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First results of the RAP experiment (acoustic detection of particles) in the low temperature regime

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Abstract.
The results on cosmic rays detected by the gravitational wave antenna NAUTILUS have motivated an experiment (RAP) based on a suspended cylindrical bar, which is made of the same aluminum alloy as NAUTILUS and is exposed to a high energy electron beam. Mechanical vibrations originate from the local thermal expansion caused by warming up due to the energy lost by particles crossing the material. The aim of the experiment is to measure the amplitude of the fundamental longitudinal vibration at different temperatures. We report on the results obtained down to a temperature of about 4 K for an Al 5056 bar, which agree at the level of 10% with the predictions of the model describing the underlying physical process. Very preliminary results for a Niobium bar at temperatures below and above the transition temperature are also reported.

1. EXPERIMENT MOTIVATIONS AND SETUP

The thermo-acoustic model [1], describing the mechanical vibration induced by the interaction of ionizing particles, has been extensively tested (at room temperature) [2, 3], and has been used [4, 5] to evaluate the background due to cosmic rays impinging on resonant cylindrical gravitational wave antennas. According to the thermo-acoustic model the amplitude of the first longitudinal mode of oscillation, B_0, is proportional to the ratio of the thermal expansion coefficient to the heat capacity. This ratio is part of the definition of the material Gruneisen parameter γ, nearly constant over a wide range of temperatures:

$$B_0 \propto \gamma \cdot W$$

$W = N\,\overline{\Delta E}$ being the total energy deposited by N ionizing particles, each losing an average energy $\overline{\Delta E}$ in the interaction with the bar.

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Cosmic rays data, observed for the first time by NAUTILUS experiment, were in good agreement with the thermo-acoustic model expectation above the thermodynamic temperature T=1.5 K [6], while in a run at T=0.14 K [7] – below the transition temperature of the NAUTILUS aluminum bar – large signals were detected at a much higher rate than expected. This result suggests that a more efficient mechanism for particle energy loss conversion into mechanical energy takes place when the bar is in the superconducting state.

The aim of RAP (Rivelazione Acustica di Particelle) experiment is to measure the amplitude of the longitudinal fundamental mode of an oscillating cylindrical test mass, either in normal or in superconducting regime, after the impact of ionizing particles.

The experiment setup consists of a suspended cylindrical bar (aluminum alloy or niobium) exposed to the high intensity electron beam provided by the DAΦNE Beam Test Facility [8]. The suspended bar is hosted in a cryostat. The oscillation amplitude measurements are performed by a low noise readout system. The cryogenic facility is ready for the insertion of a dilution refrigerator that will allow the final measurements on aluminum in superconducting state. Details on the experiment setup, readout electronics, data acquisition system, suspension system, and cryogenic facility can be found in previous publications [9, 10].

The RAP experiment started in 2003 with measurements on an Al5056 bar (the same aluminum alloy used for NAUTILUS) at room temperature in order to fully test the experiment setup. In 2004 measurements were performed for the first time at 4 K [11], showing a good agreement with the predictions of the thermo-acoustic model. In 2005 measurements on aluminum in superconducting state were planned, but the delayed delivery of the dilution refrigerator forced us to reschedule the activities. However, a niobium bar, whose transition temperature is $\sim$ 9 K, was used in order to study the thermo-acoustic model for a superconducting material (see fig. 1). Final analysis of aluminum data at 4 K and preliminary results for niobium in superconducting state are presented in the following.

Figure 1. Recent installation of the RAP detector in the DAΦNE Beam Test Facility hall. The mechanical structure, the upper part of the cryostat, as well as the suspension system and the bar are visible on the left side of the picture.

2. PROGRESSES AND EXPERIMENTAL RESULTS

During 2004 several beam pulses made of well defined average number of electrons and energy were applied to the aluminum bar down to 4 K and recently (May 2005) to the niobium bar at room temperature, at approximately the liquid nitrogen temperature, and from 12 K down to 4 K. The effects of the beam were extensively simulated using the GEANT 3.21 [15] package in order to evaluate the average energy lost by electrons inside aluminum and niobium, taking also into account the cryostat materials and the beam divergence effects. Data available on literature have been used in order to evaluate the Gruneisen parameter for aluminum [12] and niobium both in normal and superconducting state.

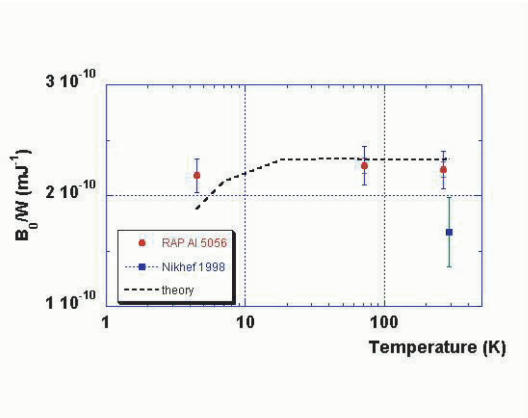

Figure 2. Maximun amplitude of the 1st longitudinal mode of oscillation of the Al5056 bar normalized to the deposited energy vs. temperature. The plot shows that the experimental data are in agreement (within 10%) with the thermo-acoustic model predictions.

Data collected in 2004 down to 4K with the aluminum bar were extensively analyzed [13]. The 100 kHz RAP data acquisition system allows an effective bandwidth of 50kHz, including up to the 4th higher harmonics, while a high dynamic is ensured by a 16 bit ADC, needed in order to cover the beam characteristics with almost two orders of magnitude without changing the electronics setup. Collected data are written on local disk and an on-line monitor performs a first analysis of the acquired samples, including first mode amplitude and decay time evaluations. Each run was followed by a calibration, performed applying a well known pulse to the readout made up by a piezoelectric ceramic followed by a Stanford SR560 amplifier [14]. Moreover, we checked the calibration procedure inserting a commercial calibrated accelerometer with 5% accuracy at the center of one of the bar end surfaces. At room temperature the displacement measured by the piezoelectric ceramic was 2.4% smaller than the one measured by the accelerometer and at T $\sim 77K$ the displacement was $\sim$ 6% smaller. Consequently we assumed a 6% systematic error in measuring the displacement amplitudes.

The average number of electrons was monitored by a calibrated commercial Beam Current Monitor. The device accuracy is $\sim$ 3% and the sensitivity, dominated by the associated digitizer, is $\sim 1.4 \times 10^7$ electrons, corresponding to a standard deviation $\sigma \sim 4 \times 10^6$ electrons. The beam, with energy of 510 MeV and energy spread less than 1%, was monitored by a fluorescence flag placed at the entrance of the cryostat. Beam data were collected by the BTF data acquisition system shot-by-shot and a beam trigger was sent to the RAP data acquisition system for the offline synchronization. At the end of each shift data were copied on the LNF LINUX cluster to perform the offline analysis based on the ROOT package.

In order to optimally identify the mode excited by the beam arrival, Fast Fourier Transform is made on a record of 2.6 seconds before and after the beam signal. The obtained frequencies are then used for the analysis performed up the 6^{th} order mode. A window of 10 Hz around any excited frequency is then chosen, while the amplitude of data out of such window is substituted by zero value. An inverse Fourier Transform procedure is then applied in order to obtain the

$T[K]$	$\alpha[10^{-8}K^{-1}]$	$c_v[Jmol^{-1}K^{-1}]$	state
12.0	6.3 [16]	0.32 [17]	n
8.0	1.7[16, 18]	0.21 [19]	s

Table 1. *Nb. Thermophysical data*

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optimal estimation of the amplitude at the resonances frequencies. A systematic error of 7%, obtained from the quadrature of the beam monitor (3%) and calibration (6%) accuracies, affects the measurements: in fig. 2 the measured amplitude of the first harmonic is shown with respect to our expectation [13].

Preliminary analysis on data collected with the niobium bar (fig. 3) in May 2005 apparently shows that the amplitude of the signal is depressed well below the transition temperature: this behavior is not foreseen by the standard thermo-acoustic model, predicting that superconductivity is locally broken by the increase of temperature due to the energy lost by particles. In this case, normal state thermal expansion coefficient and specific heat should be used.

Indeed, if the material Grüneisen parameter for cubic solids is defined as $\gamma = 3\alpha K_T V_m/c_v$ (where α is the linear thermal expansion coefficient, K_T is the bulk module, V_m is the molar volume and c_v is the specific heat), by indicating with the superscripts n and s respectively the normal and superconducting state and assuming that the s-n transition doesn't give appreciable changes of the value of K_T, one has:

$$\gamma^n(T_1)/\gamma^s(T_2) = (\alpha^n/c^n{}_v)|_{T=T_1}/(\alpha^s/c^s{}_v)|_{T=T_2}$$

where T_1 and T_2 are respectively temperatures above and below the transition temperature. Table 1 shows thermophysical data available in literature for Nb. While it is expected that $\gamma^n(12)/\gamma^n(8) \sim 1$, Table 1 shows that $\gamma^n(12)/\gamma^s(8) \sim 2.4$ and this value can be compared with the ratio of the raw data normalized amplitudes, which gives ~ 3.4.

The depression of the signal is fairly in agreement with a model where the Gruneisen parameter takes into account the thermodynamic properties of niobium in superconducting state. On the contrary, an enhancement of the amplitude could be expected [12] for aluminum in superconducting state. Data analysis is very preliminary: effective signal amplitude estimation and checks of consistency with the model are in progress.

3. CONCLUSIONS

The obtained results for the maximum amplitude of the fundamental mode of longitudinal vibration of the Al5056 bar agree with the expectations of the thermo-acoustic model, describing the particle energy loss conversion into mechanical energy in the temperature range 270-4 K. This is the first time that experimental results on thermo-acoustic energy conversion in Al5056 are obtained below 270 K using our technique. Measurements performed on a niobium bar in normal and superconducting state apparently show that the amplitude is sensitive to the conduction state of the bulk material. RAP collaboration is ready to perform the final run below 1 K with the Al5056 bar, after the delivery of the dilution refrigerator, in order to definitely explain the anomalous rate of high energy cosmic rays detected by NAUTILUS in superconducting state.

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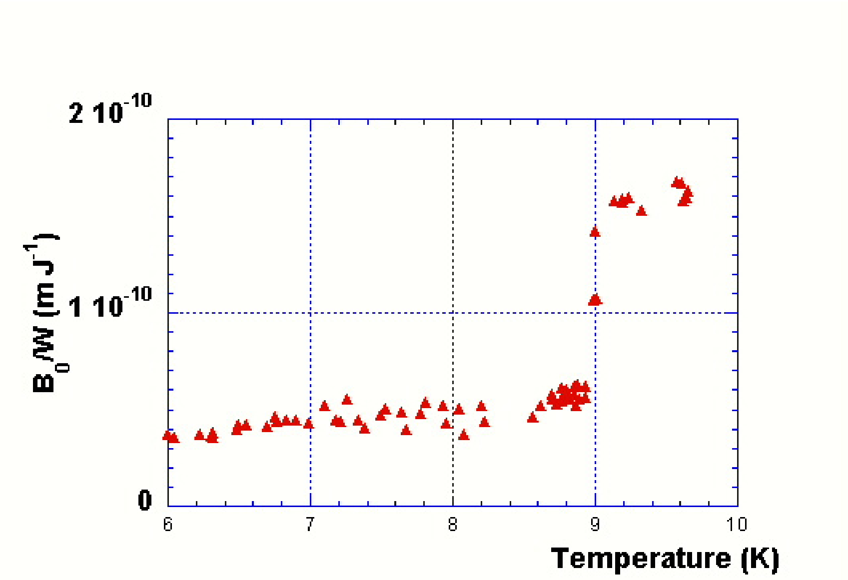

Figure 3. Maximun amplitude of the 1st longitudinal mode of oscillation of the niobium bar normalized to the deposited energy at low temperature

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