A thermal model for low-temperature TeO_2 calorimeters read out by NTD thermistors

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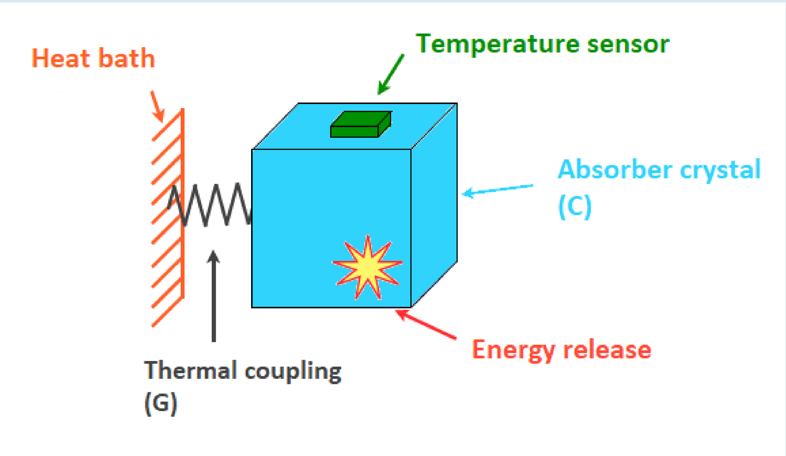
TIPP 2021 - International Conference on Technology and Instrumentation in Particle Physics
24 - 29 May 2021
Sensors: Solid-state calorimeters
Poster ID: #306

Low-temperature calorimeter



Main features of calorimeters:

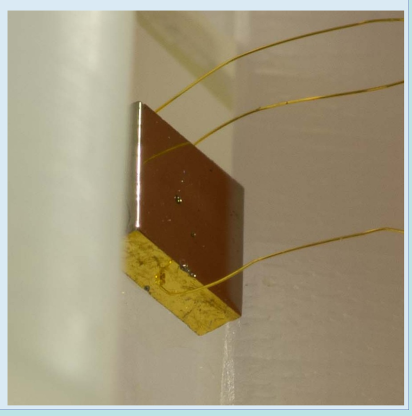
- Conversion of energy into phonons;
- Operated at temperatures T~10-100 mK;
- Low thermal capacity C;
- Temperature rise $\Delta T \propto E/C$.

Temperature sensor:

- Conversion of phonons into electric signal;
- Use Ge thermistors, doped by Neutron Trasmutation (NTD);
- Strongly compensated doping concentation near metal-insulator transition (MIT);
- Electric conduction through Variable Range Hopping regime;
- For T << 150 mK the electric resistivity follows the law:

$$\rho(T_e) = \rho_0 \exp\left(\frac{T_0}{T_e}\right)^{\frac{1}{2}}$$

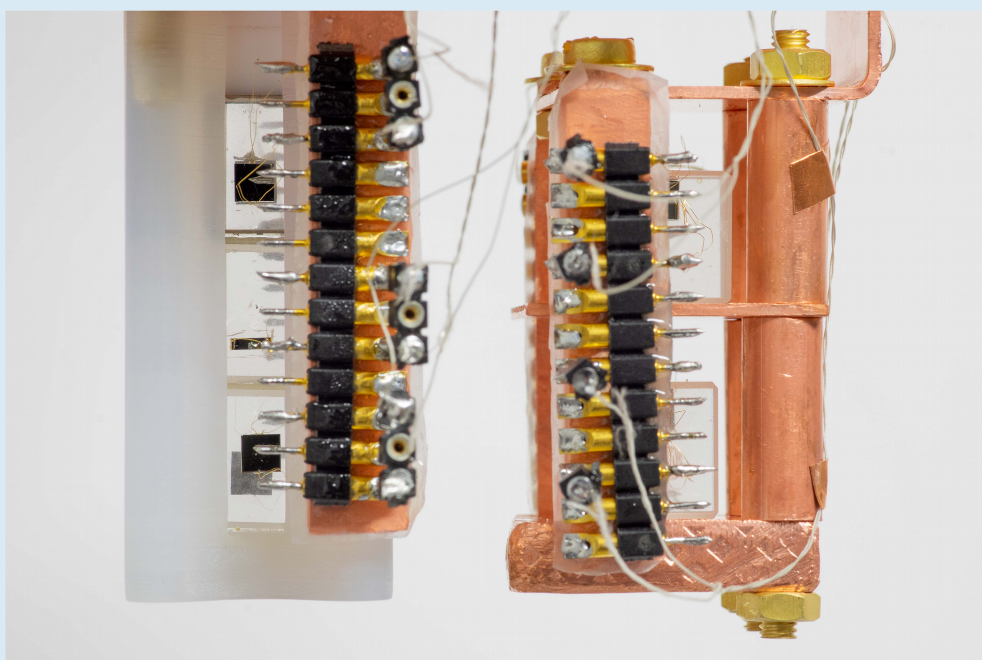
ρ_0 , T_0 are related to the concentration of dopants:
T_0 ~ (4-5) K for calorimeters operated @ T~10 mK.



Experimental setup

Detector setup:

- Five TeO_2 crystals (1x1x1 cm³);
- On four crystals, two NTDs were glued on each crystal:
  1) batch 33C (3×3×1 mm³);
  2) batch Bo1 (different sizes);
- Crystals housed in two holders:
  1) glued to a copper holder;
  2) fastened in an acrylic holder.

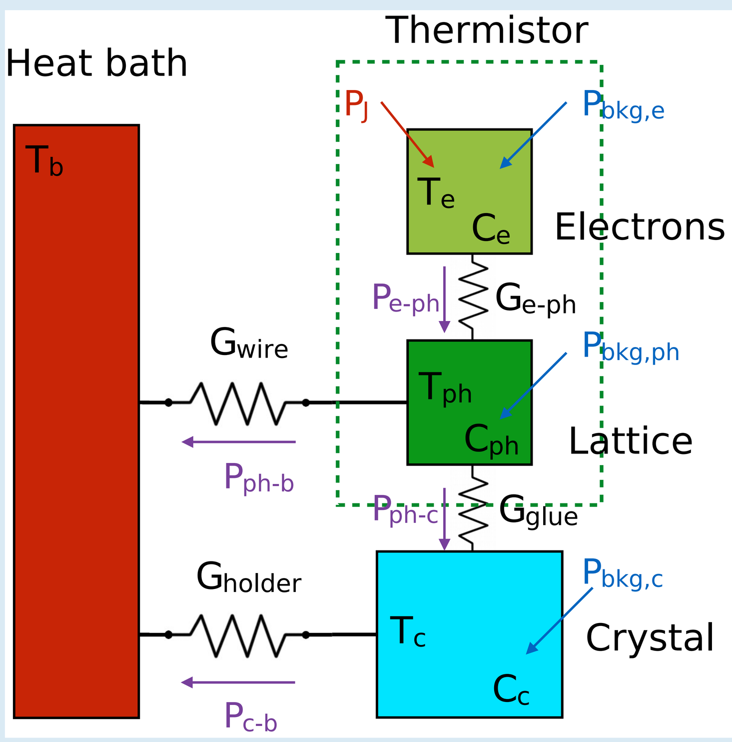


Use of holders of different materials in order to:
1) study how it affects the thermalization of the calorimeters;
2) study of the possibility of using scintillating plastic holders instead of passive holders in future experiments → scintillation veto for background suppression (superficial contaminations, degraded α).

Thermal model and load curve analysis

Static thermal model

- Model the detector as a thermal circuit;
- Solve the associated thermodynamic equilibrium equations: the solution R(P) depends on few parameters (R_0, T_0, thermal conductances G).



Load curve analysis

- Acquisition of NTDs 33C load curves (LC) at temperatures between 10 mK and 25 mK;
- Fit of all LC with the solution R(P) of the thermal model → parameters estimation.

Cu holder, crystal A, NTD α		
Free parameter	Value	Uncertainty
First run		
R_0 (Ω)	0.52	0.05
T_0 (K)	4.76	0.02
g_{e-ph} ($W/K^{\beta+1}$)	$4.4 \cdot 10^{-2}$	$0.1 \cdot 10^{-2}$
β	3.99	0.03
g_{eff} ($W/K^{\alpha+1}$)	$3.9 \cdot 10^{-3}$	$0.4 \cdot 10^{-3}$
α	3.00	0.10
T_{offset} (K)	$4.9 \cdot 10^{-3}$	$1.0 \cdot 10^{-3}$
Second run		
R_0 (Ω)	0.52	0.05
T_0 (K)	4.75	0.02
g_{e-ph} ($W/K^{\beta+1}$)	$4.4 \cdot 10^{-2}$	$0.1 \cdot 10^{-2}$
β	3.96	0.01
g_{eff} ($W/K^{\alpha+1}$)	$1.7 \cdot 10^{-3}$	$0.2 \cdot 10^{-3}$
α	3.01	0.10
T_{offset} (K)	$0.7 \cdot 10^{-3}$	$0.2 \cdot 10^{-3}$

Cu holder, crystal B, NTD β		
Free parameter	Value	Uncertainty
First run		
R_0 (Ω)	0.93	0.03
T_0 (K)	4.79	0.02
g_{e-ph} ($W/K^{\beta+1}$)	$4.5 \cdot 10^{-2}$	$0.1 \cdot 10^{-2}$
β	4.02	0.01
g_{eff} ($W/K^{\alpha+1}$)	$3.2 \cdot 10^{-3}$	$0.4 \cdot 10^{-3}$
α	2.98	0.10
T_{offset} (K)	$4.8 \cdot 10^{-3}$	$1.6 \cdot 10^{-3}$
Second run		
R_0 (Ω)	0.89	0.04
T_0 (K)	4.78	0.02
g_{e-ph} ($W/K^{\beta+1}$)	$4.6 \cdot 10^{-2}$	$0.2 \cdot 10^{-2}$
β	4.06	0.03
g_{eff} ($W/K^{\alpha+1}$)	$3.1 \cdot 10^{-3}$	$0.3 \cdot 10^{-3}$
α	2.92	0.11
T_{offset} (K)	$0.4 \cdot 10^{-3}$	$0.1 \cdot 10^{-3}$

Acrylic holder, crystal C, NTD γ		
Free parameter	Value	Uncertainty
R_0 (Ω)	0.48	0.06
T_0 (K)	4.69	0.05
g_{eff} (mW/K$^{\alpha+1}$)	0.096	0.015
α	2.58	0.10
T_{offset} (mK)	-2.8	1.1

Acrylic holder, crystal D, NTD δ		
Free parameter	Value	Uncertainty
R_0 (Ω)	0.65	0.05
T_0 (K)	4.79	0.02
g_{eff} (mW/K$^{\alpha+1}$)	0.018	0.006
α	2.32	0.07
T_{offset} (mK)	-3.2	1.6

Conductances in copper holder's system:

- Electron-phonon: $G_{e-ph} = g_{e-ph} T^{\beta}$, $\beta \sim 4$;
- Glue: $G_{glue} = g_{glue} T^{\alpha}$, $\alpha \sim 3$.
- Crystal A was reglued after first run → different g_{glue} during second run.

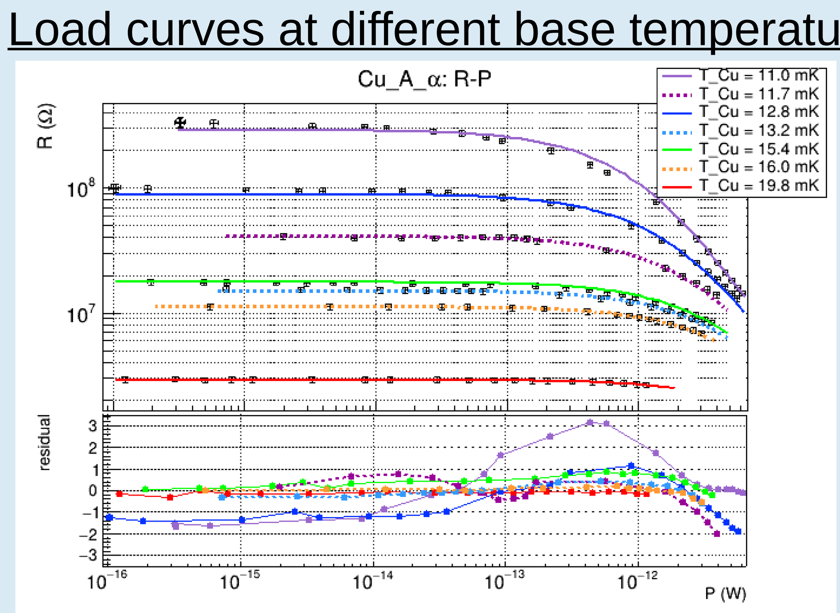
Conductances in acrylic holder's system:

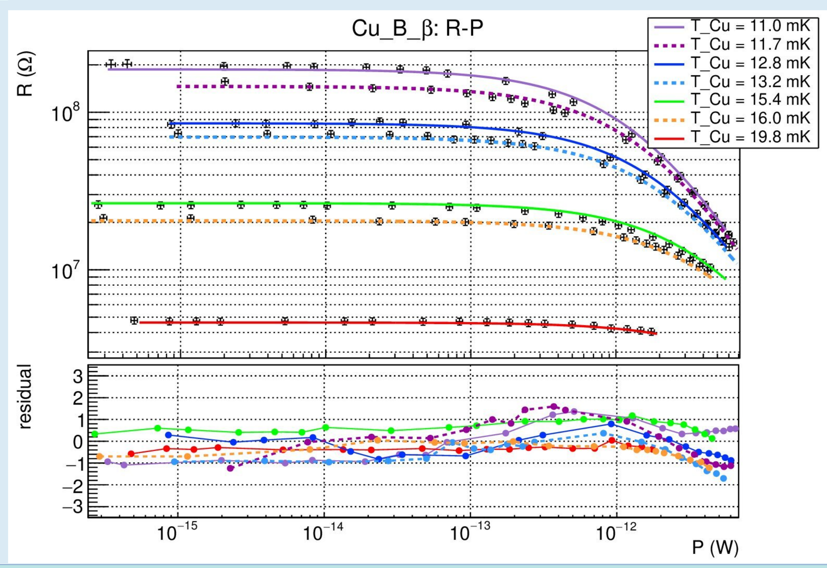
- Read-out wires: $G_{wire} = g_{wire} T^{\alpha}$, $\alpha \sim 2.4$.

Conclusions on LC analysis

- Thermalization process of detectors progresses through different paths:
  1) through glue between crystals and frame for calorimeters in the copper holder;
  2) through NTD's read-out wires for calorimeters in the acrylic holder.
- Electron-phonon conductance in agreement with the metal hot electron model.

- Load curves at different base temperatures:





Conclusions

- We studied the behaviour of low-temperature calorimeters in copper/acrylic holders. The different thermal properties of copper/acrylic influence the system's thermal behaviour and the thermalization process.

- Load curves analysis:
  1) static thermal model → analytic calculation of R(P) by solving the thermodynamic equilibrium equations;
  2) fit of LC acquired at different temperatures with R(P) → good agreement with data;
  3) estimation of T_0 consistent in all measurements;
  4) identification of the main conductances that govern the thermalization process: they are different in the two systems due to the different thermal coupling between detectors and thermal bath.

- Considerations about acrylic holder:
  1) no mechanical damages observed after multiple cooling-downs;
  2) after any bias voltage changes during LC acquisition, ~ 8 minutes were required in order to reach thermal stability (compared with few seconds required in copper holder).

- Future development:
  1) modeling of the dynamic response of calorimeters through a dynamic thermal model for the description of the pulses' shape;
  2) identification of the physical parameters that determine the characteristic time constants of thermal pulses.

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