Cosmic Rays Observed by the Resonant Gravitational Wave Detector NAUTILUS

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The passage of cosmic rays has been observed to excite mechanical vibrations in the resonant gravitational wave detector NAUTILUS operating at temperature of 100 mK. A very significant correlation (more than 10 standard deviations) is found.

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Beron and Hofstander, already in 1969, carried out experiments aiming to detect oscillations of piezoelectric disks excited by a GeV electron beam. The 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 could provide an accidental background for experiments on gravitational waves [1,2]. Later, a group at the University of Milan [3] estimated the possible effects of particles on a small aluminum cylinder and made an experiment which verified the calculations, although with rather large experimental errors.

The mechanical vibrations originate from the local thermal expansion caused by the warming up due to the energy lost by the particles crossing the material. The effect depends on the thermal expansion coefficient and the specific heat of the material. The ratio of these two quantities is the Grüneisen coefficient. It turns out that while both the expansion coefficient and the specific heat vary with temperature, the Grüneisen coefficient practically does not. In the case of aluminum, this is certainly true above 1 K, but no data are available at lower temperatures when the aluminum becomes superconductor.

Subsequently, more refined calculations were made by several authors [4–8]. All these models agree in predicting, for the vibrational energy in the fundamental mode of an aluminum cylindrical bar, the following formula expressed in Kelvin units:

$$\epsilon = 7.64 \times 10^{-9} W^2 f , \qquad (1)$$

where W (in GeV) is the particle energy dissipated in the bar, and f is a geometrical factor of the order of unity.

The resonant-mass gravitational wave (g.w.) detector NAUTILUS [9], operating at the INFN Frascati Laboratory, consists of an aluminum 2300 kg bar cooled at 100 mK. The mechanical vibrations are converted by means of an electromechanical resonant transducer into an electrical signal which is amplified by a dc SQUID. The bar and the resonant transducer form a coupled oscillator system, which has two resonant modes, whose frequencies are $f_1 = 906.40$ Hz and $f_2 = 921.95$ Hz.

NAUTILUS is equipped with a cosmic ray (c.r.) detector system 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 over the cryostat. Four superimposed layers are under the cryostat, each one with area of 16.5 m^2. The signal from each counter is digitized 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, saturation begins to show for multiplicity greater than 1000 particles/m^2. In the present data analysis we have put a lower threshold on the multiplicity M of the bottom layer detection, $M \geq 10^4$, because with this threshold a signal of the order of 1 mK is expected on the NAUTILUS detector [10].

The data regarding the vibrational energy 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 by a filter [11] optimized to detect impulsive signals applied to the bar.

For investigating the effect of c.r. 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 time when the number of particles (due to the c.r. event) crossing the lower detector exceeded $M = 10^4$.

(b) The data stretches with noise temperature $T_{\rm eff}$ (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 properly working 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.

We average these data by 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 decreases with the number of stretches. The result of this analysis is shown in Fig. 1, where we plot the averages for each data sample (4.54 ms) versus the time relative to the cosmic ray trigger.

In order to increase our confidence that the observed effect is due to c.r. we have repeated the above procedure raising the threshold on the multiplicity to 15×10^3. In this way we have selected a subset of 46 stretches. The result of the analysis is shown in Fig. 2, where the signal at zero delay is higher, as expected. These results are also reported in Table I.

For checking that the observed events are due to mechanical vibrations of the bar and not just to electrical noise we have performed the following three tests.

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. 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 to -26.8 s, and for those from 26.8 to 45.4 s, obtaining the spectra 2 and 3, respectively. The plots of Fig. 3 show that only at the two resonances f_1 and f_2 the signal spectrum 1 differs from the background spectra 2 and 3. This is a proof that at the times of the cosmic ray events a mechanical disturbance exited the detector resonances.

Test II.—We have checked that the observed signals are due to mechanical excitations of the g.w. detector also by examining in greater detail the time behavior of the signals near zero delay. The behavior of the signal energy with time for each sample averaged over the 46 events ($M \geq 15 \times 10^3$) is shown, near the zero time, in Fig. 4. This behavior agrees very well with the behavior described in Ref. [11] for a simulated delta excitation and the envelope, as expected, follows 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.

The periodicity we notice in Fig. 4 is in good agreement with the beat period due to the two resonance modes ($\frac{1}{f_2-f_1} = 64$ ms). Thus we are in the presence of mechanical excitations, and the data filter we are using behaves in the proper way.

We can estimate the bandwidth Δf from the data shown in Fig. 3. We find $\Delta f = 0.27 \pm 0.03$ Hz in very good agreement with the envelope obtained from Fig. 4 and described by Eq. (2).

Test III.—We have considered the possibility that the mechanical excitations be due to a back action from the electronics. To eliminate this possibility we generated, very near the electronics of the transducer, strong electrical sparks, 6 orders of magnitude above any possible electrical disturbance which would excite the transducer and in turn the bar. No signal was observed.

Finally, one could think about the possibility of a direct effect of c.r. on the transducer. This could occur in two ways. One way is to directly shake the transducer. It is easily recognized that this mechanical vibration due to few particles is extremely small, much smaller

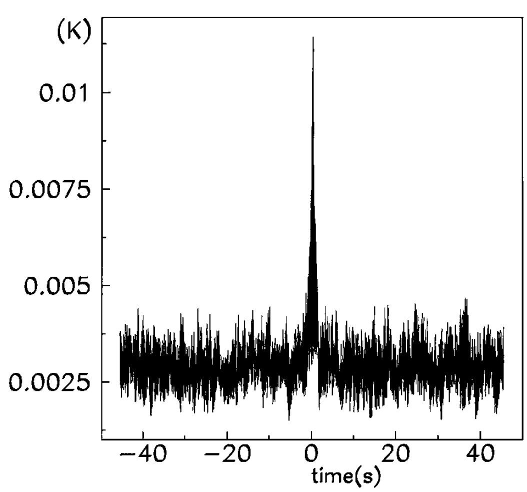

FIG. 1. The average energy over 92 (for $M \geq 10^4$) stretches of NAUTILUS data versus time. A large signal appears at the cosmic ray arrival time.

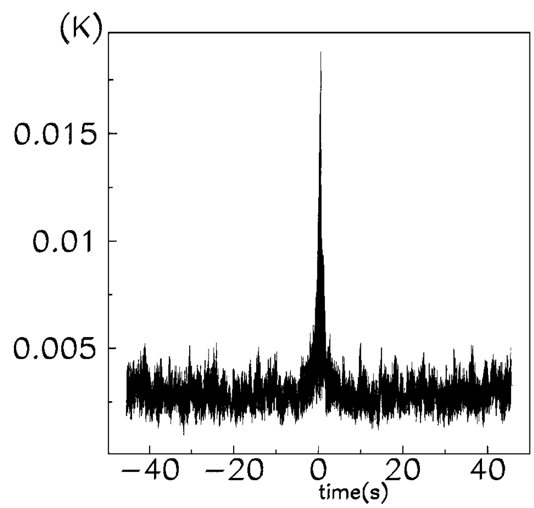

FIG. 2. The average energy over 46 (for $M \geq 15 \times 10^3$) stretches of NAUTILUS data versus time.

TABLE I. Results of the analysis for two thresholds of the multiplicity. The noise statistics were taken from Figs. 1 and 2 excluding data sampled between ±2 s.

$M \geq$	Maximum [mK]	Average [mK]	σ [mK]	Excess [mK]	Excess in σ units
10^4	11.5	2.89	0.43	8.6	20
1.5×10^4	18.8	2.89	0.57	15.9	28

than that produced in the bar by thousands of particles, each particle releasing much more energy in a longer trajectory in the bar itself. The other possibility is that one particle strikes the transducer extracting some electrons which would be accelerated by the transducer electrical field, but with no electron multiplication because of the extreme high vacuum. This would give a few hundred eV for an impulsive excitation, orders of magnitude below the energy of several GeV released by an EAS in the bar. Thus we believe that the mechanical excitations are originated in the bar itself.

It is important to verify that the observed average effect is due to several events and not just to one. To this aim we have considered each cosmic ray event and taken the maximum energy value in the time range from −64 to 64 ms, obtaining 92 maximum values near zero time. We repeat this procedure for the time interval 10 000 ± 64 ms obtaining a new set of maximum values.

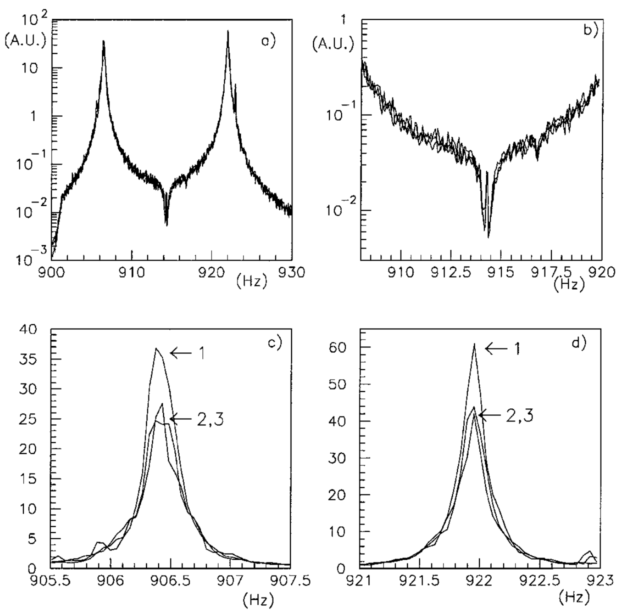

FIG. 3. (a) Power spectra 1, 2, 3, with arbitrary units on the ordinate scale. (b) Zoom of (a) off-resonance. (c), (d) Zoom of (a) at the two resonances. (b) shows that the three spectra off-resonance are equal (the dip is due to the calibration signal of the detector). (c) and (d) show that the signal spectrum 1 is fairly larger than the background spectra 2 and 3 at the resonances.

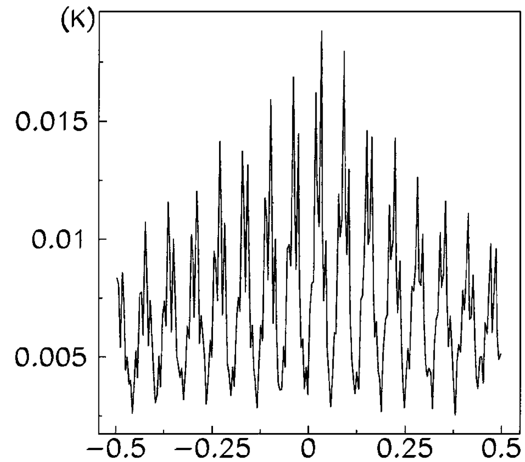

FIG. 4. Zooming the average energy over 46 (for $M \geq 15 \times 10^3$) stretches of NAUTILUS data versus time.

We determine the distributions of these two quantities for the 92 events and show them in Fig. 5. Using the Kolmogoroff test we find a probability of 0.016 that the two distributions are compatible. The upper one shows a spread of values. This verifies that the observed effect is due to several events.

The largest signals in NAUTILUS are associated with the largest c.r. events. The largest one is associated with a c.r. event with multiplicity $M = 32 \times 10^3$ (here the c.r. counters have a saturation effect). For the second largest we have $M = 22 \times 10^3$. Considering the six largest signals we have an average multiplicity of $M \sim 26 \times 10^3$, while for the remaining 86 signals the average multiplicity is $M \sim 17 \times 10^3$ and for the smallest fifty signals the corresponding average multiplicity is

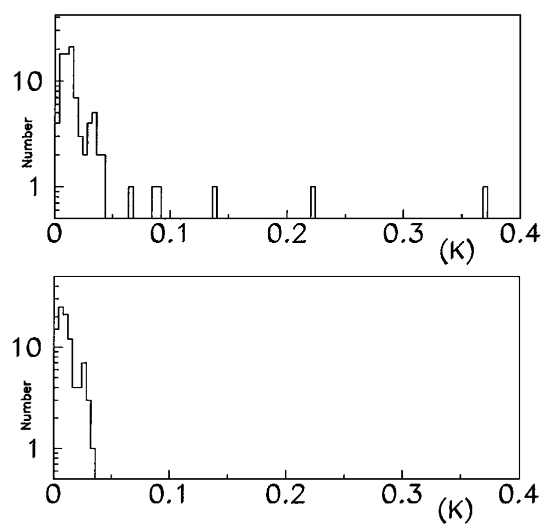

FIG. 5. In the upper part we show the distribution of the maximum values in the time range from −64 to 64 ms (see text). In the lower part we show the distribution of the maximum values taken in the range 10 000 ± 64 ms.

$M \sim 15 \times 10^3$. If we remove the two largest events the excess shown in Table I reduces from 28 to 12 standard deviations, for $M \geq 15 \times 10^3$

The number of observed large signals agrees with the expectations. We expect in the 47.7 days [see Eqs. (1) and (3)] from one to four antenna signals due to c.r. with energy greater than 50 mK. In view of the error on the absolute estimation of the released energy this result is acceptable.

The data of Fig. 5 allow us to estimate an upper limit for the energy delivered to the bar by the EAS. This is done by taking the average value of the maxima and subtracting the mean background energy 2.9 mK (see Table I).

Now we calculate the expected energy of the signals due to the EAS. At sea level, the rate of expected EAS (in agreement with previous experiments [10]) is given by [12]

$$H(\geq\Lambda) = k\Lambda^{-\lambda} \text{ EAS/day}, \tag{3}$$

where Λ is the particle density in the shower in units of number of charged particles per square meter, $\lambda = 1.32 + 0.038 \ln\Lambda$ and $k = 3.54 \times 10^4$.

Using Eqs. (1) and (3) we take into account distribution reported in Ref. [13] and the antenna geometry. With a threshold of 10^4 particles in the lower detector we obtain with this calculation 8 mK. Using the experimental multiplicity as measured by the lower detector we calculate 2.4 mK. We think the discrepancy is due to the saturation effects in the streamer tubes. All calculations are reported in Table II providing ranges of values that depend on the simplifications and on the systematic error in measuring the particle multiplicity.

The experimental result indicates that, for the aluminum, the Grüneisen factor remains of the same order after the transition to the superconducting state.

Very important is the experimental demonstration of the overall well functioning of the apparatus with applied physical impulsive excitations and, in particular, the verification of the filtering algorithm performance, both in reducing noise and in extracting small signals.

This experiment confirms the calculations on the cosmic ray effect made by various authors, both in terms of rate of occurrence and in terms of amplitude of the cosmic ray interaction with the resonant detectors. It also confirms previous conclusions [14,15] based on calculations, for a two detectors coincidence experiment. For the present detectors, there is no need to use an underground laboratory. For possible future more massive detectors operating near their quantum limit (noise temperature of the order of 10^{-7} K), it might be convenient to install just one of them in an underground laboratory.

TABLE II. Comparison of the theoretical predictions with the observations. ϵ_1 is the expected event energy averaged from the given multiplicity to ∞. The observed number of EAS per day (respectively, 92 and 46 over a time of 47.7 days) is in agreement with the expectation. In the last column we report the lower and upper limits for the measured average excess E. The lower limit is obtained from Table I, the upper limit by summing the maxima of Fig. 5 and subtracting the average background 2.9 mK.

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

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[1] B. L. Beron and R. Hofstander, Phys. Rev. Lett. **23**, 184 (1969).
[2] B. L. Beron, S. P. Boughn, W. O. Hamilton, R. Hofstander, and T. W. Tartin, IEEE Trans. Nucl. Sci. **17**, 65 (1970).
[3] A. M. Grassi Strini, G. Strini, and G. Tagliaferri, J. Appl. Phys. **51**, 849 (1980).
[4] A. M. Allega and N. Cabibbo, Lett. Nuovo Cimento **38**, 263 (1983).
[5] C. Bernard, A. De Rujula, and B. Lautrup, Nucl. Phys. **B242**, 93 (1984).
[6] A. De Rujula and S. L. Glashow, Nature (London) **312**, 734 (1984).
[7] E. Amaldi and G. Pizzella, Il Nuovo Cimento **9**, 612 (1986).
[8] G. Liu and B. Barish, Phys. Rev. Lett. **61**, 271 (1988).
[9] ROG Collaboration, P. Astone *et al.*, Astropart. Phys. **7**, 231 (1997).
[10] E. Coccia, A. Marini, G. Mazzitelli, G. Modestino, F. Ricci, F. Ronga, and L. Votano, Nucl. Instrum. Methods Phys. Res., Sect. A **335**, 624 (1995).
[11] P. Astone, C. Buttiglione, S. Frasca, G. V. Pallottino, and G. Pizzella, Il Nuovo Cimento **20**, 9 (1997).
[12] G. Cocconi, in *Encyclopedia of Physics,* edited by S. Flügge (Publisher, City, 1961), Vol. 46, p. 228.
[13] M. Aglietta *et al.*, Phys. Lett. B **333**, 555 (1994).
[14] G. Pizzella, IR LNF-99 **001** (1999), http://wwwsis.lnf.infn.it/pub/LNF-99-001(IR).pdf.
[15] ROG Collaboration, E. Coccia *et al.*, Nucl. Phys. B (Proc. Suppl.) **70**, 461 (1999).