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Vibrational excitation induced by electron beam and cosmic rays in superconductive aluminum bars

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Abstract. We report new measurements of the acoustic excitation of an Al5056 superconductive bar when hit by an electron beam, in a previously unexplored temperature range, down to 0.35 K. These data, analyzed together with previous results obtained for $T > 0.54$ K, show a vibrational response enhanced by a factor ~ 4.9 with respect to that measured in the normal state. This enhancement explains the anomalous large signals due to cosmic rays previously detected in the NAUTILUS gravitational wave detector.

1. Introduction

Cosmic ray showers can excite sudden mechanical vibrations in a metallic cylinder at its resonance frequencies; in experiments searching for gravitational waves (gw) these disturbances are hardly distinguishable from the searched signal and represent an undesired source of accidental events, thus increasing the background. This effect was suggested many years ago and a first search was carried out with limited sensitivity with room temperature Weber type resonant bar detectors and ended with a null result [2]. Later on, the cryogenic resonant gw detector NAUTILUS [3] was equipped with a streamer tube extensive air shower detector [4] and the interaction of cosmic ray with the antenna has been studied in detail. This apparatus allowed the first detection of cosmic ray signals in a gw antenna, that took place in 1998, when NAUTILUS was operating at a temperature $T = 0.14$ K [5], i.e. below the superconducting (s) transition critical temperature $T_c \simeq 0.9$ K. During this run many events of very large amplitude were detected[6]. This unexpected result prompted the beginning of a dedicated experiment (RAP) [7], that was planned at the INFN Frascati National Laboratory to study the vibration amplitude of a small Al5056 bar caused by the hits of a 510 MeV electron beam. A detailed study of this effect is indeed useful to study the performance of gw bar detectors for exotic particles [8] and to understand the noise due to cosmic rays in interferometric gw detectors [9]. In this paper we report the final results of the RAP experiments presenting measurements down to 0.35 K, and show how these new data help in shedding light on the 1998 anomalous NAUTILUS high energy events. More detailed informations are in Ref. [10, 11].

2. The thermo-acoustic model

The interaction of energetic charged particles with a normal mode of an extended elastic cylinder has been extensively studied over the years, both on the theoretical and on the experimental

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aspect.

The first experiments aiming to detect mechanical oscillations in metallic targets due to impinging elementary particles were carried out by Beron and Hofstander as early as in 1969 [12]. A few years later, Strini et al. [13] carried out an experiment with a small metallic cylinder and measured the cylinder oscillations. The authors compared the data against the thermo acoustic model in which the longitudinal vibrations are originated from the local thermal expansion caused by the warming up due to the energy lost by the particles crossing the material. In particular, the vibration amplitude is directly proportional to the ratio of two thermophysical parameters of the material, namely the thermal expansion coefficient and the specific heat at constant volume.

The "maximum amplitude of oscillation for the fundamental longitudinal elastic mode", in the following referred to as "Amplitude", for a material in a normal (n) state of conducting is given, according to this thermo acoustic model by:

$$B_n^{\mathrm{th}} = \frac{2\alpha L W}{\pi c_V M} \tag{1}$$

where the "th" stand for the theoretically expected value. This result applies to a thin cylinder (with radius R and length L, $R \ll L$ and mass M), for a beam hitting on center of the cylinder lateral surface. Here W is the total energy released by the beam to the bar, α is the linear thermal expansion coefficient and c_V is the isochoric specific heat. This relation is valid for particles the material normal-conducting (n) state and some authors (see Ref. [14, 15]) have extended the model to a super-conducting (s) resonator, according to a scenario in which the vibration amplitude is due to two pressure sources, one due to $s-n$ transitions in small regions centered around the interacting particle tracks and the other due to thermal effects in these regions now in the n state. Therefore the value of Amplitude due to a particle creating hot spots in a material in s state is given by:

$$B_s^{\mathrm{th}} = B_n^{\mathrm{th}}(1 + \mathcal{R}) \tag{2}$$

where $\mathcal{R}$ is due to this additional effect due to the transition from s to n state.

Eqn. (1) and (2) show that the Amplitude B^{th} linearly depends on W, the energy released by particle, both in the n and in the s states. Therefore it appears natural to consider, as we do in the following, the ratio B^{th}/W as a measure of the relevant material properties.

3. The RAP measurements at low temperatures

The RAP experiment has been fully described in Ref. [7]. Here we briefly recall that the test mass is a cylindrical bar ($R = 0.091$ m, $L = 0.5$ m, $M = 34.1$ kg) made of Al5056, the same aluminum alloy (nominal composition 5.2% Mg and 0.1% of both Cr and Mn) used for NAUTILUS. For this alloy the transition critical temperature is $T_c \simeq 0.9$ K. The frequency of the fundamental longitudinal mode of oscillation of the bar is $f_0 = 5414.31$ Hz below $T = 4$ K. The RAP cryogenic setup consists of a KADEL commercial liquid helium cryostat, suspended on a vertically movable structure, and containing a dilution refrigerator.

Two piezoelectric ceramics (Pz), electrically connected in parallel, are inserted in a slot milled out in the center section of the bar, opposite to the bar suspension point, and are squeezed when the bar shrinks. In this Pz arrangement the strain measured at the bar center is proportional to the displacement of the bar end faces. The Pz output is first amplified, and then sampled at 100 kHz by an ADC embedded in a VME system, hosting the data acquisition system. The RAP experimental set-up was installed about 2.5 m away from the exit electron beam of the Frascati 510 MeV linac. The minimum temperature reached by the bar during the data taking was 343 mK, read by a RuO_2 thermometer placed at the center of one of the bar end faces.

The RAP measurements for $T \leq 1.6$ K of the years 2007 and 2009 are shown in Fig. 1. This plot shows the measured B/W (with sign) as function of the temperature and of the deposited energy W. The sign of B is inferred by the sign of the first value of the ADC over the noise after the beam shot. The sign is positive for an expansion, negative for a contraction.

The most relevant features of this plot are:

- a constant value of B/W for $T \geq T_c \simeq 0.9$ K.
- a change of sign of B/W for $T \leq T_c$ predicted by the model because the effect due to the $s \rightarrow n$ transition can lead to a negative sign due to the competitive terms in Eqn. (2).
- a nonlinear dependence of B on W for $T \leq T_c$, not predicted by the model.

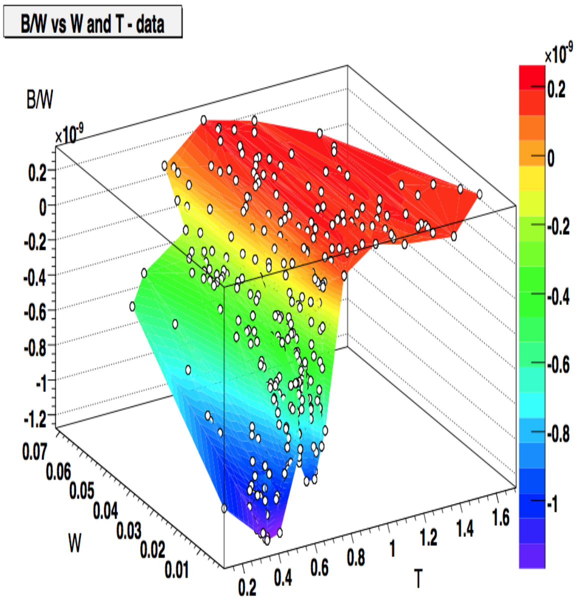

Figure 1. Synoptic view of the data for temperature $T \leq 1.6$ K, the transition temperature is about 0.9 K. The plot shows the measured B/W (with sign) *vs* temperature T and deposited energy W. Units are Kelvin, meters and Joules. The most relevant feature of this plot are: a constant value of B/W for $T \geq T_c$, the change of sign of B/W for $T \leq T_c$ and the dependence on W of B/W for $T \leq T_c$. The experimental data are the open circles. The shadowed regions are interpolations of the data. The point at the lowest temperature $T = 0.14$ K is obtained from the cosmic ray NAUTILUS data, This value has been obtained from the ratio of the NAUTILUS data at $T = 0.14$ K and the NAUTILUS data at $T = 2$ K. The NAUTILUS point correspond to a value of the energy $W \sim 0.5$ μJ.

As our investigation is aimed at understanding the interactions of cosmic rays with a *gw* detector, we need a model to make prediction of B/W at very small value of W: we have used the model described in section 2, adding to it, as suggested by the data, a possible saturation of the $s \rightarrow n$ transition effect, due the high energy density in the volume crossed by the beam.

In order to extrapolate the RAP results to values of W and T outside the measured range, we used the following four parameters fit to the data for $T < T_c$:

$$\frac{B}{W} = a + (b(T) - a) \exp\left(\frac{-W}{p_0 \ \rho \ C_I(T)}\right) \tag{3}$$

$$b(T) = p_1 + p_2 T + p_3 T^2 \tag{4}$$

Here $a \sim 2.25 \times 10^{-10}$ m J^{-1} is the constant value of B/W for $T > T_c$ and $b(T)$ the value of B/W for $T < T_c$ and $W \rightarrow 0$, $b(T) \sim -10^{-9}$ m J^{-1} for $T = 0.5$ K is a function weakly dependent on T and accounts for small variations of physical parameters at low temperatures. C_I is the integrated specific heat between T and the critical temperature. Eqn. (3) derives from the consideration that if an electron crosses a region that has already undergone the $s \rightarrow n$ transition, the response is the one of the n state.

All the RAP measurements are summarized in Fig (2). The point for $T < T_c$ are obtained from the fit for $W \rightarrow 0$. We observe a roughly constant value of B/W for $T > T_c$ and a change of

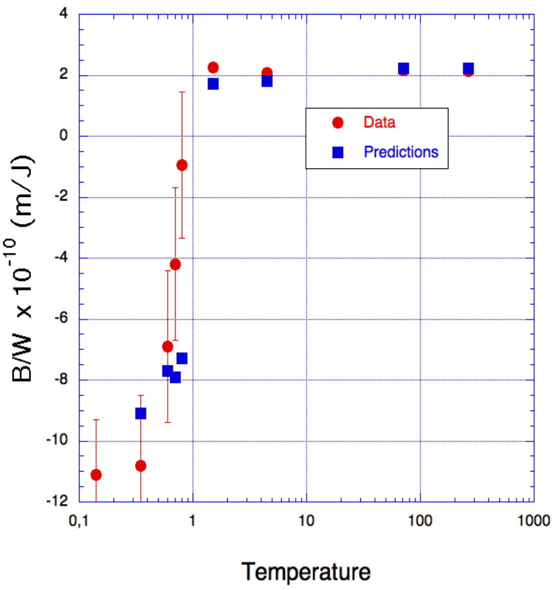

Figure 2. Summary of the RAP measurements of B/W (with sign) (filled circles) compared with the best available predictions (filled squares) as function of the temperature

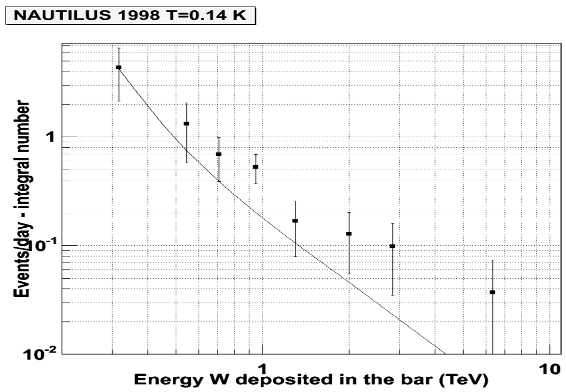

Figure 3. The cosmic rays data of NAUTILUS 1998, at $T = 0.14$ K. The integral distribution of the event rate after the background unfolding, compared with the expected distribution (continuous line). The prediction is computed using the RAP measurements extrapolated to T=0.14K. The good agreement suggests the absence of anomalous components of cosmic rays or anomalous interactions of cosmic rays with a superconductive bar.

sign with an enhancement of the absolute value by a factor ~ 4.9 with respect to that measured in the normal state.

In Ref. [6], very large cosmic rays signals at a rate much greater than expected were reported in NAUTILUS at $T = 0.14$ K . In the light of the analysis reported above, it is now clear that the enhancement measured by RAP should be used to evaluate the predictions. The NAUTILUS 1998 data event rate per day after the unfolding of the background, with the procedure described in [17] is shown in Fig. 3. We find now a good agreement between measurements and predictions; previously hypothesized exotic explanations, based on anomalous component of cosmic rays or anomalous interactions of cosmic rays with a superconductive bar can now be excluded.

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