Evidence for signal enhancement due to ballistic phonon conversion in NbSi thin films bolometers.

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This work is related to the EDELWEISS collaboration.

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Abstract:

We demonstrate the sensitivity of NbSi thin film thermometers to ballistic phonons. This effect leads to signal amplitudes up to 7 times larger than the theoretically predicted thermal equilibrium signal amplitudes. A simple model of the device in good agreement with quantitative analysis of data is presented.

Introduction:

Neutrino experiments and search for WIMPS have been motivating the development of cryogenic detectors since 1986 [1]. The main challenges to face are: (i) drastically reduce and identify the radioactive backgrounds; (ii) achieve a detector threshold and resolution of 1 keV for 0.1 to 1 kg absorbers. In order to improve detection threshold and to discriminate the background from signal events, the Stanford group[2] proposed to measure accurately the non-equilibrium phonon component of bolometer signals. M. Frank et al. [3] using superconducting thin films thermometers, achieved a remarkable sensitivity via the long-lived ballistic phonon-induced transient energy transfert to the electron bath. We used niobium silicon (NbSi) thin films thermometers [4], directly deposited on the surface of the absorber Al_2O_3. NbSi films are Anderson insulator type materials, similar to NTD Ge[5,6]. In the following, we show that these thermometers are sensitive to non-equilibrium phonons and produce signal amplitude enhancement, relative to a bolometer working at thermal equilibrium.

Experimental Setup:

The detector is made of a 24 g cylindrical sapphire crystal with optically polished faces. A 70 nm thick, 150 mm^2 NbSi film was evaporated on the top face[7]. Contacts are pure Nb or Al on which Al wires are ultrasonically bounded. Three gold pads of 0.2 mm^2 surface were evaporated on the sapphire absorber, with gold wires ultrasonically bounded to set the thermal impedance to the cold bath. This heat leak is dominated by the Kapitza resistance between sapphire and gold pads and was measured to be 1.5 $10^{-4}\, T^3$ (W K^{-1}), where T is in Kelvin. At low bias power, the thermometer resistance follows a Coulomb gap variable range hopping law: R= $R_0 \exp(T_0/T)^{1/2}$, where R is the resistance of the thermometer, R_0= 110 Ω, T_0=1.9 K. In the following analysis, this law is inverted to obtain the temperature of the sensor electron bath from the measured resistance. Under bias, the resistive behaviour is well described by the electron-phonon decoupling model[6] $P=g\ [T_e^6-T_{ph}^6] \equiv G_{eph}[T_e-T_{ph}] \approx k\ T_e^5[T_e-T_{ph}]$. where T_e is the thermometer electron temperature and T_{ph} the thermometer phonon temperature. We assume that the heat capacity of the thermometer is dominated by the sensor electrons. Thus the thermometer heat capacity C_t is given by $C_t=\gamma T_e$. From measurements on previous devices, we estimate γ to be less than 1.6 10^{-5} (J.cm^{-3} K^{-2}) (25 % that of gold). The heat capacity of the sapphire absorber's is assumed to be given by the Debye's law: βT^3 J.K^{-1}, β=2.06 10^{-6}. Thus the device's heat capacity should be dominated by the absorber for temperatures above 10 mK.

We used a ^{241}Am source (60 keV γ and 5.5 MeV α) to measure the bolometer sensitivity. Within the experimental errors, the detector is linear in energy up to 5.5 MeV, and we checked that the reported phenomena are independent of the energy of the events.

Athermal pulse enhancement

Fig. 1) shows an average of 10 typical events. The pulses display a composite structure: a short risetime (τ_r) of 35 μs is followed by a short decay time (τ_f) of 230 μs, ended by a long decay time (τ_l) of 13 ms. This long decay time agrees (table 1) with the calculated thermal relaxation of the sapphire crystal through the thermal leak (14 ins). Assuming that the slow component is the thermal equilibrium bolometer signal, we extrapolate a thermal signal amplitude A_{th} in good agreement with the signal amplitude calculated from the thermometer sensitivity and the heat capacity of the absorber. The signal amplitude is seven times larger than the expected thermal amplitude. This shows that there is a transient overheating of the thermometer leading to an enhancement of the bolometer signal amplitude.

A simple model (Fig 2)

Following the Munich group [8], we assume that a constant fraction ε of the event's energy E directly enters the thermometer electron bath, leading to the short risetime observed at high temperature. The energy relaxes to the sapphire absorber via the electron phonon coupling in the thermometer and the Kapitza resistance between thermometer and sapphire: this leads to the fast decay time. The long decay time results from the thermal link through the gold pack' thermal impedance to the refrigerator.

Quantitative analysis.

Table 1 summarises data and results from the computations of the preceding model, at five temperatures. The thermometer was biased so its temperature was less than 10% above the cold bath temperature, Thus we neglected the electrothermal feedback effect in our analysis. The mains results are:

Above 90 mK, τ_l does not vary with the temperature. This agrees with the fact that both the heat capacity of the absorber and the heat leak vary as T^3. Below 90 mK, τ_l becomes significantly larger than expected and the factor R (table 1) decreases. This behavior can be explained by an excess heat capacity, relative to Debye's law, in our sapphire crystals at low temperatures.

On the other hand, τ_f displays a strong temperature dependence. Our G_{eph} is much smaller (by a factor 100) than the calculated Kapitza conductance between the thermometer and the sapphire absorber. Thus $\tau_f = C_t/G_{eph} = \gamma/k\ T^{-4}$ as we observe in fig(3). However the heat capacity deduced from previous devices leads to τ_f values four time smaller than the measured values.

Consider A_{ath}, the amplitude of the fast component of the signal, and K the sensitivity of the thermometer as $K=dV_t/dT$ (V. K-l), where V_t is the voltage at the thermometer leads. In this model $A_{ath}= K\varepsilon E/C_t$, E total energy of event and $A_{th}=KE/C_d$, C_d device heat capacity dominated by the absorber. Then $A_{ath}/A_{th} = \varepsilon\ C_d/C_t=\varepsilon\gamma/\beta\ T^2$. As shown in Fig(4), the data fit the temperature dependence. This provides a value for & of 10% with γ values extracted from the data on τ_f. Since values of τ_f do not fit measurements on previous devices, the value of E should be taken as preliminary. Note that the temperature dependence of the enhancement is reversed relative to the Munich group data. The main difference comes from the device setup. Their detector thermal leak is bonded on the thermometer instead of on the absorber. In our setup, transient effects always induce an increase of signal amplitude.

An accurate quantitative modelling of this bolometer requires more data and is clearly premature.

Conclusion

We have shown that NbSi thin films thermometers are sensitive to ballistic phonons, thus providing a large enhancement of the signal amplitude. Quantitative analysis gives support to a simple model derived from Ref. [8], with an essential difference in the thermal leak of the bolometer. Unfortunately, due to our design and some inhomogeneity in the thermometer, we could not achieve optimal resolution. We hope to extend in the future our quantitative understanding at the lower temperatures and to demonstrate an improvement of the performance of bolometers.

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Figure captions:

Fig 1: Typical pulse shape, showing two decay time constants. Pulses of fig a) were taken using an amplifier's bandwidth of 12 Hz to 50 kHz, so as to study short rise and decay times, with a gain of 3104. Pulses of fig b), in semilog scale, were taken using a lockin amplifier with an effective bandwidth of DC to 2 kHz, and a gain of 5104 in order to measure accurately the slow decay time.

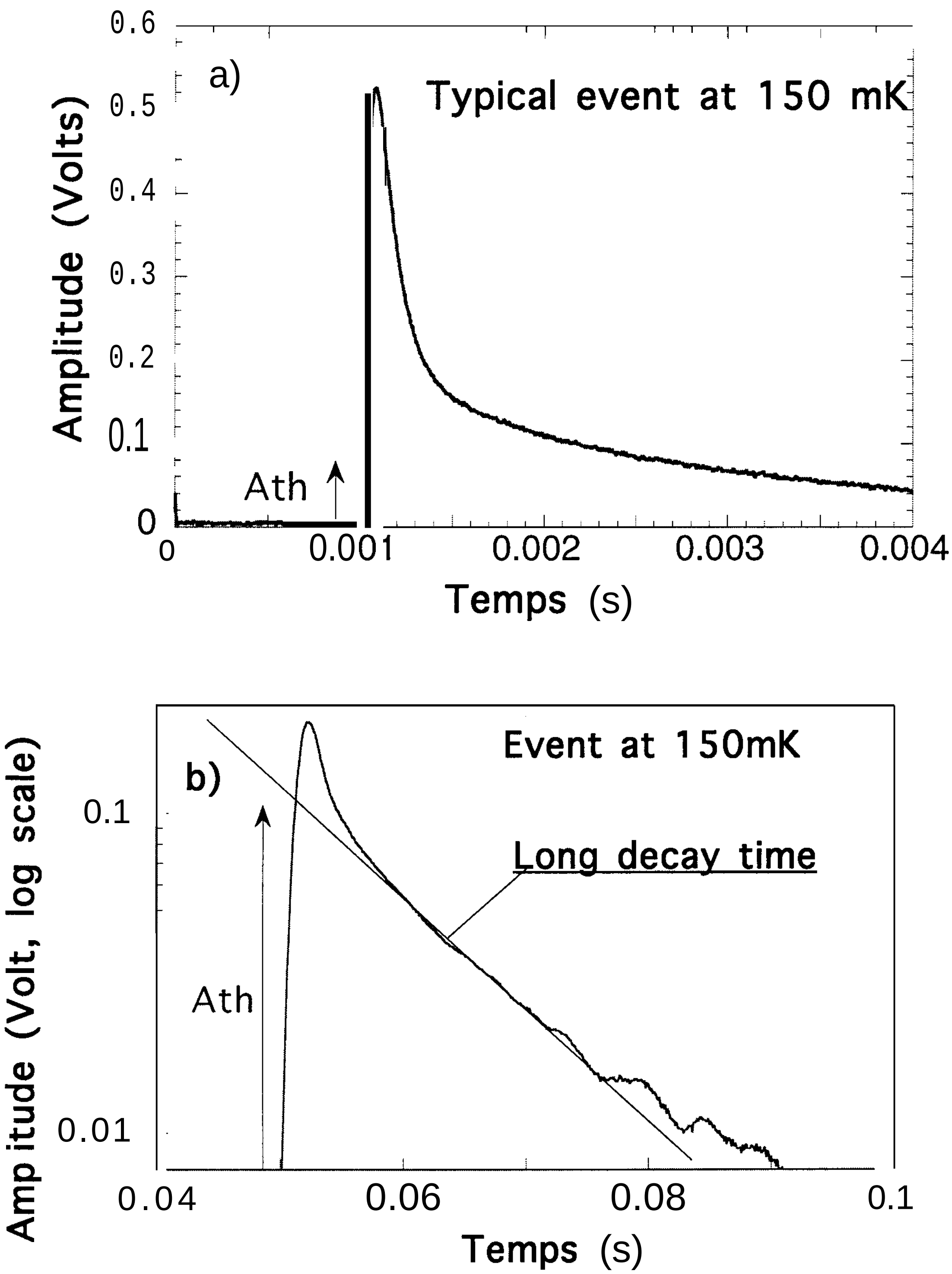
Fig. 2: Model of the thermal behavior of the device.

Fig. 3: Fast decay time as a function of temperature. The line is the predicted T^{-4} dependence.

Fig. 4: Athermal signal enhancement $(V_\alpha - A_{th})/A_{th}$ as a function of T^2.

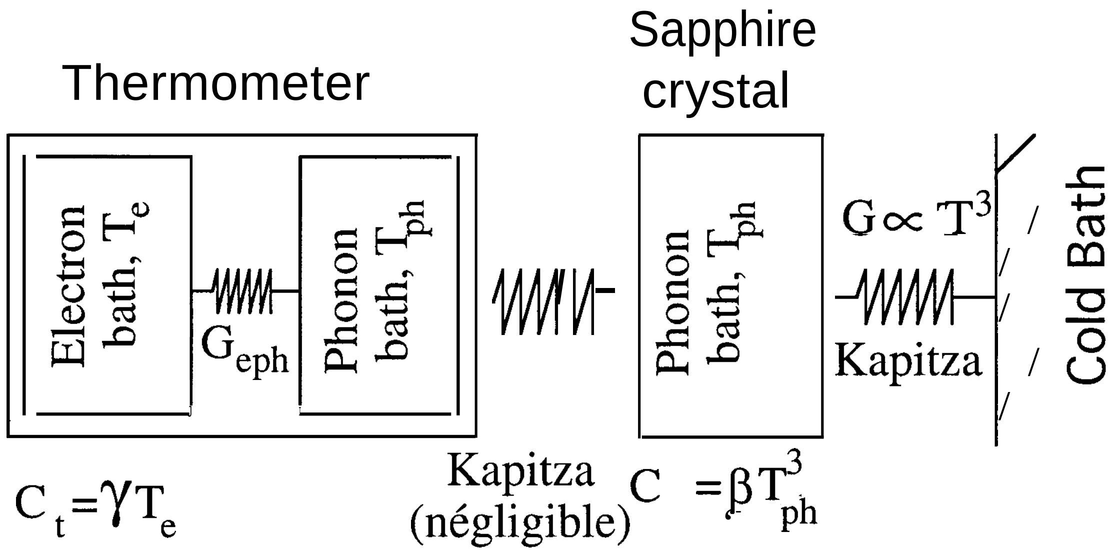
Table 1 shows at the five working temperatures the main results extracted from data and model. These are: measured risetime τ_r, fast decaytime τ_f, and long decay time τ_l. 5.5 MeV α line amplitude, V_α, provide an absolute calibration of the bolometer sensitivity using large bandwidth electronics. A_{th} is the measured α thermal amplitude as extracted from figure lb. R is the ratio between the measured and the expected value of the thermal amplitude as computed from sapphire heat capacity and thermometer calibration, Enhancement is equal to $(V_\alpha - A_{th})/A_{th}$.

T	τ_r	τ_f	τ_l	V_α 5.5MeV	A_{th}	R	Enhance -merit.
(mK)	(ins)	(ins)	(ins)	(μV)	(μV)		
44	1	18	59	32	11	0.12	2.0
60	0.3	8.8	26	35	14.4	0.28	1.4
90	0.1	2.	13	33.5	8.2	0.60	3.1
120	0.06	0.5	12	27.6	4.	0.83	5.9
150	0.035	0.23	13	18.5	2.4	0.86	6.7



a)
Typical event at 150 mK
Amplitude (Volts)
Ath
Temps (s)
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.001
0.002
0.003
0.004
b)
Event at 150mK
Long decay time
Amplitude (Volt, log scale)
Ath
0.1
0.01
0.04
0.06
0.08
0.1
Temps (s)

Figure 1)



Thermometer
Sapphire
crystal
Electron
bath, T_e
G_eph
Phonon
bath, T_ph
Phonon
bath, T_ph
G ∝ T^3
Kapitza
Cold Bath
Kapitza
(négligible)
C_t = γT_e
C = βT_ph^3

FIGURE 2)

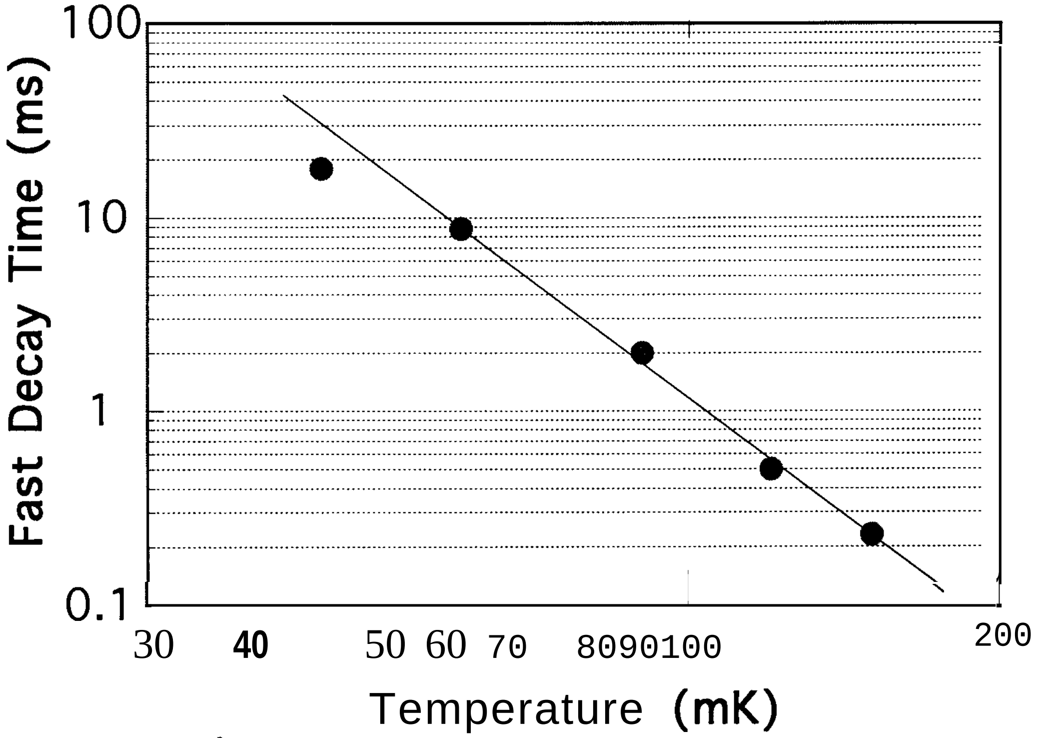


Figure 3)

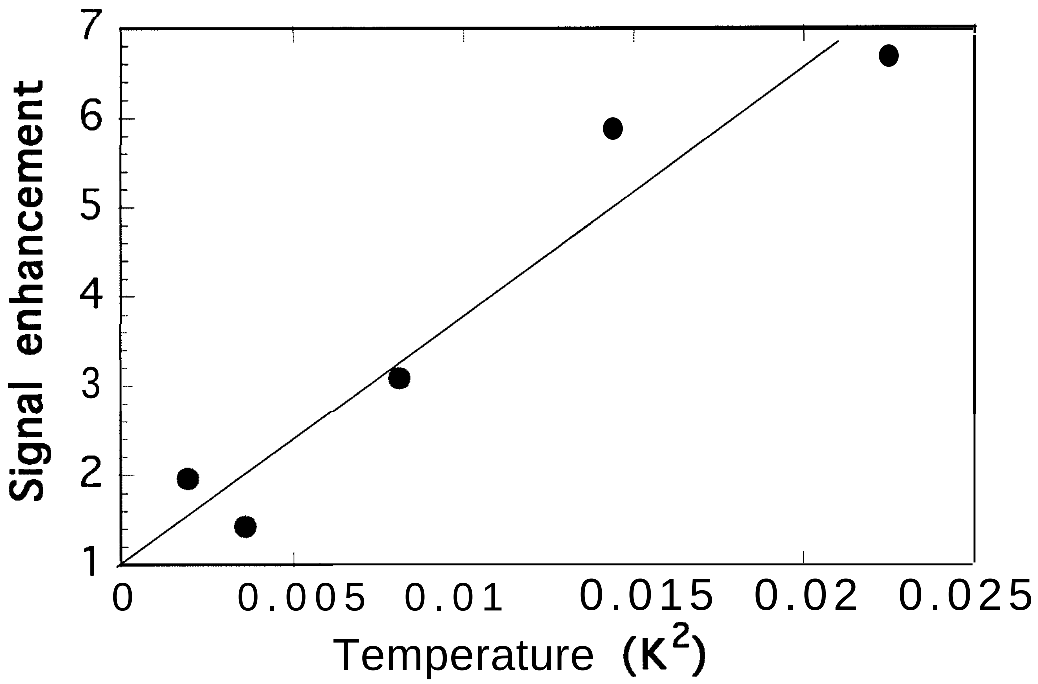


Figure 4)