HE.6.4.07

Cosmic Rays observed by the resonant gravitational wave detector NAUTILUS

P.Astone^1, M.Bassan^2, P.Bonifazi^3, P.Carelli^4, E.Coccia^2, V.Fafone^6, S.Frasca^5, A.Marini^6, E.Mauceli^6, G.Mazzitelli^6, Y.Minenkov^2, I.Modena^2, G.Modestino^6, A.Moleti^2, G.V.Pallottino^5, M.A.Papa^2, G.Pizzella^7, F. Ronga^6, R. Terenzi^3, M. Visco^3, L. Votano^6

$^{1)}$ *Istituto Nazionale di Fisica Nucleare INFN, Rome*
$^{2)}$ *University of Rome ”Tor Vergata” and INFN, Rome*
$^{3)}$ *IFSI-CNR and INFN, Rome*
$^{4)}$ *University of L’Aquila and INFN, Rome*
$^{5)}$ *University of Rome ”La Sapienza” and INFN, Rome*
$^{6)}$ *Istituto Nazionale di Fisica Nucleare INFN, Frascati*
$^{7)}$ *University of Rome ”Tor Vergata” and INFN, Frascati*

Abstract

The passage of cosmic rays (Extensive Air Showers) has been observed to excite mechanical vibrations in the resonant-bar gravitational wave detector NAUTILUS operating at temperature of 100 mK. A very significant correlation is found (more than ten standard deviations).

1 Introduction:

Beron and Hofstander, already in 1969, carried out experiments aiming to detect oscillations of piezoelectric discs excited by a GeV electron beam.

Their results brought the authors to suggest that *a very large cosmic-ray event could excite mechanical vibrations in a metallic cylinder at its resonance frequency and they could provide an accidental background for experiments on gravitational waves*(Beron,1969).

Later a group at the University of Milan (Grassi,1980) gave a rough estimation of the possible effects of particles on a small metallic cylinder and made an experiment that was in agreement with the calculations, although with rather large experimental errors. The physical mechanism consists in the heating produced by the energy lost by the particle along its trajectory in the bar. The energy loss produces a mechanical wave whose amplitude depends on the thermal expansion coefficient and the specific heat of the material. The ratio of these two quantities is the Gruneisen coefficient. It turns out that while both the expansion coefficient and the thermal conductivity depend on temperature, the Gruneisen coefficient practically does not. This last statement is certainly true for aluminium down to 1 kelvin, but it remains to see what happens at lower temperatures when the aluminium becomes superconductor.

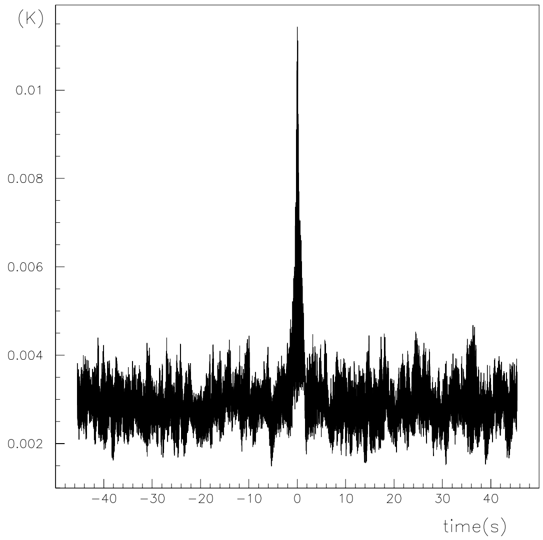

Figure 1: The weighted average energy over 92 (for M=10^4) stretches of NAUTILUS data versus time. A large signal appears at the cosmic ray arrival time.

Subsequently more refined calculations were made by several authors (Allega, 1983),(Bernard, 1984), (Amaldi, 1984), (Barish, 1988) for a cylindrical resonant gravitational wave (g.w.) detector.

The resonant ultracryogenic detector NAUTILUS (Astone,1997a) consists of an aluminium 2300 kg bar cooled at 100 mK. The mechanical vibrations are converted into an electrical signal which is amplified with a dc-

SQUID. NAUTILUS has been equipped with a cosmic ray detector (c.r.) system (Coccia ,1995) consisting of seven layers of streamer tubes for a total of 116 counters. Three superimposed layers, each one with area of 36 m^2 are located on the top of the cryostat. Four superimposed layers are under the cryostat, each one with area of 16.5 m^2. The signal from each counter is fed to an ADC to measure the charge, which is proportional to the number of particles. For extensive air showers (EAS) the efficiency is close to 100 $\%$, but the systematic error on the absolute number of particles crossing the apparatus is of the order of 30 $\%$. In addition, a saturation begins to show for multiplicity greater then $1000\frac{particles}{m^2}$. In the present data analysis we have put a lower threshold on the multiplicity of the bottom layer detection, $M \geq 10^4$, such that signals of the order of 1 mkelvin should be detected.

2 Data Analysis:

The data regarding the vibrations of the bar have been correlated with the data obtained by the cosmic ray detector in the period October 1998 to January 1999.

The NAUTILUS data, recorded with a sampling time of 4.54 ms, are processed with a filter (Astone,1997b) optimized to detect impulsive signals applied to the bar. For investigating the effect of cosmic rays we have selected the NAUTILUS data as follows:
a)for each c.r. event we have used 20,000 samples (for a total time of 90.8 s) centered at the times when the number of particles (due to the c.r. event) crossing the lower detector exceeded $M = 10^4$. Considering the geometry of the cosmic ray detector, in order to obtain the number of particles per square meter we divide M by 16.5 (with a systematic error of 30 $\%$ as stated above).
b)the data stretches with the noise temperature T_{eff} (obtained by averaging the filtered data over 6 minutes, included the time of the cosmic ray event) larger than $5\ mK$ were rejected, in order to select periods when the detector was not disturbed and the noise was of the order of the expected signals.
In this way we selected 93 stretches for $M \geq 10^4$ during a total time of 47.7 days. One of the 93 stretches of data contained a large (about 0.5 K) mechanical excitation at a delay of + 6.2 s and was removed from the analysis, although there was no external veto.

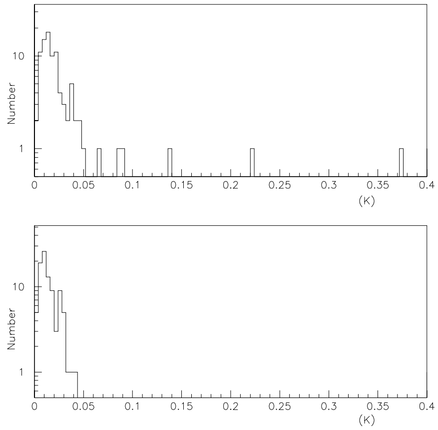

Figure 2: Distribution of maximum values in Kelvin (see text).

Using these data we make weighted averages superimposing the selected stretches of data taken at the same time relative to the cosmic ray trigger time. In this way we expect a noise variance that reduces with the number of stretches. The weighted averages are defined as follows:

$$E_w(k) = \frac{\sum \frac{E_i(k)}{T_i}}{\sum \frac{1}{T_i}} \tag{1}$$

where T_i is the noise temperature (T_{eff}) of the apparatus for the i^{th} detected cosmic ray event and $E_i(k)$ is the energy of the k^{th} sample for the corresponding i^{th} stretch of NAUTILUS data. Because of our above selection criterion b), it turns out that the various T_i do not differ one from each other by more than a factor of two. The result of this analysis is shown in fig.1, where we plot the weighted averages for each data sample (4.54 ms) versus the time relative to the cosmic ray trigger. There is a 20 σ excess at the time $t = 0$ respect to the background.

It is important to verify that the observed average effect is due to several events and not just to one. In order to do this we have considered each cosmic ray event and taken the maximum energy value in the time range from -64 ms to 64 ms, obtaining 92 maximum values near zero time (fig 2 upper part). We repeat this procedure for the time interval $10.000 \pm 0.064\ s$ obtaining a new set of maximum values (fig 2 lower part). The two distributions are different and the upper one shows a spread of values, so to justify our conclusion that the observed effect is due to several events.

For checking that the observed signals are due to mechanical oscillations of the bar and not just to electrical noise we have performed the following two tests:

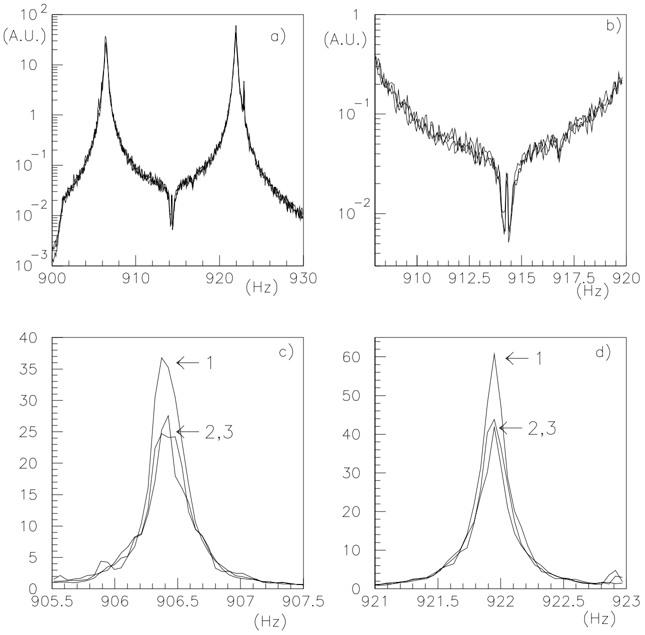

Figure 3: Power spectra (see text)

TEST I

We computed the average spectrum of the data both at the time of the c.r. trigger and at two other times off the c.r. trigger (fig 3). More precisely, we computed spectrum 1 by averaging the 92 spectra obtained from 4096 samples (18.6 s), centered at the trigger time, for each of the 92 stretches of data. We then repeated the same procedure for the 4096 samples from -45.4 s to -26.8 s, and for those from 26.8 to 45.4 s, obtaining the spectra 2 and 3, respectively. Fig 3b refers to the zoom of fig 3a off of the resonance. Figure 3c and 3d are the zoom of figure 3a at the two resonances. The plots of fig.3 show that only at the two resonances (the detector has two resonances (Astone 1997a) at frequencies of f_1=906.40 and f_2 =921.95) the signal spectrum *1* differs from the background spectra *2* and *3*. This is a proof that the signals in time coincidence with the c.r. events are due to mechanical excitations of the g.w. detector.

TEST II.

We have checked that the observed events are due to mechanical excitations of the g.w. detector also by examining in greater detail the time behaviour of the signals near zero delay. We know (Astone 1997b) that, after filtering, the response to a pulse excitation has an oscillation behaviour decaying with time, with the envelope following the law

$$E(t) = E_o\, e^{-2\pi \Delta f |t - t_o|} \tag{2}$$

where t_o is the time of the excitation and Δf is the bandwidth of the detector. We have verified that the value of Δf from fig 3 is the same of the one computed from equation (2).

We now calculate the expected energy of the signals due to the cosmic rays EAS. Taking into consideration the characteristics of the apparatus at the liquid helium temperature, in particular putting $\gamma = 1.6$ for the Gruneisen coefficient, we obtain from (Barish 1988),(Coccia,1995) the formula to convert the dissipation of an energy W, expressed in GeV, in a signal ϵ expressed in kelvin units:

$$\epsilon = 7.64 \cdot 10^{-9}\, W^2 \ \cdot\ f(z_o, \theta_0) \tag{3}$$

Where f is a geometrical factor (Barish ,1988) and the energy W is dissipated by the M secondaries due to each EAS. We have computed the expected EAS signal from eq 3 using the EAS density distributions (Cocconi,1966),(Coccia,1995) and the antenna geometry. In addition we have done the following simplifying assumptions:

1) No particle absorption in the bar (all particle go through). This approximation is justified from the small radiation length in the bar compared to the total radiation length in the atmosphere. Actually, due to the different

M	$\frac{particles}{m^2}$	calculated $\frac{number}{day}$	detected $\frac{number}{day}$	ϵ_1 $[mK]$	E $[mK]$
10^4	600 ± 200	$3.3 \div 0.95$	1.96	$2.4 \div 16$	$8.6 \div 21$
$1.5 \cdot 10^4$	900 ± 300	$1.6 \div 0.45$	0.98	$8 \div 26$	$16 \div 31$

Table 1: Comparison of the theoretical predictions with the observations. ϵ_1 is the expected event energy averaged from the given multiplicity to ∞. In the last column we report the lower and upper limits for the measured average excess E.

critical energy in aluminium with respect to the air, we have seen an increase of the number of particles in the cosmic ray detector under the cryostat with respect to the detector above the cryostat.
2) The energy loss for a single particle is computed assuming ionization energy losses for electrons having the aluminium critical energy.
3) We have used the showers angular distribution as reported in reference (Aglietta,1994).
4) We have neglected the contribution of hadrons that could be present in the core of the showers.

With a threshold of 10^4 particles in the lower detector we obtain with this calculation 8 mK. Using the experimental multiplicity as measured with the lower detector we obtain 2.4 mK. The discrepancy, we think, is due to the saturation effects in the streamer tubes. The result of the calculation is reported in the table 1 and provides a range of values that depends on the simplifications in the calculations and on the systematic error in measuring the particle multiplicity. In the last column of table 1 we report the lower and upper limits for the measured average excess of the antenna signal. The agreement between the values in the last two columns of table 1 is satisfactory, taking in account the large uncertainties involved.

3 Conclusions:

We have detected, for the first time, cosmic ray signals in a gravitational wave bar detector. The experiment shows that the Gruneisen coefficient of superconducting aluminium is similar to the one for the normal aluminium, that NAUTILUS is properly working, and, in particular, that the efficiency of our matched filter algorithm to detect small signals embedded into noise is experimentally well proven. This experiment, furthermore, gives useful information for designing future resonant detectors of gravitational waves and for evaluating a possible use of underground laboratories to reject the background due to cosmic rays.

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