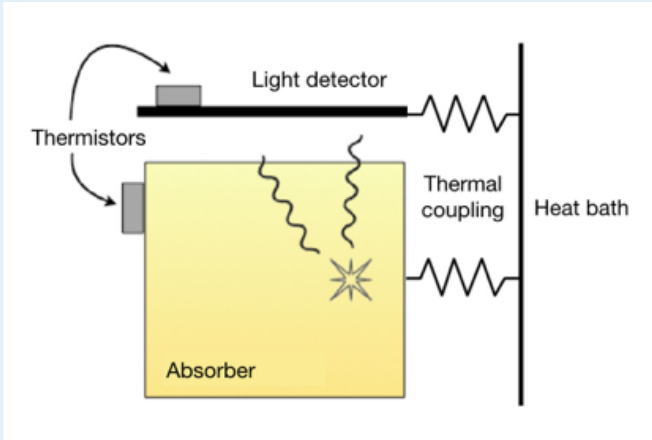
Optimizing the time resolution of cryogenic calorimeters with NTDs: the CALIPSO project

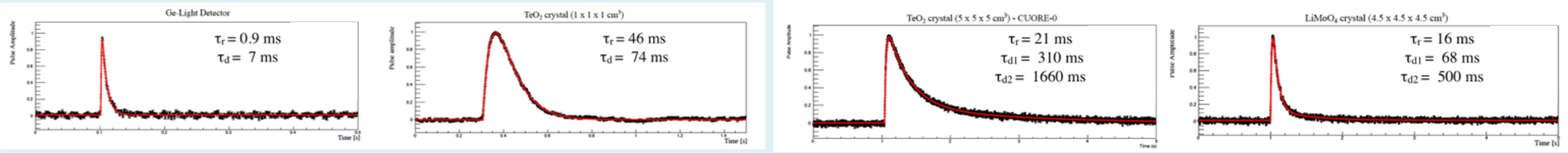
I. Nutini, Università degli Studi di Milano Bicocca and INFN – Milano Bicocca

1. Cryogenic calorimeters in astroparticle physics: current status

Low temperature detectors (LTD), or cryogenic calorimeters, have been widely utilized for the last 50 years in astroparticle physics [1], in particular for the search of neutrinoless double beta decay (CUORE, CUPID-0, CUPID-Mo, AMoRE,..), dark matter searches (COSINUS, CRESST-II, CDMS,..), direct measurement of the neutrino mass (HOLMES, ECHo,..), neutrino coherent scattering (NUCLEUS,..).

A LTD consists in an absorber weakly coupled to the heat bath at ~10 mK; the former is equipped with a sensor, for measuring the temperature variation due to some energy deposition. For few cryogenic calorimeters, it is possible to read out also the scintillation channel [2]; this is usually done with a second LTD (eg. Ge-wafer), called light detector (LD), absorbing the phonons and converting those into a temperature variation as well. A double readout of both phonons-temperature and photons-scintillation allows a better discrimination among the interacting particles. The most utilized temperature sensors are resistive thermometers, such as the neutron transmutation doped (NTD) semiconductor (Ge) thermistors [3]. The Ge-NTD thermistors can be produced in large quantities with uniform and homogeneous properties; they can also be operated in a wide range of temperatures (10 - 100 mK) and they need simple bias circuitry and readout electronics. However, the cryogenic calorimeters read out with NTD thermistors suffer of a limited time resolution, with characteristic times of 1-100 ms or more.





Adapted from [6]

Cryogenic calorimeters with NTDs have demonstrated to be a valid detection technology for the neutrinoless double beta decay searches, due to the possibility of utilizing different crystals (and consequently multiple double beta decay candidates) with an excellent energy resolution (~ keV). An outstanding example is the CUORE experiment, utilizing 1 tonne of TeO_2 crystals at 15 mK, taking data since 2017 [4]. The future perspective is CUPID, utilizing Li_2MoO_4 scintillating crystals with NTDs [5], with a similar mass scale as CUORE, and aiming to a 'zero background' regime; the current limit of the time response for this kind of detectors (Hz - kHz) may be an obstacle when there is an irreducible background at high rate, such as the pile-up between double beta decay events in crystals highly enriched in the candidate isotope [7].

2. The CALIPSO project: goals

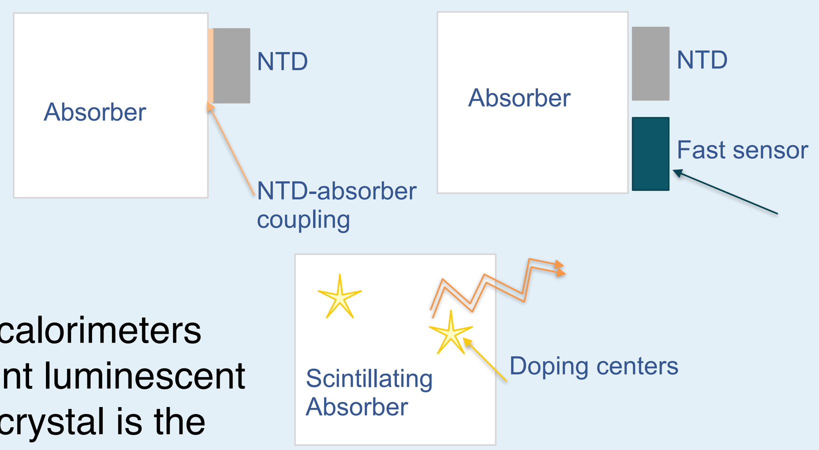
The project aims to explore the limits in time response of the current implementations of cryogenic calorimeters with NTD thermistors, with a particular focus on the scintillating crystals

- Optimization of the NTD-detector couplings and of the configuration for the thermal signal readout.

The goal is to identify a suitable configuration of the experimental setup (absorber, NTD, holders, thermalization, readout) leading to fast response detectors, with still good energy resolution.

- Doping of the scintillating calorimeters for increasing the light yield at low temperatures.

For scintillating calorimeters the light could be used to obtain a temporal information for each event, potentially better than the one from the heat channel. However the scintillation light yield of cryogenic calorimeters is generally small at low temperatures (LY ~ 0.1 - 10 keV/MeV at 10 - 50 mK), due to the lack of efficient luminescent centers and to the trapping of the charge carriers [8]. A general strategy to improve the light yield of a crystal is the introduction of new luminescent centers, by doping.

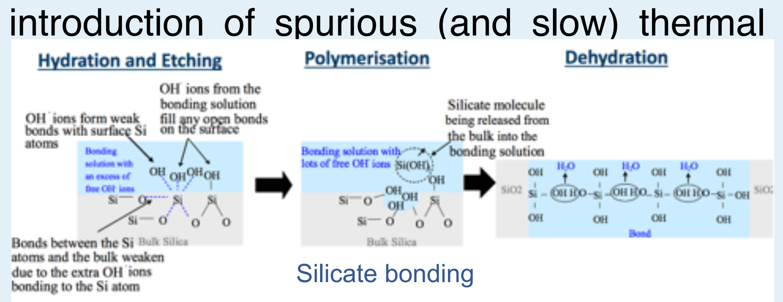


3. The CALIPSO project: proposed research activities

- Sensors and readout

I. Single readout. Optimization of the couplings among all the thermal elements in order to avoid the introduction of spurious (and slow) thermal constants.

- Traditional coupling: glue/resins (eg. araldite) for NTD-absorber coupling, copper holders, teflon spacers
- CALIPSO proposal: new techniques for NTD-absorber coupling, different holders
  - Hydroxide catalysis bonding (HCB) with sodium silicate solution ('silicate bonding') [9] for coupling the Ge-NTDs on different substrates with low roughness: crystals (eg. oxides - TeO_2, Li_2MoO_4) and LDs.
  - Eutectic bonding for coupling substrates (eg. Si, Ge) with an intermediate metallic layer, which produces an eutectic system [11]. For coupling the Ge-NTD to the LDs and the crystals (eg. oxides), it could be possible to use the eutectic alloy Au-Ge, obtained while preparing the NTD electrodes.



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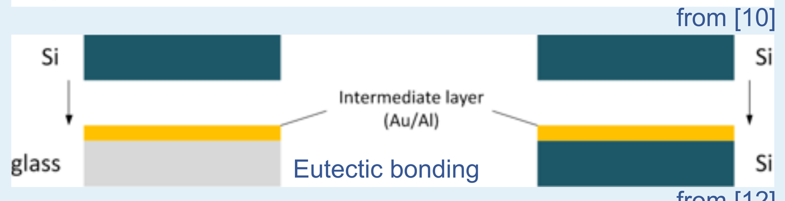
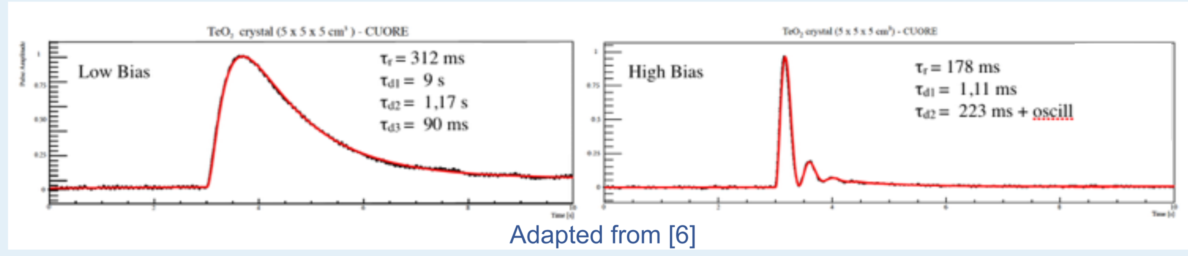


from [12]

II. Double readout. Adding a second sensor with better time resolution, to obtain a more precise temporal information for the heat signals acquired by the primary NTD.

- CALIPSO proposal: utilize a NTD operated in high bias current regime, as the second sensor. When a NTD is operated in this regime, the negative electrothermal feedback affects the shape of the thermal signal, shortening the pulses' time constants while deforming the falling edge.



Adapted from [6]

- Scintillating crystals

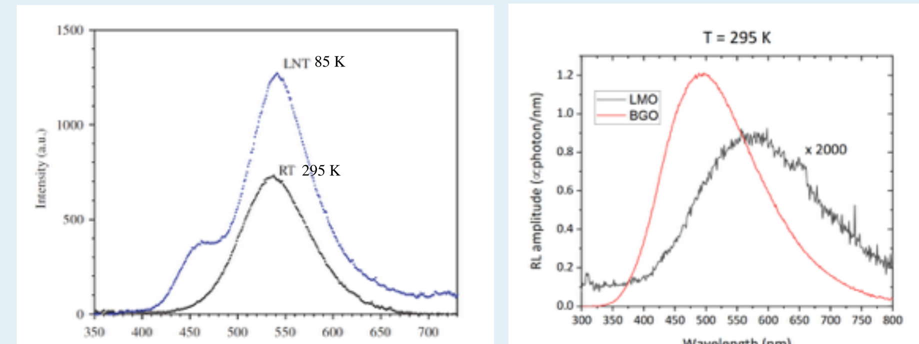
Doping the scintillating cryogenic absorbers in order to improve their light yield at low temperatures.
Choice of the doping element: emission properties, incorporation in the crystal lattice, stable isotopes, avoid introduction of paramagnetic centers

- Previous tests: doping TeO_2 crystals, limited doping uniformity and performances at low temperature
- CALIPSO proposal: doping Li_2MoO_4 crystals [13]. Dedicated study of possible doping elements for the crystals (eg. Cu1+, Ag1+; Mn2+, Cr3+), growth and production of doped crystals, and characterization of the scintillation properties at different temperatures and excitations

- Experimental measurements

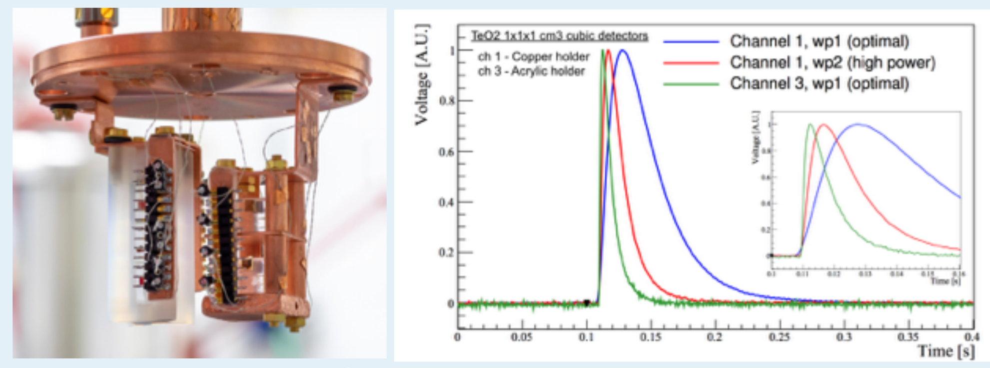
The proposed CALIPSO experimental measurements campaign would be divided in two sections:

1. Characterization of scintillation light of doped and undoped crystals at T = 10 - 300 K at Dip. Scienze dei Materiali UniMiB
Investigate the nature of the emission centers, the presence of traps and the detrapping times at different temperatures.
- Transmission curves
- Luminescence spectra (UV and X-ray stimulated)
- Thermoluminescence spectra



from [14] from [15]

2. Cryogenic measurements of the performances of scintillating calorimeters at T = 10 - 50 mK at Dip. Fisica UniMiB - Cryogenic Lab
- Design of the holders (copper, acrylic, hybrid solutions) for optimal thermalization of the detectors and effective polarization of the NTDs
- Detector assembly (NTD-detector couplings, installation in the holders, wiring)
- Thermal characterization of different detector implementations: static and dynamic measurements, in order to identify which configuration (NTD-crystal/NTD-LD coupling, crystal doping, single/double readout,..) leads to a better time resolution at ~10 mK



from [16]

The innovative aspect of the proposed characterizations is the possibility to perform multiple comparative measurements with different detectors but with the same experimental instrumentation, thus reducing the systematic uncertainties due to the data-taking and analysis methods.

4. The CALIPSO project: applications and perspectives

The results of the CALIPSO project may have an impact on rare events, neutrino and astroparticle experiments.

Developing cryogenic calorimeters read with NTDs with faster time response could be applied to:

- CUPID experiment. CUPID baseline: rise times 10-50 ms for heat signals and < 500 us for light signals; this should reduce the pile-up between ^{100}Mo double beta decay events, reaching a 'zero background' regime considering the large mass scale of CUPID. CUPID may apply few of the CALIPSO solutions, the ones with lower technical impact on the baseline project, to improve its time resolution more.
- Measurements of beta decays at high rates with large scale cryogenic calorimeters

A better comprehension of the detector performance with different setups (crystals, NTDs, couplings, holders) may support the thermal modeling works for experiments employing cryogenic calorimeters read with NTDs, such as CUORE and COSINUS. For example, CUORE can profit of the thermal model inputs also for the optimization of the data analysis: pule shape selection, choice of the time coincidence windows among multiple crystals, …

Scintillating cryogenic calorimeters with an improved light yield, such as the doped Li_2MoO_4, and with a better discrimination capability among events (alpha, beta/gamma, neutrons/nuclear recoils) could be also utilized for neutrons measurements and search for solar axions, dark matter searches and measurements of rare alfa decays.

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