Anomalous signals due to cosmic rays observed by the bar gravitational wave detector NAUTILUS

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Abstract. Cosmic-ray showers interacting with the resonant mass gravitational wave Antenna NAUTILUS,cooled at 0.1 Kelvin, have been detected. The experimental results show large signals at a rate much greater than expected. Since August 2000 NAUTILUS is running a T=1.1 Kelvin (non superconductor Aluminum). There is an evidence at 3 standard deviation level that the rate of the large signals is dependent from the bar temperature. The rate is compatible with 0 at a bar temperature of 1.1 Kelvin.

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1. Introduction

The gravitational wave detector NAUTILUS has recently proven to be capable of recording signals due to the passage of cosmic rays [1, 2]. In the ongoing analysis of the data obtained with NAUTILUS in coincidence with cosmic ray detectors we found new interesting results.

The work initially done by Beron and Hofstander [3, 4], Strini and Tagliaferri [5] and refined calculations by several authors [6, 7, 8, 9, 10] 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 holds:

$$E = \frac{4}{9\pi}\frac{\gamma^2}{\rho L v^2}(\frac{dW}{dx})^2 f(x,\theta) \qquad (1)$$

where E is the energy of the excited vibration mode, $\frac{dW}{dx}$ is the energy loss of the particle in the bar, ρ is the density, v the sound velocity in the material, $f(x,\theta)$ is a function of the angle and position, $f(x,\theta) = 1$ for an orthogonal particle in the middle

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of the bar and γ is the Grüneisen coefficient (depending on the ratio of the material thermal expansion coefficient to the specific heat) which is commonly 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 [11], using a small Aluminum cylinder and an electron beam. We notice that the gravitational wave 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 gravitational wave detector NAUTILUS [12], operating at the INFN Frascati Laboratory (described elsewhere at this conference), consists of an Aluminum 2300-kg bar cooled at 0.1 Kelvin, below the superconducting transition temperature [13] of 0.92 K.

NAUTILUS is equipped with a cosmic ray detector system consisting of seven layers of streamer tubes for a total of 116 counters [14]. 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 number of particles. The detector is able to measure particle density up to $5000\frac{particles}{m^2}$ without large saturation effects. and it gives a rate of showers in good agreement with the expected number [14, 15].

2. The normal low amplitude events

The rate of events due to cosmic ray in the NAUTILUS Antenna has been calculated using the GEANT package, developed at CERN, to simulate NAUTILUS. The muons and the electromagnetic component of the extensive air showers (EAS) was simulated using data measured at sea level. We have used the CORSIKA[16] Montecarlo, as input to GEANT, to simulate the effect of the hadrons produced by the cosmic ray interactions in the atmosphere. The results are in the table 1.

Energy(K)	Muons	Ext Air Showers	Hadrons	Total
10^{-5}	12.7	50	24.2	87
10^{-4}	1.2	7	3	11.2
10^{-3}	0.18	0.8	0.33	1.3
10^{-2}	0.002	0.1	0.05	0.15

Table 1. Calculated rate (events/day) due to cosmic rays in NAUTILUS

There is a quite large uncertainty in the calculation of the rate of the high energy events. This is due to uncertainties in the cosmic ray compasition and uncertainties in the models of hadronic interactions at high energies (see later).

Since the expected signal amplitude is quite small, in our first [1] search for signals due to cosmic rays we have done an analysis using a zero threshold method; this means that we have done a search adding the Nautilus signals with a time offset given from the cosmic ray events, selected with a cut on the particle density bigger than 600 particles/m^2. The conclusion of this work was that the amplitude of the detected signal was in rough agreement with the calculations. Later we have seen a few events having very large amplitude in the NAUTILUS , so we have started a search of coincidences between the cosmic ray detector and NAUTILUS.

3. Search for coincidences

In the present data analysis we consider NAUTILUS 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. We have searched for coincidences in 3 different periods: September-December 1998, February-July 2000, August 2000-August 2001. In the first 2 periods Nautlius was cooled at 0.1 Kelvin; in the last period NAUTILUS was cooled at 1.1 Kelvin and therefore the Aluminum was not superconductor.

We have determined the number of coincidences, using a time window of 0.5 s, as a function of the particle density of the cosmic ray events; the corresponding background of accidental coincidences is estimated by performing shifts of the NAUTILUS event times. The result is given in fig.1.

Clear coincidence excess above background is found, when the showers have particle density large enough to give a signal in the bar. There are eighteen coincidences for the down particle density greater than 300 $\frac{particles}{m^2}$ while the expected number of accidentals is $n = 2.1$. For a particle density greater than 600 $\frac{particles}{m^2}$ the coincidences reduce to twelve, with n=0.78.

We have an unexpected extremely large NAUTILUS event in coincidence with a cosmic ray event, with energy E=57.89 Kelvin. The particle density of the cosmic ray. detector is the largest ones in this data set $(3600\frac{particles}{m^2})$. The time of the NAUTILUS event is obtained with good accuracy from the data, given the very large value of SNR=15860. The time difference between the NAUTILUS event and the cosmic ray event is 6 ms within the experimental error of the Nautilus event, of the order of 10 msec (at present our time accuracy for the NAUTILUS apparatus has been improved). The good agreement between the two times excludes the possibilty that the large amplitude signals are due to electrical noise on the SQUID. Using eq. (1) we find that the largest NAUTILUS event requires that W=87 TeV of energy be released by the shower to the bar. The 57.89 Kelvin value should be compared to the value obtained using the down particle density under the hypothesis of electromagnetic shower. In the previous work [1], finalized to the study of small signals, we have found that this energy is given by $E = \Lambda^2\ 4.7\ 10^{-10}\ Kelvin$ 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. 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, we find that the electromagnetic showers account for the energy observations within a factor of three. For the previous result [1] the energy of the small signals is correlated with the cosmic ray particle density. Instead no correlation with the lower particle density is found for the eighteen large signals. This is shown in fig.2, and it 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 cosmic ray showers. In one family the signals can be interpreted as due to the electromagnetic component of the showers, in the other family the electromagnetic component of the shower do not justify the amplitude or the rate of the observed signals.

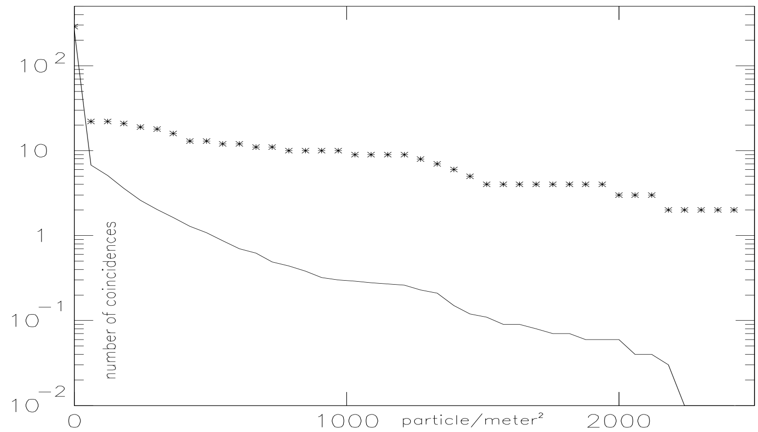

Figure 1. Coincidences between NAUTILUS and the cosmic ray detector for the data set September - December 1998. The asterisks show the integral number of observed coincidences versus the particle density observed by the cosmic ray counters located under the NAUTILUS cryostat. The continuous line shows the estimated number of accidental coincidences.

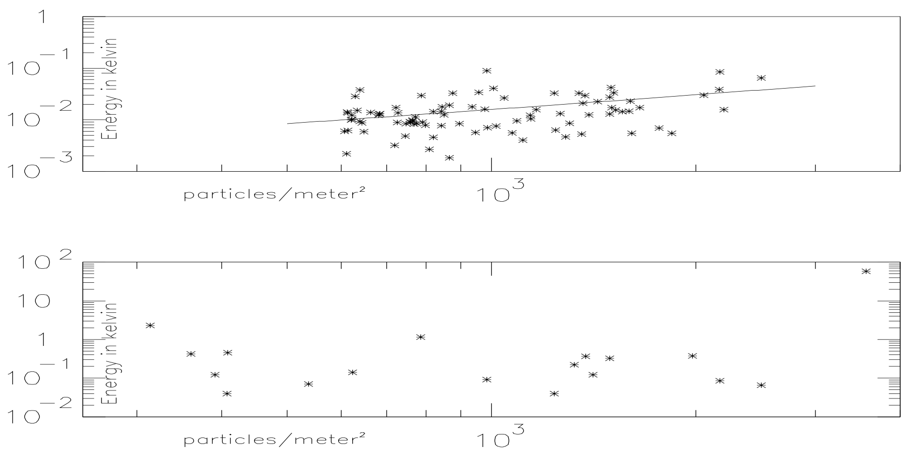

Figure 2. Correlation between the NAUTILUS signals and the cosmic ray particle density. The upper graph shows the correlation of the NAUTILUS energy at zero delay (respect to the cosmic ray events) versus the corresponding cosmic ray lower particle density, for the 92 data points considered in the previous analysis. The correlation coefficient is 0.30, with a probability to be accidental of less than 1%. Instead the lower plot shows no correlation between the energy of the NAUTILUS coincident events analyzed in this paper and the corresponding cosmic ray particle density. The data set is August-December 1998.

4. Possibilities to explain the high energy events

To explain the high energy events we have considered the presence of hadrons inside the electromagnetic shower. The energy lost in the bar due to a single hadron could be quite large. So in the case of hadrons arriving together with the electromagnetic

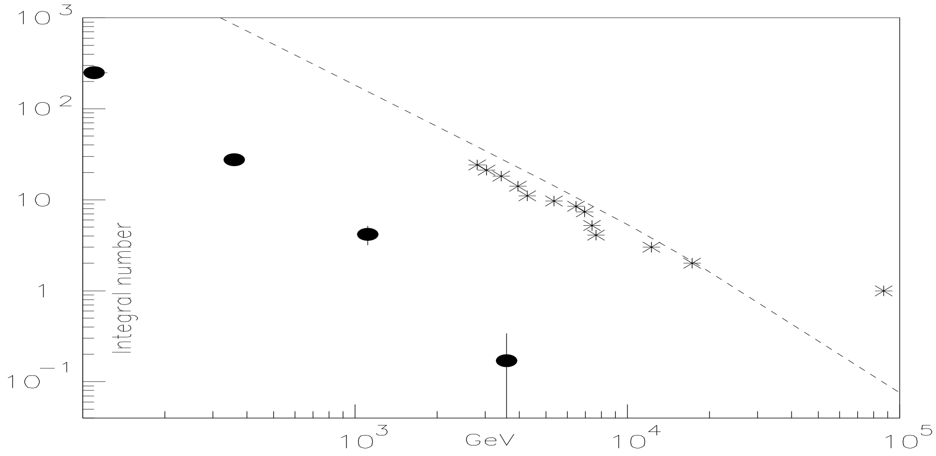

Figure 3. Comparison between calculations and measurements. The asterisks indicate the integrated number of coincident events versus the energy delivered by the cosmic ray to the bar, expressed in GeV units, to be compared with the points having error bars, which give the number of events due to hadrons, 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. See text.

component, the particle density is not related to the energy in the bar. However the rate calculated in table 1 appear to disagree with our observation by more than an order of magnitude. In figure 3 the calculated numbers are compared with the integrated number of coincidences versus the NAUTILUS event energy. Using eq. (1) we can express the integral number in terms of the energy delivered to the NAUTILUS bar by the cosmic rays.

In this figure we also report recent measurements [17] 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. 3 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.3. 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, but we also notice a large disagreement between predicted and observed rates for all other events.

In conslusion our observations exceed the expectation for hadronic showers by one or two orders of magnitude.

Other possibilities to explain our observations must be considered, as anomalous composition of cosmic rays (the observed showers might include other particles, like nuclearites [8, 19, 20] or Q-balls [21]).

We must also consider the possibility that formula (1) does not always apply, either because the Grüneisen coefficient might be larger at the temperature of NAUTILUS when the Aluminum is superconductor and the specific heat approaches rapidly zero, or because the impact of a particle could trigger non-elastic

Data	Bar Temper.	Days	Events	Accidentals	Rate(ev/day)
Sept-Dec 1998	0.1	83.4	18	2	0.19 ± 0.051
Feb-Jul 2000	0.1	31.8	13	2.3	0.33 ± 0.11
Total T=0.1 K	0.1	115.2	31	4.3	0.23 ± 0.048
Aug 2000 Aug 2001	1.1	65.7	6	3.4	0.04 ± 0.04

Table 2. Coincidences Cosmic Rays - Nautilus for superconductor and not superconductor Alluminum

audiofrequency vibrational modes with a much larger energy release. This has been already suggested [18] for the case of the interaction with gravitational waves, to explain cross-sections possibility higher than calculated. However, in this case, the agreement we have found for the small signals between experiment and calculation using eq. (1) requires that the breaking of the model occur rather infrequently.

The favorite hypothesis is currently the one related to an anomalous behavior of the superconductor Aluminum. In fact since August 2000 NAUTLUS is running at a temperature higher than the critical temperature for Aluminum. The result of the coincidence analysis for the overall NAUTILUS data, is shown in table 2. In order to have a direct comparison the event selection is very similar to the one for the 1998 data (noise temperature less than 10 mKelvin, signal noise ratio bigger than 19.5, particle density bigger than $300\frac{particles}{m^2}$). From this table there is an evidence at about 3 σ level that the rate is related at the Aluminum temperature. This support the hypothesis that equation (1) for a fraction of the cosmic ray events does not apply to the superconductor Aluminum.

The reason for this possible anomalous behavior of superconductor aluminum is under investigation: we have proposed a dedicated experiment to check equation (1) at lowe temperatures using an electron particle beam hitting a superconductor alluminum bar.

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