Institute of Physics Publishing Journal of Physics: Conference Series **39** (2006) 46–48
doi:10.1088/1742-6596/39/1/011 TAUP 2005: Proc. Ninth Int. Conf. on Topics in Astroparticle and Underground Physics

Acoustic detection of particles, the RAP experiment: present status and results

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Abstract. Cosmic ray events with rate and energy much higher than expected were detected by the ultracryogenic gravitational antenna Nautilus located at the Laboratori Nazionali di Frascati, when it was operating in superconducting state. Mechanisms related to the superconductivity state of the material could be involved in such a way to enhance the conversion efficiency of the particle energy into vibrational energy of the detector. The RAP experiment has the aim to study the mechanical response of a small metallic resonant bar to short pulses of high energy electron beam, investigating the response of the bar both in normal and in superconducting state. The results obtained for an Al5056 bar down to a temperature of 4 K are reported and the preliminary results for a niobium bar at temperature below and above the superconducting-normal transition are also discussed.

1. Introduction

It has been shown that the resonant gravitational wave detectors are sensitive to the passage of the cosmic rays [1]. In fact, the particle impinging on the detector ionizes the atoms along its 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 [2], [3], [4] and several experiments ([5],[6]) have confirmed its validity at room temperature. According the T.A. model the energy deposited in the longitudinal fundamental mode of a metallic bar is:

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

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 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).

Aim of the RAP experiment is to test the validity of the T.A. model also in the case of a superconducting bulk. In fact, the rate of cosmic ray events observed by the Nautilus detector are in good agreement with the T.A. model expectations when the Nautilus operating temperature (T=1.5 K) is above the transition one ($\simeq 1K$) [7], while in a run at T=0.14 K [8] large signals were detected at a much higher rate than expected, suggesting that a more efficient mechanism of particle energy loss conversion into mechanical energy could take place when the bar is in superconducting state. In this context, the main material under examination is the Al5056 alloy (superconducting state below 1 K), of which the Nautilus detector is made. In order to go below 1 K a dilution refrigerator is necessary, and since it will be mounted not before 2006, a test on a bulk of niobium (the transition temperature for this last one is around 9 K) has been also performed in the meanwhile.

2. Experimental Setup

The experimental setup consists of a suspended cylindrical bar exposed to the high intensity electron beam provided by the $DA\phi NE$ Beam Test Facility [9], the e^- e^+ LNF collider. The overall assembly (suspension+bar) is hosted in a cryostat, where a fast cooling down to 4 K is obtained using gaseous helium as exchange gas. The longitudinal vibration amplitude measurements of the bar are performed by a commercial piezoelectric ceramic (PZT). More details on the readout electronic, data acquisition system, suspension and cryogenic facility can be found in reference [10], [11]. The RAP experiment started in 2003 with measurements on an Al5056 bar at room temperature and during 2004 measurements were performed for the first time at 4K [13]. In 2005 a niobium bar has been used in order to check the T.A. model for a superconducting material. Final analysis of aluminum data and preliminary results for niobium in superconducting state are presented in the following.

3. Experimental Results

In the RAP experiment the maximum amplitude, B_{exp}, of the first longitudinal mode of an oscillating cylindrical bar is measured after the collision with 510 MeV electron beam generated by the DAϕNE Linac. The experimental values are compared with the ones expected according the T.A. model (B_{th}) [5]. Data collected in 2004 down to 4 K with the Al5056 bar have been extensively analyzed [13] and the correlations between B_{exp} and B_{th} at various temperature (264, 71 and 4.5 K) have been found. In figure 1 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 [6] 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 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.

Preliminary analysis on data collected with the niobium bar in April 2005 above and under the transition temperature allows to observe that the least square fit correlation coefficient 'm', that relates the experimental values with the theoretical ones according the expression $B_{exp} = m \cdot B_{th}$, is practically equal to 1 above the transition temperature (that means an excellent agreement between experimental values and T.A model in normal state), but $m \simeq 0.6$ for the superconducting state. In figure 2 the maximum amplitude of the 1st longitudinal mode of the niobium bar normalized to the deposited energy is shown. Below 9 K, the measured signal (blue squares) is depressed with respect to the theoretical values (the green dots). The depression of the signal is fairly in agreement with the model if the superconducting thermodynamic properties

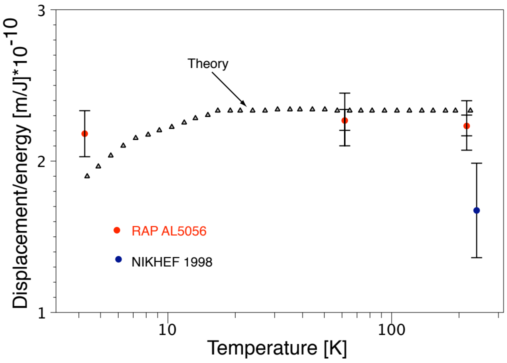

Figure 1. Al5056. Maximum amplitude of the 1st longitudinal mode normalized to the deposited energy vs. temperature.

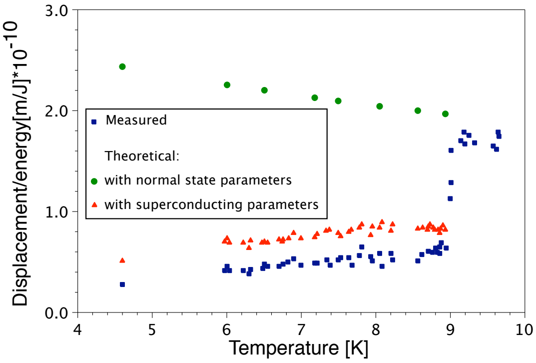

Figure 2. Niobium. Maximum amplitude of the 1st longitudinal mode normalized to the deposited energy vs. temperature.

of the niobium (red triangles) are used to estimate B_{th}. However, this data analysis is only preliminary and work for a more accurate data analysis and estimation of the errors is ongoing. A theoretical study to check the consistency with the model is also in progress.

4. Conclusions

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. Measurements on a niobium bar have been performed either in normal and in superconducting state (down to 4K). The presented results are preliminary and a more accurate data analysis is in progress. Anyway, a first analysis allows to assert that above the transition temperature the theoretical predictions agree with the experimental values. On the other side, below the transition, the measured values do not agree with the predictions if the thermodynamic properties of normal state are used in the calculation of the expected amplitudes. Nevertheless, the measured values fairly agree with the model if the Grüneisen coefficient is estimated using the superconducting thermodynamic parameters. More accurate studies are planned in order to check the consistency of the results below the transition with the model. The RAP collaboration is going to perform the measurements on superconductive Al5056, soon after the dilution refrigerator installation foreseen for the beginning of 2006.

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