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The RAP experiment: Acoustic Detection of Particles

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The RAP experiment is based on the acoustic detection of high energy particles by cylindrical bars.

In fact, the interacting particles warm up the material around their track causing a local thermal expansion that, being prevented by the rest of the material, causes a local impulse of pressure. Consequently the bar starts to vibrate and the amplitude of the oscillation is proportional to the energy released. The RAP experiment has the aim to investigate the mechanical excitation of cylindrical bars caused by impinging particles depending on the conducting status of the material of which the detector is made.

In particular physical phenomena related to the superconductivity state could be involved in such a way to enhance the conversion efficiency of the particle energy into mechanical vibrations. Essentially, two materials have been tested: aluminum alloy (Al5056) and niobium. In this report we report the measurements obtained for a niobium bar from room temperature down to 4K, below the transition temperature, and those obtained for an Al5056 bar above the transition (from 4 to 293 K).

1. INTRODUCTION

Particles impinging on the detector ionize the atoms along their path causing a local heating of the material. The consequent thermal expansion originates an impulse of pressure inside the detector exciting its acoustic vibrational modes. This behaviour is well explained by the so called Thermo-Acoustic (T.A.) model [1], [2], [3], whose validity has been confirmed by several experiments ([4],[5]) at room temperature. According to the T.A. model the energy deposited in the longitudinal fundamental mode of a metallic bar is:

$$E = \frac{1}{2}\frac{l^2}{V}\frac{G^2}{\rho v^2}\gamma^2\left(\frac{dW}{dx}\right)^2 \quad (1)$$

where l is the bar length, dW/dx the energy lost per unit length by the particle in the bar, ρ the density of the bar material, v the sound velocity

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in a thin bar, V the volume, G a geometric factor (depending on the particle track length and orientation inside the bar) and γ is the Grüneisen coefficient (depending on the ratio of the thermal expansion coefficient to the specific heat). Applying the T.A. model to a thin cylinder and in the case that particles impinge normally to the cylinder axis on the center, the maximum amplitude of the first longitudinal mode (the monitored variable) is given by [4]:

$$B_0 = \frac{2\alpha l W}{\pi c_V M} \tag{2}$$

where M is the mass, c_V is the isochoric specific heat, and α is the linear thermal expansion coefficient.

The ultra-cryogenic resonant gravitational wave detector Nautilus (an Al5056 cylinder of 2300 kg) [6] detected high energy cosmic ray events at a rate higher than expected, when it was operating in superconducting state [6]. On the contrary the observed rate of high energy cosmic rays was in agreement with expectations when the bar was operated at temperature higher than 1 K, that is in normal state.

The hypothesis to investigate is that a local transition from superconducting to normal state around the particle tracks could give an important contribution to the entity of mechanical vibration detected and could explain the anomalous signals detected in the Nautilus bar.

In order to investigate the validity of the T.A. model also for a superconducting bulk material, in the RAP experiment small cylindrical bars are exposed to high intensity electron beam provided by the $DA\phi NE$ Beam Test Facility [7], the e^- e^+ LNF collider. The BTF provides single pulses of 10 ns length, containing up to 10^9 electrons per pulse with an energy of 510 MeV (the nominal energy of $DA\phi NE$ collider). The number of electrons is measured with an accuracy of about 3% by an integrating current transformer placed closed the beam line exit. The bars tested are suspended and hosted in a cryostat, where a fast cooling down to 4 K is obtained using gaseous helium as exchange gas. The vibration amplitude measurements of the bar are performed by a commercial piezoelectric ceramic (PZT), that is placed in the position diametrically symmetric respect to the suspension point, at the bar center, where the PZT measures the maximum strain (proportional to the displacement of the bar end faces). The PZT output is first amplified and then sampled by an ADC at 100 kHz. Details on the experimental set-up, calibration procedure, readout electronic and data acquisition system can be found in reference [8].

1.1. EXPERIMENTAL RESULTS

The maximum amplitude, X_{exp}, of the first longitudinal mode of the oscillating cylindrical bar is measured and the experimental values are compared with the ones expected according the T.A. model(X_{therm}), corrected by a factor ϵ:

$$X_{therm} = B_0(1+\epsilon) \tag{3}$$

The corrective parameter ϵ is estimated by montecarlo simulations and allows to overcome some simplifying assumption, taking into account: the $O(R/L)^2$ terms in the estimation of the displacements, the finite transverse beam spot dimensions at the impact point and the trajectories of the secondary particles generated inside the bar.

1.2. Aluminum Measurements

The aluminum test mass that has been used for the RAP experiment is described in the Table 1 and is shown in Fig.1, hanged onto the suspension system.

Data collected down to 4 K with the Al5056 bar have been extensively analyzed [8] and the correlations between the experimental values and the theoretical ones, at various temperature (264, 71 and 4.5 K), have been found. In Fig.2 the amplitude of the first longitudinal mode, normalized to the deposited energy by the impinging particles, is reported in the investigated range of temperature, together with the theoretical predictions and the results obtained by a past experiment [5] performed at room temperature.

The results allow to conclude that a good agreement (within 10%) exists between the expected values from T.A. model and the measured ones. Furthermore the comparison with past experiments at room temperature, based on the same technique, shows that the RAP measurements are

Table 1
The test mass for the *Aluminum* case

M (kg)	$L(m)$	$R(m)$	$f_L(Hz)$
35.17	0.50	0.09	5096 at 300 K

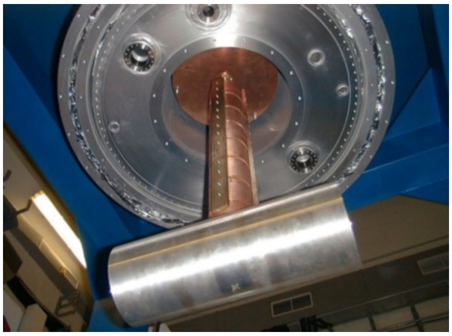

Figure 1. Al5056 cylinder and its suspension system.

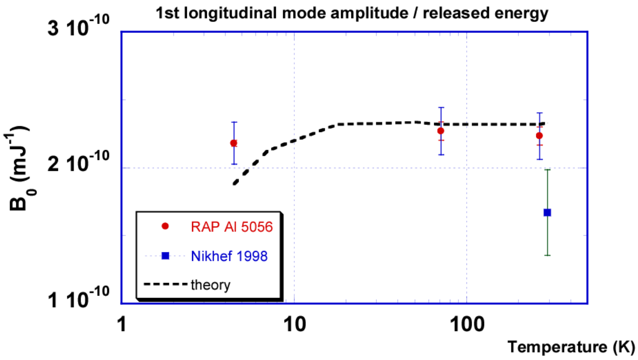

Figure 2. Maximum measured amplitude of the 1st longitudinal mode normalized to the deposited energy vs. Temperature.

more consistent with the theoretical model. It is also interesting to emphasize that the RAP measurements are the first experimental results on thermo-acoustic energy conversion obtained for a bulk of Al5056 below room temperature. Because the tested aluminum becomes superconducting at temperature below 1K, a He3-He4 dilution refrigerator is necessary to reach this temperature. At present time the dilution refrigerator is available and has been already mounted and tested down to the nitrogen temperature. The RAP collaboration is going to perform the measurements on superconductive Al5056, soon after having completed the engineering operating tests, foreseen for the end of 2006.

1.3. Niobium Measurements

The niobium test mass that has been used for the RAP experiment is described in the Table 2 and is shown in Fig.3:

In Fig.4 the experimental values and the theoretical ones are correlated by the expression $X_{exp} = m \cdot X_{therm}$, with a least square fit correlation coefficient 'm', practically equal to 1, above the transition temperature, that means an excellent agreement between experimental values and T.A. model in normal state. Instead in case of material in superconducting state $m \simeq 0.6$, showing a small discrepancy between data and theoretical expectations. In Fig.5 the experimental values (dots) differ from the middle point of the green band (theoretical values with their error bar) of about 50%, while this difference reduces to 20% around 8 K. In this figure the theoretical values have been evaluated using the material properties (α and c_V) for superconducting state. In any case, the measured signal is always proportional to the energy deposited by the beam pulses in the bar, even if the proportional constant is abruptly depressed below the transition temperature[2]. The agreement between the measured values and the predicted ones can be improved when the contribution to the oscillation amplitudes coming from the s-n transition

[2]In case of superconducting aluminum bar the expected behavior is reversed respect to that of niobium: calculations based on available data of the critical magnetic field H vs T and p give $|B_0(SC)| > |B_0(NC)|$.

Table 2
The test mass for the *Niobium* case.

M (kg)	$L(m)$	$R(m)$	$f_L(Hz)$
18.43	0.274	0.05	6700 at 300 K

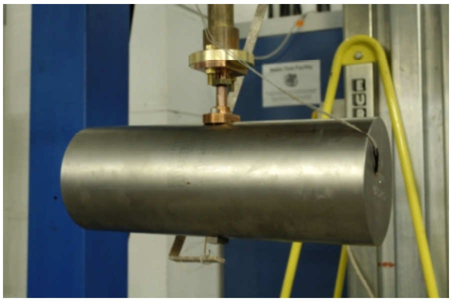

Figure 3. Niobium cylinder.

is taken into account, according several theoretical models (i.e, the Allega-Cabibbo[2] and the Bernard, De Rujula, Laudrup[1]). In this case the overall displacement of the faces is estimated by two contributions:

$$X = X_{tr} + X_{therm} \tag{4}$$

where X_{tr} comes from the s-n transition in the region around the particle track and X_{therm} is the term related to the heat transfer and thermal expansion in the normal conducting state. In Fig.6 the experimental values are compared with the two models in the range 4-9 K. As shown in figure, the theoretical model that takes into account also the transition is better in agreement with experimental data, with a discordance less than 30% over all the investigated range of temperature.

1.4. Conclusion

The obtained results for the maximum amplitude of the oscillation fundamental longitudinal mode of an Al5056 bar, excited by a high energy electron beam, very well agree (within 10%) with the expectations (thermo-acoustic model) from 270 down to 4 K. The RAP collaboration is going to perform the measurements on superconductive Al5056, for the beginning of 2007 , soon after having put into operation the dilution refrigerator already installed . Measurements on a niobium bar have been performed either in normal and in superconducting state (down to 4K) and according to these we can assert that above the transition temperature the theoretical predictions agree with the experimental values. In the superconducting state the model that is better in agreement with the experimental results takes into account the local material transition from superconducting to normal state. In this case the discrepancy is less of 30% (near the transi-

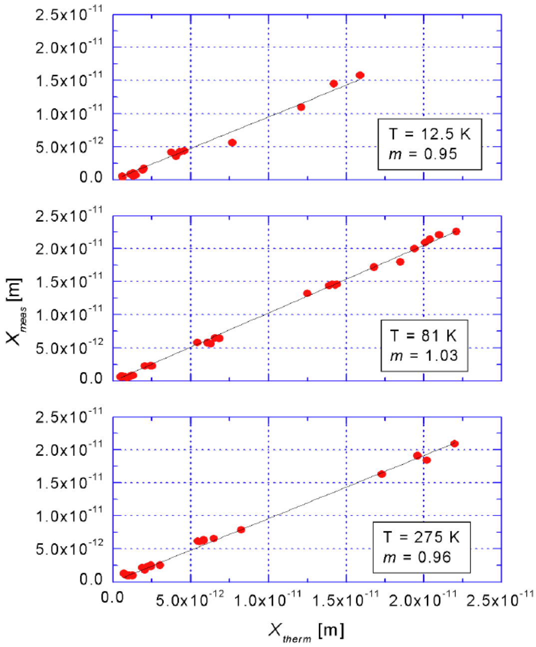

Figure 4. T=12.5 (top), 81 K (center), 275 K (bottom). Measured maximum amplitude of the 1st longitudinal mode for different beam pulses vs. expected values

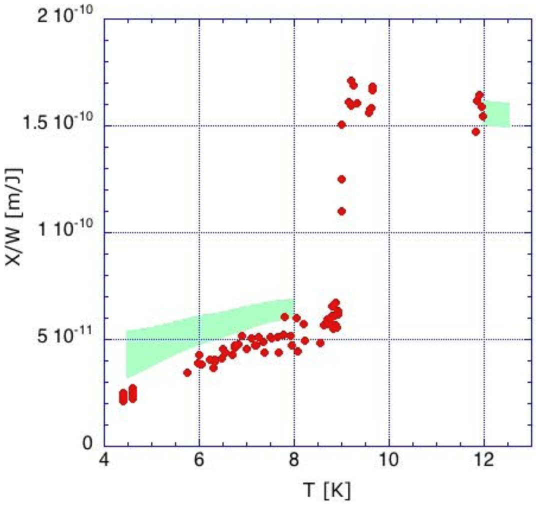

Figure 5. 1st longitudinal maximum amplitude normalized to the total energy lost per beam pulse (W) vs. Temperature (T). Dots: measured values. Light green bands: expected values from thermophysical data for pure Nb in the n state ($9 < T < 12K$) and in s state ($T < 9K$) with their error bars.

tion temperature) over the investigated range of temperature (down to 4 K).

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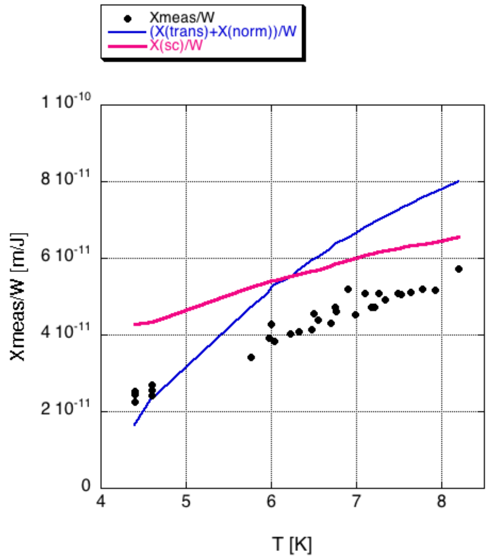

Figure 6. Line: maximum amplitude normalized to the energy lost by the beam evaluated respectively with the supeconducting parameters (thick-line) and with the normal ones (taking into account also the transition) (thin-line) vs Temperature. Dots: observed values