Novel techniques for thermal detectors and applications for rare events physics

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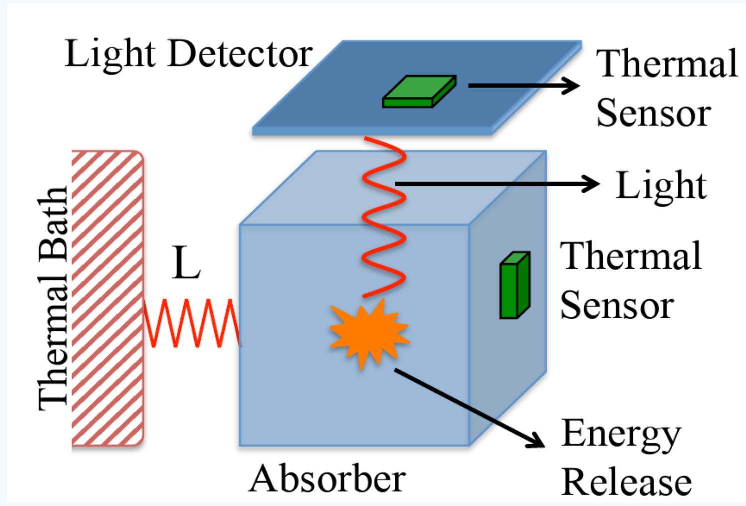
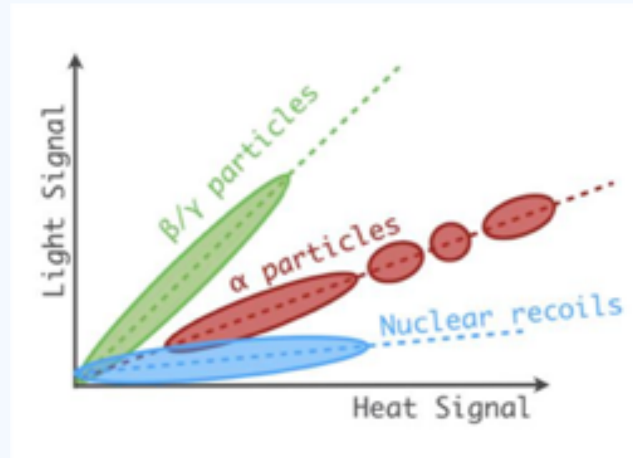
Cryogenic detectors: status and perspectives

The current technology of thermal detectors for rare events physics is based on large cryogenic calorimeters read with NTD thermistors. Measuring the total energy deposition via the heat release in the crystal lattice allows for optimal energy resolutions when the detectors are operated at 10mK. In case the crystals are made of a scintillating material, a double readout of heat and scintillation light could allow for an improved discrimination between alpha and beta/ gamma events.

A cryogenic calorimeter 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 the energy deposition. Generally, the scintillation light from the absorber is read with second thermal detector (eg. Ge-wafer), called light detector (LD). The most utilised temperature sensors are resistive thermometers, such as the neutron transmutation doped (NTD) semiconductor (Ge) thermistors.

Refs. [1-3]





Improvement of the light collection and output

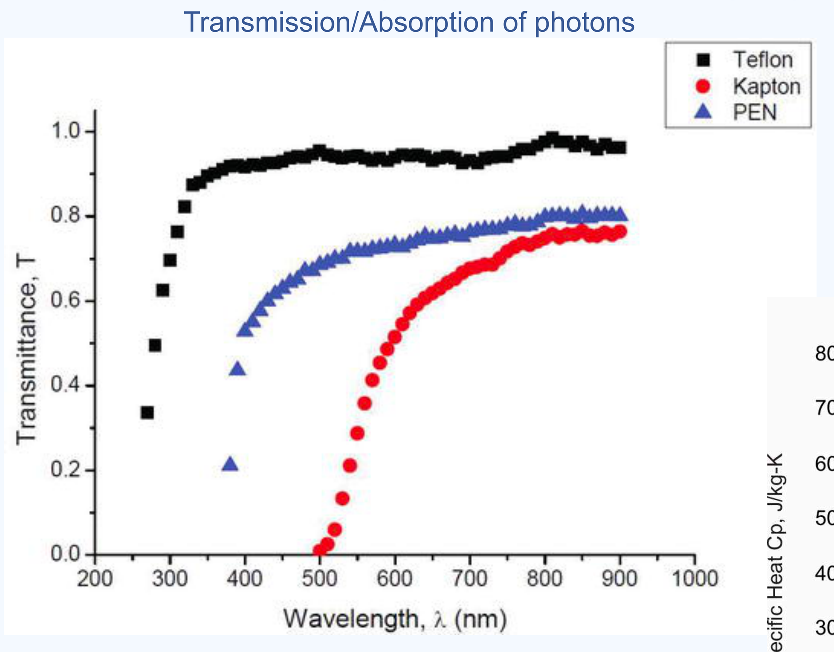
For scintillating calorimeters the light can be used to obtain both the particle discrimination and a temporal information for each event, potentially better than the one from the heat channel. Besides the scintillation light output improves with decreasing temperature, the light yield of cryogenic calorimeters is still generally small (LY 0.1 - 10 keV/MeV at 10 - 50 mK), due to the lack of efficient luminescent centres in the compounds, to the trapping of the charge carriers and to a limited light detection efficiency. *Ref. [4]*

Strategies:

- **Enhance the scintillation of the crystals by doping**: emission properties of the doping center, incorporation in the crystal lattice, use of stable isotopes, avoid introduction of paramagnetic centers
- **Increase the scintillation light collection**
  - Coating of the crystal surfaces with reflective (metal) layers (500 nm-1um)
  - Improve the light detector technology
    - Cryogenic Ge-LD geometric detection efficiency optimisation
    - **Development of novel cryogenic LDs with plastics**: organic compounds absorbing the scintillation photons, to be operated as cryogenic calorimeters at 10mK: Polyimide (Kapton) LD, PEN LD (+ self-fluorescence), …

Assessment of optical and thermal properties of the plastic materials

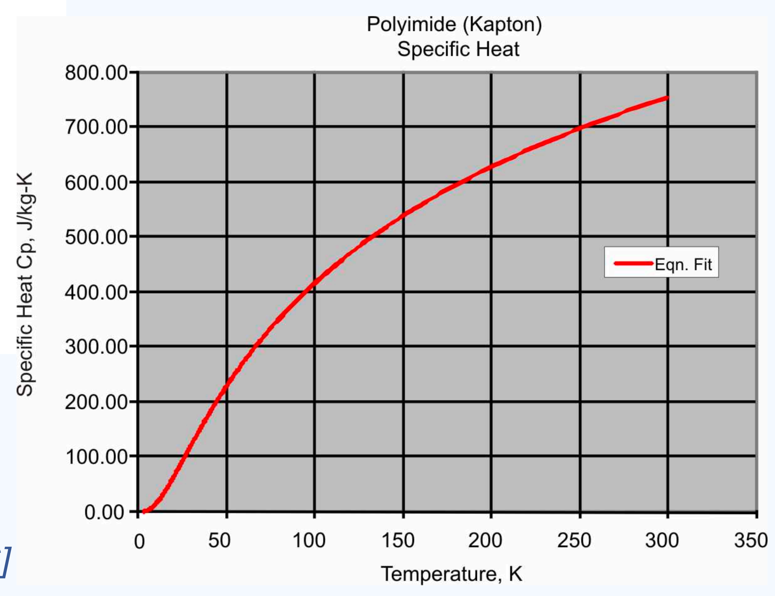
Transmission/Absorption of photons



- High absorption for optical photons
- Kapton has almost 100% absorption for all photons up to 500nm

Ref. [5]

Specific heat c_p temperature dependence



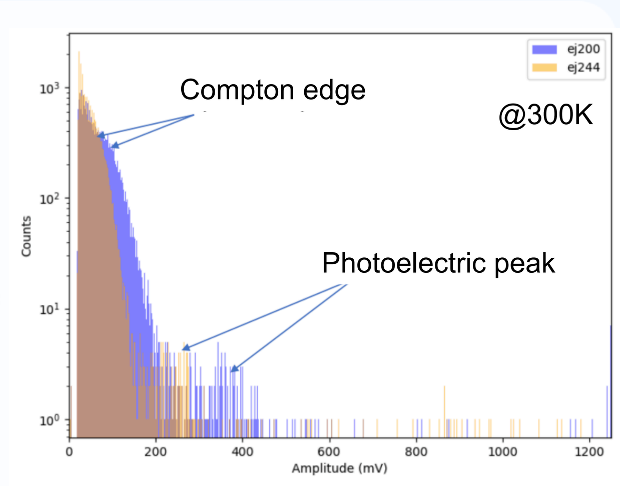
Ref. [6]

- Amorphous material, no ideal Debye law for specific heat
- Measured specific heat c_p decreases with T

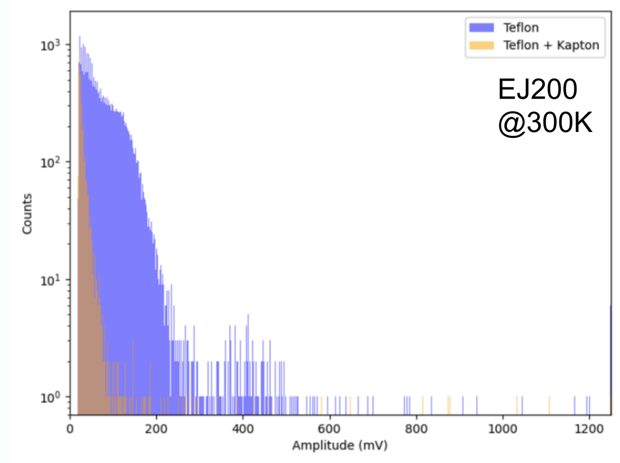
Towards the Kapton LD idea, realisation and tests

EJ200, EJ244 PVT scintillators - Measurements at 300K

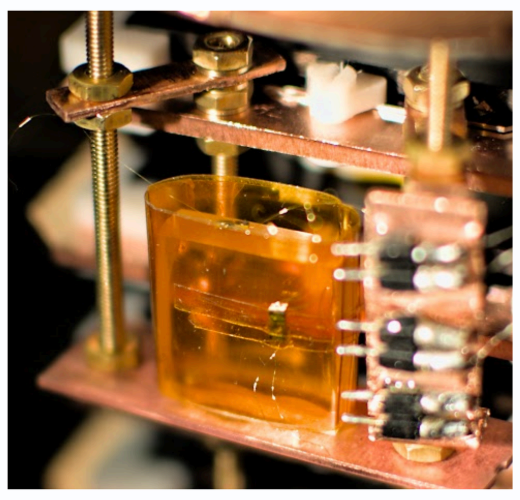
- Scintillator disks wrapped with teflon tape and optically coupled to SiPM for light readout
- Exposed to ^{57}Co gamma source
- Wavelength of Max Emission: 425 nm (EJ200), 434 nm (EJ244)
- Light Output (% Anthracene): 64% (EJ200), 56% (EJ244)



Kapton tape applied to one surface of the scintillator (EJ200): absorbs most of the optical scintillation photons



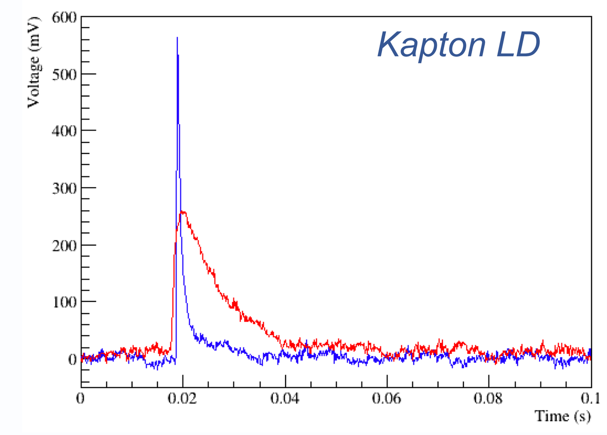
Preliminary design of a Kapton LD:



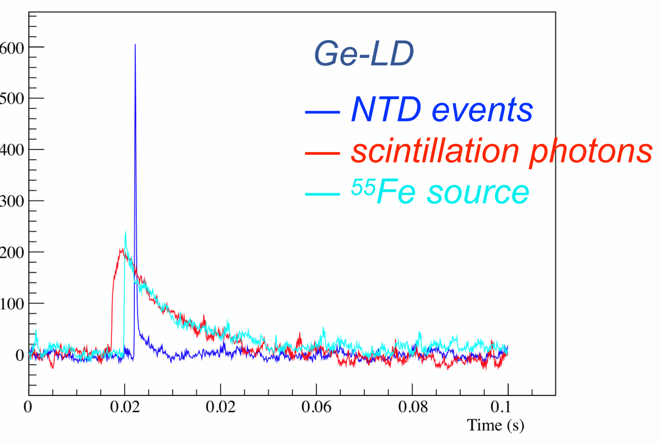
Thin layer of Kapton tape (0.5mm) readout with a NTD thermistor, positioned around an EJ200 scintillator and cooled down to 15mK

- Heat capacitance for 50mg detector (from NIST c_p data): C ~ 10^{-2} J/K [10 K], 10^{-4} J/K [4 K]

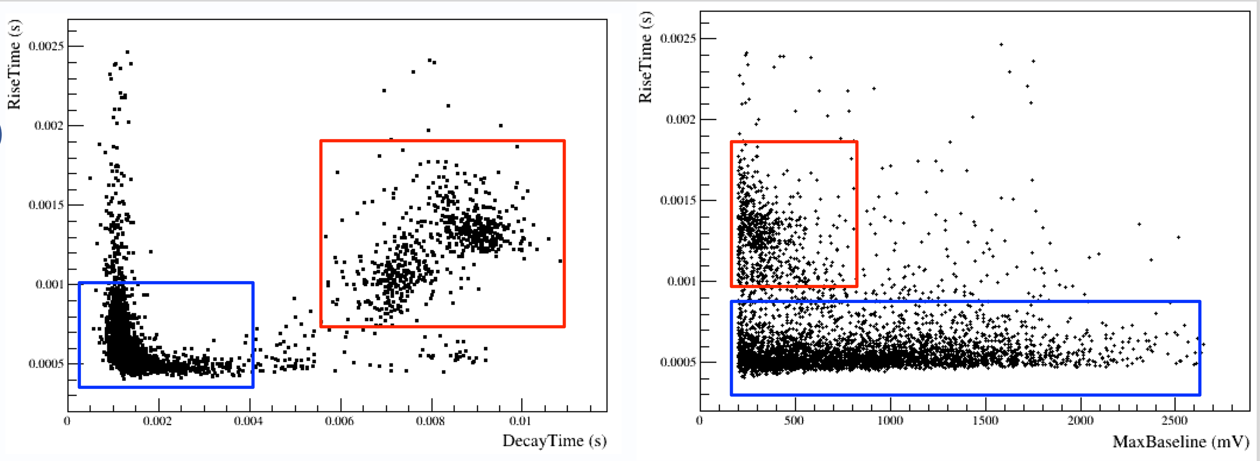
Data-taking at 15mK (January 2022) - Cryostat @UniMiB



Kapton LD & traditional Ge-LD; both LDs had NTD readout and were facing EJ200 scintillators exposed to external ^{232}Th gamma sources



Kapton LD - Preliminary results
Two populations of thermal pulses
- *'fast' pulses (large amplitude range) RT~500-800us, DT~ 1-2.5ms Hp: events on NTD*
- *'slow' pulses (lower amplitudes) RT~1-1.5 ms, DT~7-10ms Hp: scintillation photons absorbed in Kapton*

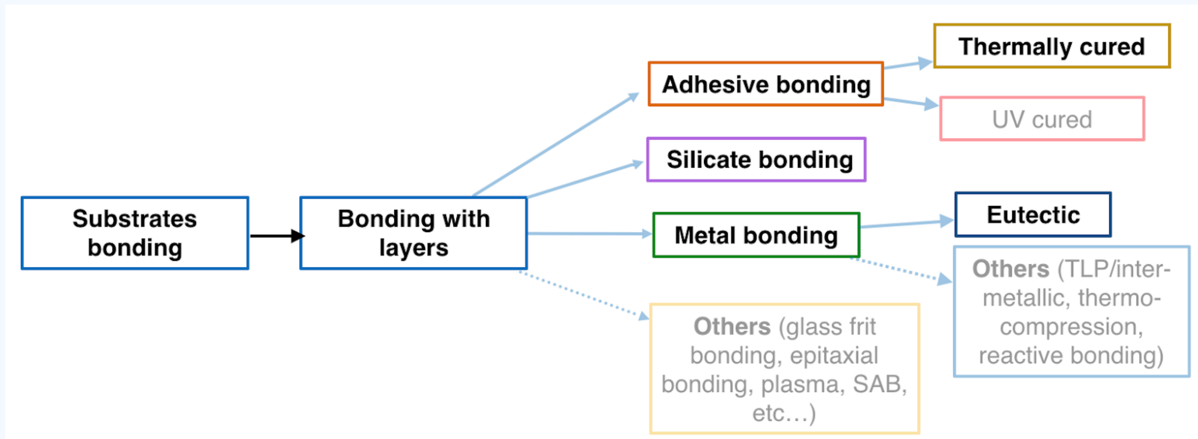


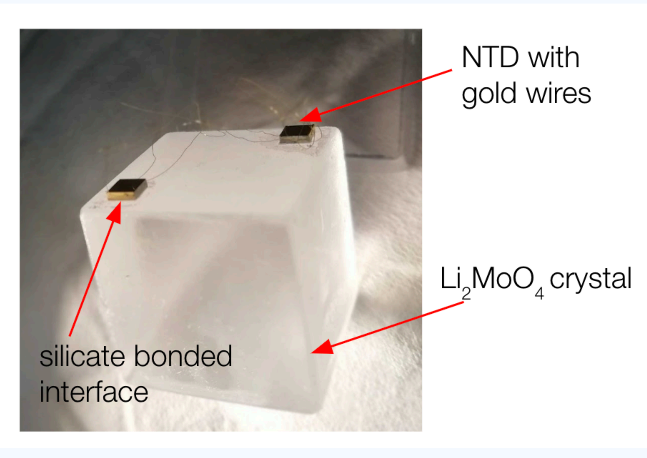
Intriguing and promising results for the Kapton LD. *New cryogenic run foreseen in June 2022*: improved design for the Kapton LD & dedicated characterisation measurements

Improvement of the thermal detector sensitivity

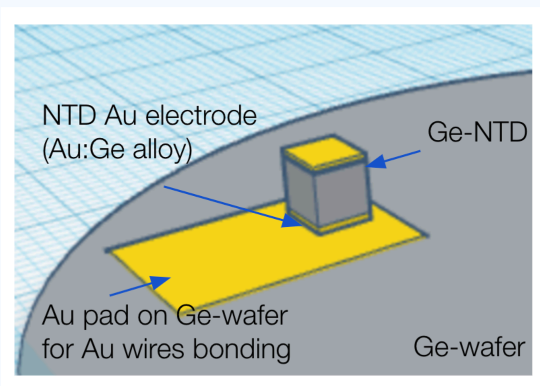
The response of cryogenic detectors read with NTD is generally limited by the several thermal factors playing a role in the signal formation, particularly the **coupling between the absorber and the thermistor**.

- Traditional approach: adhesive bonding using glue/resins
  - High reproducibility of the bonding (~1000 chips)
  - Limited sensitivity due to glue conductance: auxiliary thermal node and non-negligible thermal stress on the chips
- New techniques
  - **Silicate bonding** (applied already in several fields of satellite and optical physics). Hydroxide catalysis bonding (HCB) with sodium silicate solution.
    - Low roughness of the substrate surfaces (< 10nm) *Ref. [7]*
    - Mechanical tests from 300K to 77K
    - Test of the bonding conductance at 10 mK
  - **Eutectic bonding** (utilised for Si-wafers coupling in semiconductor industry). Coupling substrates (eg. Si, Ge) with an intermediate metallic layer, producing an eutectic system
    - Surface outgassing and thermal stress post heating up (~150-300°C) and pressure application
    - Stability and properties of the eutectic junction at 10 mK *Ref. [8]*





First test of silicate bonding Ge-NTD / Li_2MoO_4 @UniMiB (in collab. with INFN Ferrara)
- *Tested at 300K, 77K*
- *Cryogenic test at 10mK planned for June 2022*



Design for the realisation of an eutectic bonding Ge-NTD / Ge-wafer
- *Preparation of the Au-pad on the Ge wafer @UniMiB*
- *Eutectic bonding @ INFN Ferrara Planned for summer/fall 2022*

Ref. (1)

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