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RAP: acoustic detection of particles in ultracryogenic resonant antenna

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Abstract

The resonant-mass gravitational wave detector NAUTILUS has recently recorded signals due to cosmic rays crossing. Very large signals have been observed in the superconductive state of the antenna. In order to investigate this anomalous response at low temperatures, the Rivelazione Acustica di Particelle experiment has been approved. Its purpose is the measurement of the mechanical vibrations in a superconducting ($T\sim 100\,\mathrm{mK}$) cylindrical aluminium bar when hit by 10^5 electrons at 510 MeV from the DAΦNE Beam Test Facility, corresponding to the energies released by extensive air showers in the NAUTILUS antenna. The results of this measurement are crucial to understand the interaction of ionizing particles with bulk superconductors and to confirm the results on the thermo-acoustic model of the past experiments.

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1. Scientific motivations

Studies of the signals due to the interactions of cosmic rays impinging on the gravitational wave antenna NAUTILUS, have shown that in a run of the detector at thermodynamic temperature T=1.5 K the results are in agreement with the thermo-acoustic model, while in a run at T=0.14 K large signals are detected at a rate higher than expected [1–3].

In the thermo-acoustic model mechanical vibrations originate from the local thermal expansion caused by warming up due to the energy lost by a particle crossing the material. In this model the relation between the detectable vibrational energy E_n in the nth longitudinal mode and the specific

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energy loss $\mathrm{d}W/\mathrm{d}x$ of a particle impinging a cylindrical bar is

$$E_n \propto \frac{\gamma^2}{\rho L v^2}\left(\frac{\mathrm{d}W}{\mathrm{d}x}\right)^2 F_n$$

where ρ is the density of the bar material, L is the length of the bar, v is the longitudinal speed of sound, γ is the Grüneisen parameter of the material and F_n is a function of the impinging track geometrical parameters [4]. The Grüneisen parameter is defined as $\gamma(T,V) = \beta V/\chi_T C_V$, where $\beta = (\partial \ln V/\partial T)_p$ is the volume expansion coefficient, V is the molar volume, $\chi_T = -(\partial \ln V/\partial p)_T$ is the compressibility at constant temperature and C_V is the specific heat at constant volume.

The thermo-acoustic model has been recently verified at room temperature by an experiment [5] that used a small suspended aluminium cylinder exposed to an electron beam.

The NAUTILUS results suggest that a more efficient mechanism for particle energy loss conversion into mechanical energy takes place when the bar is in the superconducting state. For example, in the superconducting regime the Grüneisen parameter related to the conduction electrons could assume different values from those obtained from temperatures higher than T_c, and extrapolated at 0°. In order to clarify these results the RAP experiment [6] aims to measure the effect of the passage of an electron beam in a mechanical oscillator.

RAP is intended to operate an oscillating test mass either in the normal or in the superconducting regime. The measurement will be crucial to understand which interaction of ionizing particles with bulk superconductors and to confirm the results on the thermo-acoustic model obtained by the previous experiments.

2. Experimental system

2.1. The electron beam

The beam is provided by the Beam Test Facility (BTF) of DAΦNE, the INFN-LNF e^+–e^- collider. It is taken at the end of the DAΦNE Linac and moved in the DAΦNE BTF, where it is possible to deliver electrons or positrons in pulses made by 1 up to 10^{10} particles with energy varying from 25 to 800 MeV with 1% resolution. The repetition rate is 50 Hz and the pulse duration ranges from 1 to 25 ns.

2.2. The detector

The experimental system is composed by the antenna together with the suspension system, the cryogenic system, the vacuum system and the concrete support of the cryostat. Finally, a readout with a data acquisition system is needed.

The antenna (Fig. 1) is a cylindrical aluminium bar, 500 mm in length and 181.7 mm in diameter. It is made of AL5056 (5.2% Mg, 0.1% Mn, 0.1% Cr), the same material of the NAUTILUS antenna, and has the first longitudinal mode resonance frequency of 5.1 kHz.

The suspension system consists of an 800 mm long OFHC copper tube and 7 OFHC copper cylinders inserted into it. Its main feature is the attenuation of the vibrations coming from the cryostat. A calculation gives an attenuation level of about −200 dB at the resonant frequency, with a very large frequency range of attenuation. The suspension system also provides a thermal link between the bar and the dilution refrigerator.

In order to minimize acoustic interference, the suspension and the antenna are mechanically

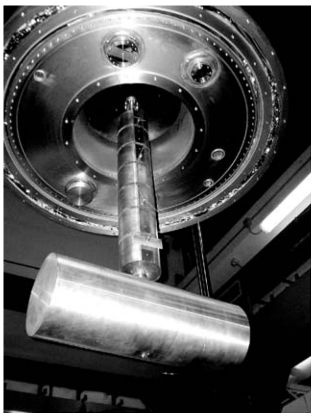

Fig 1. The antenna with the suspension system.

disconnected from the cryostat. Just three 1500 mm long stainless steel cables connect the system to the top of the cryostat.

The cryogenic system is composed of a commercial KADEL cryostat, 3200 mm in height and 1016 mm in diameter, that contains the experiment and precools it down to liquid-helium temperature, and a continuous-flow ^3He–^4He dilution refrigerator. The refrigerator is similar to the MINIGRAIL gravitational wave antenna dilution refrigerator [7]. It is able to cools the antenna down to about 100 mK with a cooling power of about 1 mW at 120 mK.

The cryostat allows a fast precooling down to 6 K, by means of a cold gaseous helium forced-flow procedure. Warm helium flows in a tube which passes inside the liquid-helium dewar of the cryostat. The tube ends in the experimental side of the cryostat, allowing forced convection between the (cold) helium gas and the antenna.

The readout is based on a commercial piezoelectric ceramic (PZT) followed by a FET amplifier. The PZT has a mechanical quality factor of 10^3 and a value of 0.3–0.4 for the ratio of the electrical energy in the transducer to the total energy in the resonator.

The data acquisition system takes information from the PZT, accelerometer, thermometers, vacuum sensors and beam monitors. It consists of a 200 k-sample/s peak-sensing 16-bit VME ADC and a VME with a Pentium III CPU and Linux operating system.

At the moment, RAP is at room temperature for the preliminary test of the detector. In July it will start to collect data at 300 K with the BTF beam. This test will be repeated in September at liquid-helium temperature (4.2 K). Then, at the end of the year, we will insert the dilution refrigerator in the cryostat.

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