IL NUOVO CIMENTO Vol. 33 C, N. 6 Novembre-Dicembre 2010
DOI 10.1393/ncc/i2011-10794-0

Colloquia: IFAE 2010

An algorithm to linearize the response function of bolometric detectors

M. Vignati

Sapienza Università di Roma - I-00185 Rome, Italy
INFN, Sezione Roma1 - I-00185 Rome, Italy

(ricevuto l'8 Ottobre 2010; pubblicato online l'8 Febbraio 2011)

Summary. — Bolometric detectors are used in particle physics experiments to search for rare processes, like neutrinoless double-beta decay and dark-matter interactions. Operating in low-temperature conditions they are able to detect particles energies from few keV up to several MeV, measuring the temperature rise produced by the energy released. We studied the bolometers used in the CUORE experiment. The response function of these detectors is not linear in the energy range of interest: the measurement of the energy is complicated and the shape of the signal depends on the energy itself. The response function changes when the operating temperature changes. The non-linearity is found to be dominated by the thermistor and the biasing circuit used to operate these detectors. An algorithm to obtain a linear response is proposed, introducing new techniques for the data analysis.

PACS `07.57.Kp` – Bolometers; infrared, submillimeter wave, microwave, and radiowave receivers and detectors.
PACS `84.32.Ff` – Conductors, resistors (including thermistors, varistors, and photoresistors).
PACS `14.60.St` – Non-standard-model neutrinos, right-handed neutrinos, etc.
PACS `95.35.+d` – Dark matter (stellar, interstellar, galactic, and cosmological).

The CUORE experiment searches for neutrinoless double-beta decay in ^{130}Te [1], using bolometers made of TeO_2 crystals whose temperature is measured by neutron transmutation doped (NTD) germanium semiconductor thermistors [2, 3]. A CUORE bolometer is composed of two main parts, a TeO_2 crystal and a NTD-Ge thermistor. The crystal is cube-shaped, weighs 750 g and its heat capacitance C at the working temperature of 10 mK is of order 2 nJ/K [4]. It is held by Teflon supports on copper frames, which are connected to the mixing chamber of a dilution refrigerator. The thermistor is glued to the crystal and the biasing wires are glued to the copper frames. It acts as thermometer, converting temperature, T, into resistance, R, according to the relationship [5]

$$R(T) = R_0 \exp\left[T_0/T\right]^{\gamma}, \tag{1}$$

where R_0, T_0 and γ are parameters that depend on the dimensions and on the material of the thermistor. To read out the signal, the thermistor is biased with constant current, which is provided by a voltage generator, V_B, and a load resistor, R_L, in series with the thermistor. The resistance of the thermistor varies in time with the temperature, $R(t)$, and the voltage across it, $V(t)$, is the bolometer signal. The dynamic behavior of the signal makes the wires capacitance, c_p, non-negligible.

In the energy range of interest the response function is found to be non-linear. The conversion from signal amplitude to energy is complicated and the shape of the signal depends on the energy itself. Moreover the amplitude of the signal depends on the temperature of the detector, which cannot be kept stable by current cryostats at a level that would not perturb the resolution. The observed non-linearities are in principle generated by the thermal capacitances and conductances of the bolometer, which depend on the temperature (the crystal capacitance, for example, depends on the temperature as $\sim T^3$, following the Debye law). The model we developed (see details in [6]), demonstrates that the thermistor and its biasing circuit can generate the non-linearities, without taking into account the thermal part of the system.

The algorithm we propose consists in a deconvolution of the thermal signal from the measured voltage one. First the variation of the thermistor resistance is extracted from the voltage variation $\Delta V(t)$ solving the biasing circuit:

$$\Delta R(t) = -\frac{\Delta V(t)[R(T) + R_L] + R_L\, R(T)\, c_p \Delta V'(t)}{\Delta V(t) + R_L c_p \Delta V'(t) + V_B\, R_L/[R(T) + R_L]} \,. \tag{2}$$

Then approximating eq. (1) for small temperature variations, the quantity $\Delta S(t)$, proportional to the temperature variation $\Delta T(t)$, is computed:

$$\Delta S(t) = \sigma\, \Delta T(t) = -\log\left[1 + \frac{\Delta R(t)}{R(T)}\right], \tag{3}$$

where σ is the sensitivity of the thermistor, $\gamma \log[R(T)/T]$,divided by the operating temperature, T. The approximation of the thermistor response is needed since its parameters (R_0, T_0, γ and also T) cannot be measured with satisfactory precision in working conditions. The unknown quantities have been hidden in a common scale factor, σ, that is not relevant if we are only interested in removing the non-linearities.The advantage of this algorithm is that it depends on parameters that can be measured with sufficient precision, the static bolometer resistance $R(T)$, the load resistance R_L, the parasitic capacitance c_p and the bias voltage V_B.The transformed response function, $\Delta S(t)$, is almost independent of the operating temperature, its calibration function is very close to a line and the pulse shape does not depend on the energy.

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