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Energetic cosmic rays observed by the resonant gravitational wave detector NAUTILUS

P. Astone [a], M. Bassan [b], P. Bonifazi [c], P. Carelli [d], E. Coccia [b], S. D'Antonio [e],
V. Fafone [f], G. Federici [a], A. Marini [f], G. Mazzitelli [f], Y. Minenkov [b], I. Modena [b],
G. Modestino [f], A. Moleti [b], G.V. Pallottino [e], V. Pampaloni [f], G. Pizzella [g,*],
L. Quintieri [f], F. Ronga [f], R. Terenzi [c], M. Visco [c], L. Votano [c]

[a] *Istituto Nazionale di Fisica Nucleare INFN, Rome, Italy*
[b] *University of Rome "Tor Vergata" and INFN, Rome, Italy*
[c] *IFSI-CNR and INFN, Frascati, Italy*
[d] *University of L'Aquila and INFN, Rome, Italy*
[e] *University of Rome "La Sapienza" and INFN, Rome, Italy*
[f] *Istituto Nazionale di Fisica Nucleare INFN, Frascati, Italy*
[g] *University of Rome "Tor Vergata" and INFN, Frascati, Italy*

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Abstract

Cosmic-ray showers interacting with the resonant mass gravitational wave antenna NAUTILUS have been detected. The experimental results show large signals at a rate much greater than expected. The largest signal corresponds to an energy release in NAUTILUS of 87 TeV. We note that a resonant mass gravitational wave detector used as particle detector has characteristics different from the usual particle detectors, and it could detect new features of cosmic rays. © 2001 Published by Elsevier Science B.V.

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1. Measurements with the gravitational wave detector NAUTILUS

The gravitational wave (g.w.) detector NAUTILUS has recently proven to be capable of recording signals due to the passage of cosmic rays [1]. In the ongoing analysis of the data obtained with NAUTILUS in coincidence with cosmic-ray (c.r.) detectors we found new interesting results, which we are going to report here. The work initially done by Beron and Hofstander [2,3], Strini and Tagliaferri [4] and refined calculations by several authors [5–9] estimated the possible acoustic effects due to the passage of particles in a metallic bar. It was predicted that for the vibrational energy in the longitudinal fundamental mode of a metallic bar with length L the following formula

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[*] Corresponding author.
E-mail address: pizzella@lnf.infn.it (G. Pizzella).

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holds:

$$E = \frac{4}{9\pi}\frac{\gamma^2}{\rho L v^2}\left(\frac{\mathrm{d}W}{\mathrm{d}x}\right)^2 \times \left(\sin\left(\frac{\pi z_0}{L}\right)^2 \left(\frac{\sin(\pi l_0 \cos(\theta_0)/2L)}{\pi R \cos(\theta_0)/L}\right)^2\right), \tag{1}$$

where L is the bar length, R the bar radius, l_0 the length of the particle's track inside the bar, z_0 the distance of the track midpoint from one end of the bar, θ_0 the angle between the particle track and the axis of the bar, E the energy of the excited vibration mode, $\mathrm{d}W/\mathrm{d}x$ the energy loss of the particle in the bar, ρ the density, v the sound velocity in the material and γ is the Grüneisen coefficient (depending on the ratio of the material thermal expansion coefficient to the specific heat) which is considered constant with temperature. The adopted mechanism assumes that 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 above formula has been recently verified by an experiment at room temperature [10], using a small aluminium cylinder and an electron beam. We notice that the g.w. bar used as particle detector has characteristics very different from the usual particle detectors, because the usual detectors are sensitive only to ionization losses. The resonant-mass g.w. detector NAUTILUS [11], operating at the INFN Frascati Laboratory, consists of an aluminium 2300-kg bar cooled at 140 mK, below the superconducting transition temperature [12] of 0.92 K. Applying Eq. (1) to the case of NAUTILUS we find

$$E = 7.64 \times 10^{-9}\ W^2 f, \tag{2}$$

where E is expressed in kelvins, W in GeV units is the energy delivered by the particle to the bar and f is a geometrical factor of the order of unity. The bar and a resonant transducer, providing the read-out, form a coupled oscillator system with two resonant modes, whose frequencies are 906.40 Hz and 921.95 Hz. The transducer converts the mechanical vibrations into an electrical signal and is followed by a dcSQUID electronic amplifier. The NAUTILUS data, recorded with a sampling time of 4.54 ms, are processed by a filter [13] optimized to detect impulse signals applied to the bar, such as those due to a short burst of g.w.

With our first analysis, whose details are given in [1], we have found that the models described by Eqs. (1) and (2) well describe, within a factor of three, the experimental data. We did observe in the NAUTILUS apparatus small signals correlated (above twenty standard deviations) with cosmic-ray showers detected by the cosmic-ray detectors located on the top and on the bottom of the NAUTILUS cryostat (see below). The signals were correlated with the shower multiplicity. For stressing this point we show here in Fig. 1 the scatter plot of the NAUTILUS signal energy versus the c.r. shower multiplicity. During these measurements NAUTILUS was operating in a superconductive regime. This indicates that the Grüneisen coefficient has the same value as in the normal status regime. We also remark that the validity of Eqs. (1) and (2) was already verified with room temperature experiments employing different apparatuses [4,10].

For the first analysis, we have made use of data selection based on the theoretical expectations. In fact, we selected the data by considering six-minute averages of the NAUTILUS background (as described in [1]) and we eliminated the corresponding data if a six-minute average was larger than 5 mK (the expected signals should have had energy smaller than a few mK over periods with durations of the order of one second). But, later, we noted a very large NAUTILUS signal (a few kelvins) in coincidence with a c.r. shower, so we decided to proceed to a new analysis on the following entirely different bases, in order to study the large signals.

We consider antenna events defined as follows. We apply to the filtered data a threshold corresponding to signal to noise ratio $SNR = 19.5$, and for each threshold crossing we take the maximum value above threshold and its time of occurrence. These two quantities define the event of the g.w. detector. We wish to stress that here we consider only events with energy greater than about twenty times the noise, a procedure entirely different from that adopted in [1]. The events produced by NAUTILUS were already posted on the WEB within the IGEC collaboration among the groups that operate resonant g.w. detectors [14]. NAUTILUS is equipped with a c.r. detector system consisting of seven layers of streamer tubes for a total of 116 counters [15]. 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. Each counter measures the charge, which is proportional to the

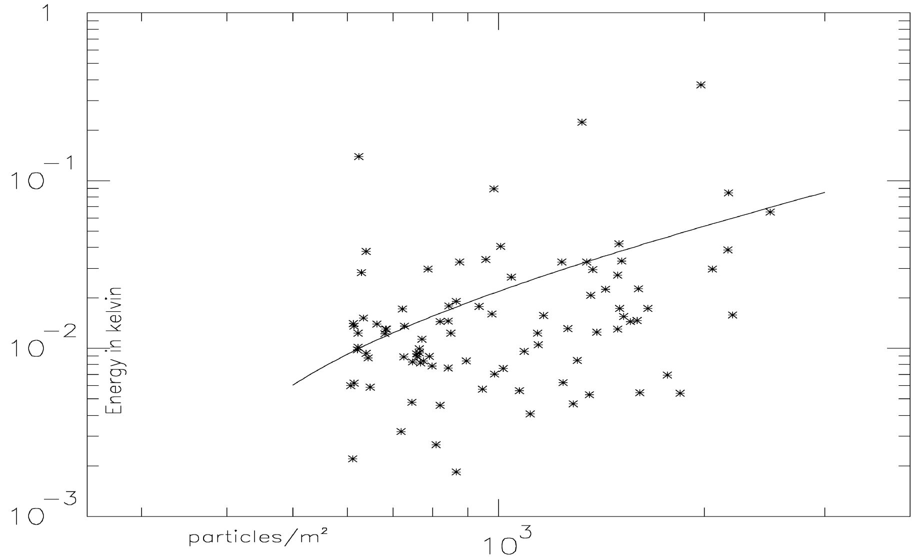

Fig. 1. Correlation between the NAUTILUS signals and the c.r. particle density. The graph shows the correlation of the NAUTILUS energy at zero delay (respect to the c.r. events) versus the corresponding c.r. lower particle density, for the 92 data points considered in the previous analysis. The correlation coefficient is 0.30, with a probability to be accidental of less than 1%.

number of particles. The detector is able to measure particle density up to 5000 particles/m^2 without large saturation effects and it gives a rate of showers in good agreement with the expected number [15,16], as verified here using the up-particle density, which is not affected by the interaction in the NAUTILUS detector. We have searched for coincidences between the NAUTILUS events and the signals from the c.r. NAUTILUS detectors, due to showers, in the period from 11 September 1998 until the end of the year 1998, for a total observation time of 83.4 days where we have 26466 NAUTILUS events and 94775 c.r. shower events. We have determined

(a) the number of coincidences, using a time window [1] of ±0.5 s, as a function of the particle density of the c.r. events,

(b) the corresponding background of accidental coincidences estimated by performing one hundred time shifts of the NAUTILUS event times, in steps of 2.

The result of the analysis, i.e., the number n_c of observed coincidences and the estimated number n of accidental coincidences versus the particle density is given in Fig. 2. Clear coincidence excess above background is found, when the showers have particle density large enough that the number of accidentals reduce to a few ones. The eighteen coincidences obtained for the down-particle density greater than 300 particles/m^2 with with expected number of accidentals $n = 2.1$ are shown in Table 1.

For a particle density greater than 600 particles/m^2 the number of coincidences reduce to twelve, with $n = 0.78$. For each coincidence we give the quantity T_{eff}, the noise of the g.w. detector during the ten minutes preceding the c.r. event. The time is that recorded by the c.r. detector. We notice an unexpected extremely large NAUTILUS event in coincidence with a c.r. event, with energy $E = 57.89$ K. Both the up and down-particle density of the c.r. detector are the largest ones in this case. The time of this NAUTILUS event is obtained with good accuracy from the data, given the very large value of $SNR = 15860: \; t_0 = 2123.928$ s with an error of the order of 10 ms. The time when the c.r. event has been observed is 2123.9222 s with a time error of the order of about 1 ms. The difference of 6 ms is within the experimental error of the g.w. time events (at present our time accuracy for the NAUTILUS apparatus has been since improved).

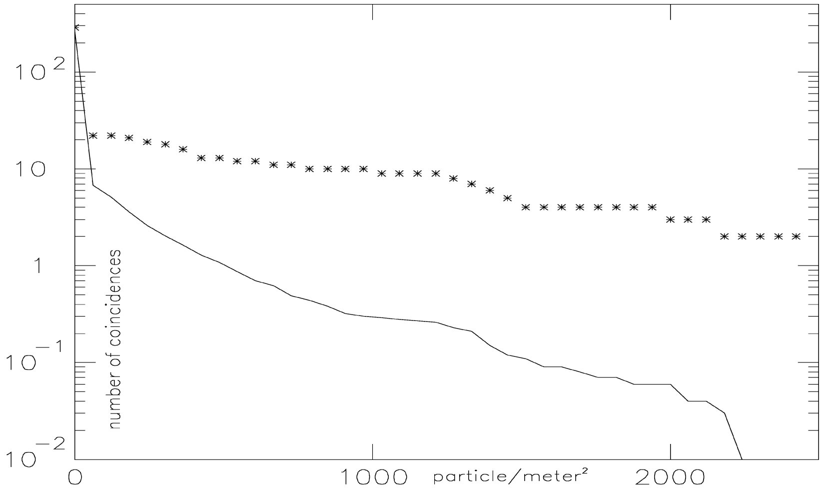

Fig. 2. Coincidences between the g.w. detector NAUTILUS and the c.r. detector. The asterisks show the integral number of observed coincidences versus the particle density observed by the c.r. counters located under the NAUTILUS cryostat. The continuous line shows the estimated number of accidental coincidences.

Table 1
List of eighteen coincidences between NAUTILUS and the c.r. detector

Day	Hour	Min	s	Energy of the event [K]	Noise of the g.w. detector T_{eff} in mK	Up-particle density [m^{-2}]	Down-particle density [m^{-2}]
262	23	11	29.581	2.28	0.003	31	312
277	22	26	35.771	0.04	0.002	99	405
285	17	23	14.9779	0.06	0.002	1032	2494
286	0	35	23.9222	57.89	0.004	2036	3556
295	21	0	34.3376	0.07	0.003	197	536
297	21	38	49.9765	0.37	0.011	456	1374
303	10	38	36.5147	0.42	0.016	190	360
306	8	19	59.5765	0.12	0.006	525	1409
311	15	24	27.1148	0.12	0.003	627	390
311	15	26	21.0289	0.14	0.004	124	623
311	23	22	8.4868	0.45	0.021	187	407
324	14	14	47.3926	1.14	0.044	216	785
350	20	56	18.6130	0.22	0.004	327	1323
354	23	54	19.2230	0.37	0.004	888	1972
356	3	17	35.7440	0.09	0.004	363	2169
358	0	19	21.9564	0.04	0.002	239	1234
361	12	49	13.9211	0.09	0.003	216	983
365	12	35	40.6593	0.32	0.007	271	1490

2. Discussion

We have found coincidences between NAUTILUS events and c.r. showers. This coincidence excess is so large to leave no reasonable doubt that NAUTILUS events and c.r. showers are correlated. Using Eq. (2) which was derived theoretically by several authors [5–9] and verified experimentally as described in Ref. [1,4,10], we find that the largest NAUTILUS event requires that $W = 87$ TeV of energy be released by the shower to the bar. There are several points, which must be clarified and discussed.

2.1. Using the down-particle density shown in Table 1 we can calculate the energy of the NAUTILUS signals that we expect under the hypothesis the shower consists of electrons. In the previous work [1], finalized to the study of small signals, we had found, using Eqs. (1) and (2), that this energy is given by $E = \Lambda^2\, 4.7 \times 10^{-10}$ K where Λ is the number of particles in the bar. For the biggest event the above formula gives $E = 0.019$ K, that is more than three orders of magnitude smaller than the recorded 58 K. In the same way we calculate energies much smaller than those reported for all the coincident events of Table 1. Thus we conclude that all, or most of, the observed NAUTILUS events are not due to electromagnetic showers. On the contrary, when using the NAUTILUS measurements at zero time delay with energy of the order or below the noise and add them up at the cosmic-ray trigger time, as done in the previous analysis [1], we find that the electromagnetic showers account for the energy observations within a factor of three. For the previous result the energy of the small signals is correlated with the c.r. particle density. Instead no correlation with the lower particle density is found for the eighteen large signals given in Table 1 as shown in Fig. 3. This result could be taken as evidence for the nonvalidity of Eqs. (1) and (2), but then the agreement of these formulas for the case of small signals as shown in Ref. [1] would remain unexplained. This figure confirms the idea that the observed large events are not due to electromagnetic showers. In conclusions, the NAUTILUS signals are associated to two distinct families of c.r. showers. In one family the signals can be interpreted as due to the electromagnetic component of the showers, in the other family the known c.r. particles in the shower do not justify the amplitude or the rate of the observed signals.

2.2. One must consider the possibility that the large events are due to the contribution of hadrons

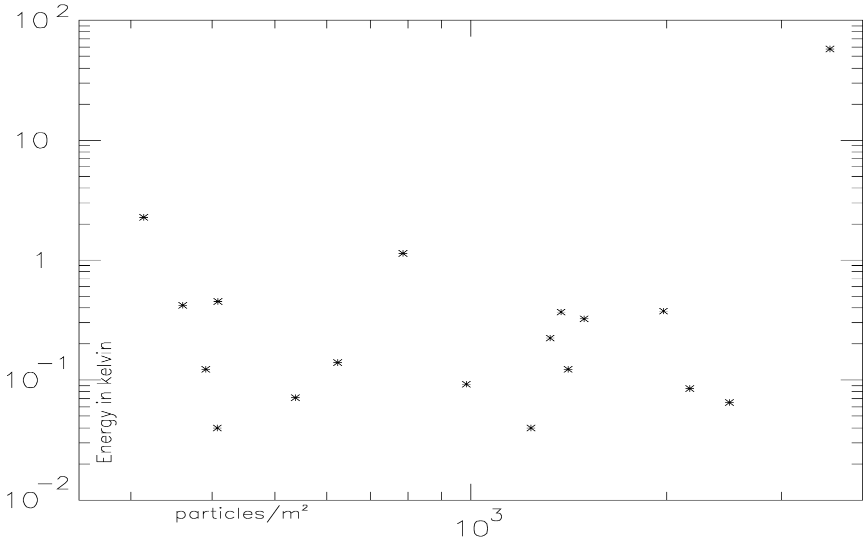

Fig. 3. The NAUTILUS event energy for the events of Table 1 versus the c.r. particle density. Unlike the result shown in Fig. 1 there is no correlation between the energy of the NAUTILUS coincident events analysed in this paper and the corresponding c.r. particle density.

in the showers [17]. Previous calculations have been made [16,18] on the frequency of both hadrons and multihadrons showers. The calculated values appear to disagree with our observation by more than an order of magnitude. Recently we have estimated the expected rate of hadronic events in the bar by means of new Monte Carlo calculations, using the CORSIKA package [19] with the QGSJET model for the hadronic interaction and simulating the NAUTILUS detector with the GEANT package. This is compared with the integrated number of coincidences, shown in Table 1, versus the NAUTILUS event energy. (The covered time periods are different for the various energy thresholds, which vary during the observations, depending on the noise. We have normalized the number of detected events to the total time of 83.4 days.) Using Eq. (2) we can express the integral number in terms of the energy W delivered to the NAUTILUS bar by the cosmic rays. The result is shown in Fig. 4. The calculation was done using a mixed composition of the primary c.r. (starting from protons up to iron; the light composition of c.r. [20]). For the energy of interest (above 10 TeV) there are large uncertainties in the c.r. composition and in the cascade model. For this reason we have compared our calculations to recent measurements [21] of the hadronic components of extensive air showers, number of hadronic showers versus their total energy measured with usual particle detectors.

The comparison of these measurements with the result of the Monte Carlo calculation shown in Fig. 4 with the error bars prove that the calculations have been done correctly, since, because of the small diameter of the bar, we expect that only a few percent of the hadronic energy is absorbed by the bar, just as shown in Fig.4.

An immediate finding is that the highest energy event occurs in a time period more than one hundred times shorter than estimated under the hypothesis that the signals in the bar are due to hadrons. This big specific event could be explained as due to a large fluctuation, for instance due to the cascade originated from some heavy nucleus, but we also notice a large disagreement between predicted and observed rates for all other events. Thus our observations exceed the expectation by one or two orders of magnitude.

2.3. Some unexpected behaviour of NAUTILUS due to its superconducting state and to the transition to the normal state along the particle trajectories can be considered. These effects have been estimated [5,6] for type I superconductor (as aluminium). They are very

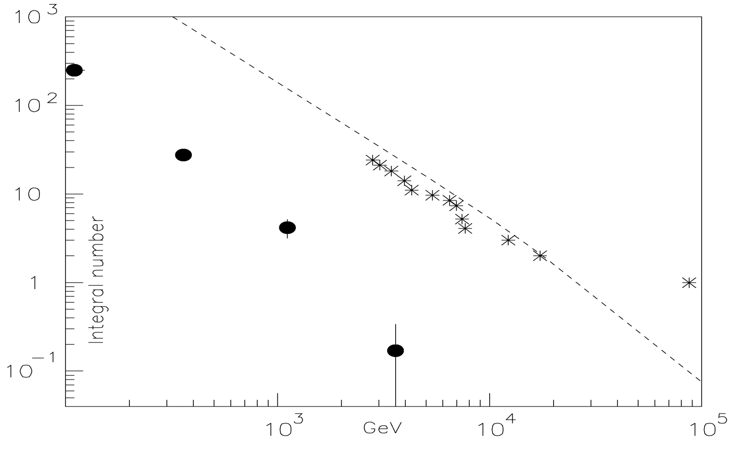

Fig. 4. Comparison between calculations and measurements. The asterisks indicate the integrated number of coincident events versus the energy delivered by the c.r. to the bar, expressed in GeV units, to be compared with the points having error bars, which give the number of events due to hadrons, we expect in the NAUTILUS bar. The dashed line is the experimental integral spectrum for the hadronic component of the showers, for the 83.4 days of observation, obtained by the Cascade experiment. Since only a few percent of the total hadronic energy can be absorbed by the bar, the apparent coincidence between the energy spectrum measured by Cascade and that determined by NAUTILUS shows, indeed, that our observations cannot be explained with the hadronic component.

small and cannot explain our observations if the showers include only electromagnetic and hadronic particles. Thus, the unexpected behaviour of NAUTILUS should be important for the field of particle detectors based on the superconducting transitions. Another possibility is that the impact of a particle could trigger nonelastic audiofrequency vibrational modes with a much larger energy release. This has been already suggested [22,23] for the case of the interaction with gravitational waves, to obtain cross sections higher than calculated. However, in this case, the agreement we have found for the small signals between experiment and calculation using Eq. (2) requires that the breaking of the model occur rather infrequently.

2.4. Other possibilities to explain our observations could be considered, as the presence in the shower of exotic particles like, for instance, nuclearities [24]. Previous search of these particles with resonant g.w. detectors have given upper limits [9,25] not inconsistent with the present experimental data. We note that a resonant g.w. detector is able to observe particles with a mechanism different from the usual c.r. detectors.

Finally we remark that the presence of signals due to c.r. does not jeopardize a coincidence experiment with two or more g.w. detectors. Even without the use of veto systems employing c.r. detectors, the few dozen of events in a file, which includes thousand events, does not appreciably affect the number of accidental coincidences.

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