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ScienceDirect
Nuclear Physics B (Proc. Suppl.) 190 (2009) 44–51
NUCLEAR PHYSICS B PROCEEDINGS SUPPLEMENTS
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Detection of high energy cosmic rays with the resonant gravitational wave detectors NAUTILUS and EXPLORER and comparison with the direct measurements with an aluminum superconductive bar

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The cryogenic resonant gravitational wave detectors NAUTILUS and EXPLORER, made of an aluminum alloy bar, can detect cosmic ray showers. At temperatures above 1 K, when the material is in the normal conducting state, the measured signals are in good agreement with the values expected based on the cosmic rays data and on the thermo-acoustic model. When NAUTILUS was operated at the temperature of 0.14 K, in superconductive state, large signals produced by cosmic ray interactions, more energetic than expected, were recorded. The NAUTILUS data in this case are in agreement with the measurements done by a dedicated experiment on a particle beam. The largest event detected up to now has an energy in the first longitudinal mode of $\sim$ 670 K corresponding to $\sim$ 360 TeV in the bar.

1. Introduction

Cosmic ray showers can excite mechanical vibrations in a metallic cylinder at its resonance frequencies and can provide an accidental background for experiments searching gravitational waves (gw): this possibility was suggested many years ago and a first search, ending with a null result, was carried out with room temperature Weber type resonant bar detectors [1].

More recently, the cryogenic resonant gw detector NAUTILUS has been equipped with shower detectors and the interaction of cosmic ray with the antenna has been studied in detail.

The first detection of cosmic ray signals in a gw detector took place in 1998 in NAUTILUS. During this run many events of very large amplitude were detected. This unexpected result suggested in 2002 the construction of a cosmic ray detector for the EXPLORER detector and a measurement with a dedicated apparatus of the response of an aluminum bar at low temperatures.

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2. The thermo-acoustic model and its experimental validation with particle beams

The interaction of energetic charged particles with a normal mode of an extended elastic cylinder has been extensively studied over the years, both on the theoretical and on the experimental aspect.

The first experiments aiming to detect mechanical oscillations in metallic targets due to impinging elementary particles were carried out by Beron and Hofstander as early as in 1969 [2,3]. A few years later, Strini et al. [4] carried out an experiment with a small metallic cylinder and measured the cylinder oscillations. The authors compared the data against the TAM (Thermo Acoustic Model) in which the longitudinal vibrations are originated from the local thermal expansion caused by the warming up due to the energy lost by the particles crossing the material. In particular, the vibration amplitude is directly proportional to the ratio of two thermophysical parameters of the material, namely the thermal expansion coefficient and the specific heat at constant volume. The ratio of these two quantities appears in the definition of the Grüneisen parameter γ.

0920-5632/$ – see front matter
doi:10.1016/j.nuclphysbps.2009.03.067

It turns out that while the two thermophysical parameters vary with temperature, γ practically does not, provided the temperature is above the material superconducting (s) state critical temperature.

Detailed calculations, successively refined by several authors [5,6,9,7,8] agree in predicting, for the excitation energy E of the fundamental vibrational mode of an aluminum cylindrical bar, the following equation:

$$E = \frac{4}{9\pi}\frac{\gamma^2}{\rho L v^2}(\frac{dW}{dx})^2 \times \\ \times [sin(\frac{\pi z_o}{L})\frac{sin[(\pi l_o cos(\theta_o)/2L]}{\pi R cos(\theta_o)/L}]^2 \quad (1)$$

where L is the bar length, R the bar radius, l_o the length of the particle track inside the bar, z_o the distance of the track mid point from one end of the bar, θ_o the angle between the particle track and the axis of the bar, $\frac{dW}{dx}$ the energy loss of the particle in the bar, ρ the density, v the longitudinal sound velocity in the material. This relation is valid for the material normal-conducting (n) state and some authors (see ref. [5,6]) have extended the model to a super-conducting (s) resonator, according to a scenario in which the vibration amplitude is due to two pressure sources, one due to $s-n$ transitions in small regions centered around the interacting particle tracks and the other due to thermal effects in these regions now in the n state. It is important to note, at this point, that a gw bar antenna, used as particle detector, has characteristics very different from the usual particle detectors which are sensitive only to ionization losses [9][10]: indeed an acoustic resonator can be seen as a zero threshold calorimeter, sensitive to a vast range of energy loss processes.

As anticipated in the introduction, the first detection of signals in a gw detector output due to cosmic ray events, took place in 1998. The NAUTILUS detector, a bar made of the aluminum alloy Al 5056 was operated by the ROG collaboration at a thermodynamic temperature $T = 0.14$ K [11], i.e. below the s transition temperature $T_c \simeq 0.9K$. During this run, many events of unexpectedly large amplitude were detected. This result suggested an anomaly either in the model or in the cosmic ray interactions[12]. However the observation was not confirmed in the 2001 run with NAUTILUS at $T = 1.5$ K [13] and therefore we made the hypothesis that the unexpected behavior be due to the superconducting state of the material. An extended paper on this argument has been recently published by the ROG group[14].

An experiment (RAP) [15] was then planned at the INFN Frascati National Laboratory to study the vibration amplitude of a small Al 5056 bar caused by the hits of a 510 MeV electron beam. The experiment was also motivated by the lack of complete knowledge of the thermophysical parameters of the alloy Al 5056 at low and ultra-low temperatures.

3. The RAP experiment

The RAP (Rivelazione Acustica di Particelle) experiment has been fully described in Ref. [15]. Here we briey recall that the test mass is a cylindrical bar (R = 0.091 m, L = 0.5 m, M = 34.1 kg made of Al5056, the same aluminum alloy) used for NAUTILUS. The bar hangs from the cryostat top by means of a multi-stage suspension system. The frequency of the bar fundamental longitudinal mode of oscillation is f0 = 5413.6Hz below $T = 4K$.

The cryostat is equipped with a continuous flow ^{3}He $-$ ^{4}He dilution refrigerator, operated in ^{3}He evaporation mode, allowing the bar cooling down to $T \sim 0.5$ K. Temperatures are measured inside the cryostat by 10 thermometers controlled by a multi-channel resistance bridge and, in particular, a calibrated RuO_2 resistor detects the temperature of one of the bar end faces. Two piezoelectric ceramics (Pz), electrically connected in parallel, are inserted in a slot cut in the position opposite to the bar suspension point and are squeezed when the bar shrinks. In this Pz arrangement the strain measured at the bar center is proportional to the displacement of the bar end faces.
BTF delivers to the bar single pulses of ~ 10 ns duration, containing N_e electrons of 510 ± 2 MeV energy. N_e ranges from about 5×10^7 to 10^9 and is measured with an accuracy of $\sim 3\%$ (for

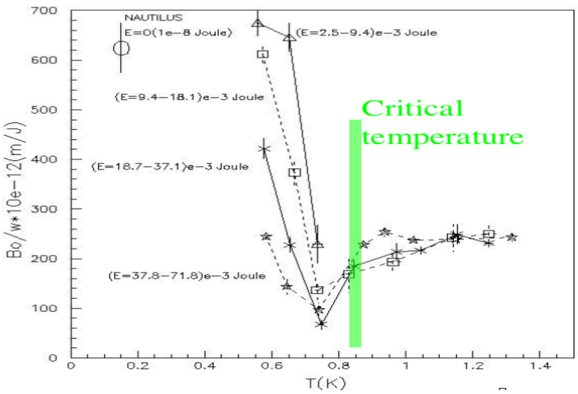

Figure 1. RAP results : the amplitude of the first longitudinal mode normalized to the electron beam absorbed energy as function of the temperature T and for different ranges of the absorbed energy. This ratio is a constant for normal conducting aluminum but has a complicated behavior for super conducting aluminum.

$N_e > 5 \times 10^8$) by an integrating current transformer placed close to the beam exit point. A Geant based Montercalo estimates an average energy lost $< \Delta E > \pm \sigma_{\Delta E} = 195.2 \pm 70.6$ MeV for a 512 MeV electron interacting in the bar and, consequently, the total energy loss per beam pulse is given by $W = N_e < \Delta E >$, $\sigma_W = \sqrt{N_e}\ \sigma_{\Delta E}$.

The full set of the RAP amplitudes of the first longitudinal oscillation mode (AFL) normalized to the energy deposited per beam pulse (W) in the explored temperature interval is shown in Fig. 1. As T decreases, the normalized AFL measured values are attenuated down to a minimum located at about 0.7 K and then increase well above the normalized AFL measured value in the n state. The increase of AFL explains the effects in the cosmic ray observations made by NAUTILUS, when operated at $T = 0.14$ K, as due to the conducting state of the material. Furthermore, AFL does not linearly depend on W at fixed T, contrary to what has been observed [16] in pure Nb in the s state. This means that the linear models in ref. [5,6]), can not fully explain the data. However is important to note that for $E \leq 1$ mJ and for $T \leq 0.5K$ the RAP measurement agrees with the Nautilus data in the s state at $T = 0.14$K.

4. The cosmic rays detectors of NAUTILUS and EXPLORER, and their expected rates

The gw detector NAUTILUS[17] is located in Frascati (Italy) National Laboratories of INFN, at about 200 meters above sea level. It is equipped with a cosmic ray detection telescope made of seven layers of gas detectors (streamer tubes) for a total of 116 counters [18]. Three superimposed layers, each with an area of 36 m^2, are located above the cryostat. Four superimposed layers are below the cryostat, each with area of 16.5 m^2. The signal from each counter is digitized to measure the charge that is proportional to the number of particles. The detector is capable of measuring particle densities up to 1000 $\frac{particles}{m^2}$ without large saturation effects. During normal runs only showers are detected, with a typical threshold of the order of 2 $\frac{particles}{m^2}$ in the lower detectors.

The gw detector EXPLORER [20] is located in CERN (Geneva-CH) at about 430 meters above sea level. Scintillators counters were installed at EXPLORER in 2002, using scrap equipment recovered after the LEP shutdown. Above the cryostat there is a single layer of 11 scintillators for a total area of 9.9 m^2. Below the cryostat there are two layers of 4 counters each, with a total area of 6.3 m^2. Each scintillator is seen by two photomultipliers (56AVP). The signals from the anode and from the last dynode of each photomultiplier are digitized to measure the total charge. No large saturation effects occur in the dynodes up to particle densities of the order of $2000\frac{particles}{m^2}$. The typical trigger threshold during normal run is of the order of $5\frac{particles}{m^2}$ in the lower detectors.

In order to compare the shower particle densities measured by the scintillators and by the streamer tubes, we have installed two scintillators, equal to the ones used in the top layer of EXPLORER, above the NAUTILUS cryostat. The scintillators measured numbers of particles +20% larger than streamer tubes for showers particle densities around 400 $\frac{particles}{m^2}$.

Most of the high energy events are due to electromagnetic showers. The rate of electromagnetic air showers (EAS) is computed starting from the empirical relation due to G. Cocconi [21].

This relation holds at sea level and in absence of absorbing material. The NAUTILUS antenna is located inside a building with a very small amount of matter in the roof, while EXPLORER is in a normal building with concrete roof. Concrete has 50 MeV critical energy, to be compared to a critical energy 88 MeV for air; therefore we expect in the EXPLORER detector an increase of the electromagnetic showers particle density due to the different critical energies and to its above sea level higher location.

The NAUTILUS data of the detector above the cryostat are in agreement with the prediction of [21] within the 25% systematic error given by the particle density measurement. There are differences between NAUTILUS and EXPLORER and between detectors over and under the cryostats due to several, already mentioned effects: the differences in altitude of the experimental locations (230 m), the presence of a concrete roof in the EXPLORER building and the materials in the cryostats.

The signal expected in a gw detector like NAUTILUS, a bar 3 m in length and 0.6 m diameter, as a consequence of the interaction of a particle releasing an energy W (in GeV units) is, according to relation (1)[11–13] :

$$E \sim \frac{7.64}{2} \cdot 10^{-9} W^2 \alpha^2 \qquad [K[\tag{2}$$

where the bar oscillation energy E is expressed, as usual in the antenna jargon, in kelvin units ($1K = 1.38 \cdot 10^{-23} J$), the numerical constant is the value computed using the linear expansion coefficient and the specific heat of pure aluminum at 4 K and α takes, as described in the previous section, either value $\alpha_n = 1.15$ above the s transition temperature or $\alpha_s = 3.7$ for superconductive Al 5056. The constant $7.64 \cdot 10^{-9}$ applies if the energy is released in the bar center. If the energy is uniformly distributed along the bar, as in the case of EAS showers, this value is reduced by a factor 2.

The cosmic ray event rate in NAUTILUS has been evaluated considering three different event categories: pure electromagnetic showers, showers produced by muons and showers produced by hadrons in the bar. We use Eq.2 with the correction $\alpha_n = 1.15$ for the response of an aluminum Al 5056 bar at T=4 K.

The rate of the EAS and the energy deposited by an EAS has been computed starting from the empirical rate [21] and Eq. 2 with the following assumptions:

1) No particle absorbed (all particles go through the bar): indeed the radiation length in the bar is small compared to the total radiation length in the atmosphere.

2) The energy loss for a single particle is computed assuming ionization energy losses for electrons having the aluminum critical energy.

3) We used the showers angular distribution as reported in[22].

4) We neglected the contribution of hadrons that could be present in the core of the showers.

Under the previous assumptions and using the density Λ of secondaries we obtain [11–13]:

$$E = \Lambda^2 \ 4.7 \ 10^{-10} \alpha^2 \qquad [K[\tag{3}$$

The production of the showers due to muon and hadrons was computed using the GEANT package[25], developed at CERN, to simulate NAUTILUS and the CORSIKA[23] Montecarlo, as input to GEANT, to simulate the effect of the hadrons produced by the cosmic ray interactions in the atmosphere, assuming a cosmic ray "light" composition. The Montecarlo simulation reflects 1 year of data taking.

The results are shown in Table 1.

The energy in the first longitudinal mode E (first column of Table 1) is proportional to the square of the absorbed energy W.

There is quite a large uncertainty in the estimation of the high energy event rate. This is due to uncertainties both in the cosmic ray composition and in the models of hadronic interactions at high energies.

Comparing the rates of the EXPLORER and NAUTILUS lower detectors we have estimated

E Vibrational (K)	W Deposited (GeV)	Total (events/day)
$\geq 10^{-5}$	≥ 44.5	107
$\geq 10^{-4}$	≥ 141	14.5
$\geq 10^{-3}$	≥ 445	1.6
$\geq 10^{-2}$	≥ 1410	0.19
$\geq 10^{-1}$	≥ 4450	0.03

Table 1
Estimated rate (events/day) of antenna excitations due to cosmic rays in NAUTILUS as a function of the vibrational energy of the longitudinal fundamental mode that such events can produce. The value at $E = 0.1K$ is obtained extrapolating from the lowest energy values. The values in the second column are the energies absorbed by the bar. Vibrational and Deposited energy are correlated by Eq. 3, with the assumption of energy uniformly distributed, and $\alpha_n = 1.15$.

that EXPLORER should have an excess of events respect to NAUTILUS of a factor 2.8 for energies larger than 0.1 K. We underline that, due to the large uncertainties involved, the expected absolute rate of events producing signals in a gravitational wave bar has also a large uncertainty. These, however affect in the same manner both our antennas, so that the uncertainty on the relative rates of EXPLORER and NAUTILUS is much smaller, being only due to systematic errors in the calibration of the EAS detectors ($\sim 25\%$) and of the gravitational wave detectors ($\sim 10\%$). In the following, we shall use only the particle densities measured by the lower detectors as they are closer to the bar.

5. Antenna Signals Induced by Cosmic Rays

The ultra-cryogenic resonant-mass gravitational wave (gw) detector NAUTILUS [19] operating since 1996 at the INFN Frascati Laboratory, consists of a 3 m 2300 kg Al 5056 alloy bar. The cryostat mainly consists of seven concentric layers: three steel vessels, two thin aluminum plus three thick copper thermal shields. During the run of 1998 it was cooled at 140 mK. The quantity that is observed (the "gw antenna output") is the vibrational amplitude of its first longitudinal mode of oscillation. This is 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, with two resonant modes, whose frequencies were, in 1998 $f_- = 906.40\ Hz$ and $f_+ = 921.95\ Hz$.

The data regarding the vibrational energy of the NAUTILUS gw antenna were recorded with a sampling time of 4.54 ms and processed with the delta-matched filter [26] optimized to detect impulsive signals. In a previous paper [11] we reported the results of a search for correlations between the NAUTILUS data and the data of the EAS detector, when for the first time acoustic signals generated by EAS were measured. In a further investigation [12], we found very large NAUTILUS signals at a rate much greater than expected. Now we know that, since the bar temperature was about 0.14 K, the value $\alpha_s = 3.7$ must be used in Eq. 3 to compute the expected response.

The correlation between the small signals detected by NAUTILUS and the impinging EAS has been described in detail in [12]. The main points of this procedure are:

1. We consider stretches of the filtered NAUTILUS antenna data corresponding to EAS with density Λ , with a lower threshold $\Lambda \geq 50 \frac{particles}{m^2}$.

2. For each stretch we calculate the average energy $\bar{E}$, in a time interval $\pm 227\ ms$ around the EAS arrival time, subtracting the value due to the noise energy (T_{eff} in the antenna jargon). The time interval is chosen to take into account the expected shape of the offline filtered signal.

3. With this averaging procedure we avoid the problem of taking either a maximum or a minimum value, which may be due to noise and, when due to signals, might not be exactly in phase among the various stretches. By doing so we get average values $\bar{E}$. In order to convert the value $\bar{E}$ into the energy at the maximum E_{exp}, we multiply

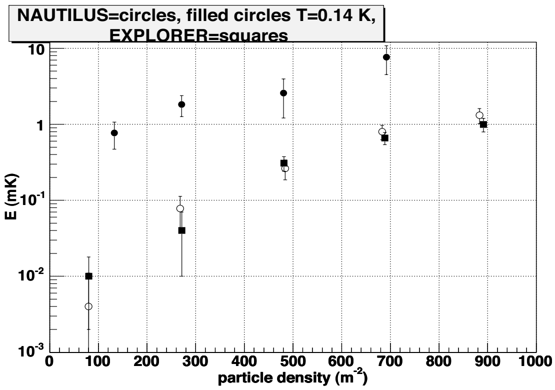

Figure 2. Averages of signals with energy $E_{exp} \leq 0.1\ K$, grouping data in ranges of particle density Λ. Filled circles NAUTILUS at T = 0.14 K, open circles NAUTILUS at $T = 3\ K$, filled squares EXPLORER at $T = 3\ K$. The data gathered at $T = 0.14\ K$ are almost one order of magnitude larger than those collected at $T = 3\ K$.

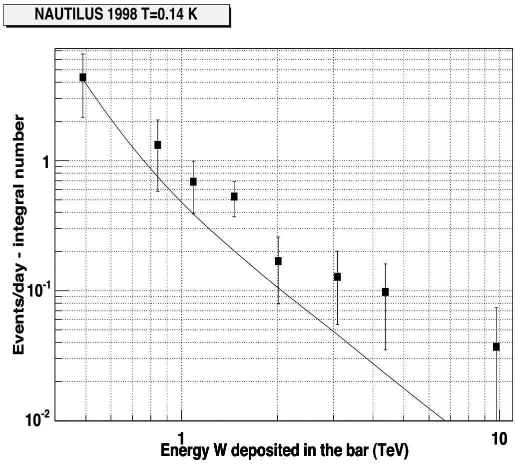

Figure 3. NAUTILUS 1998. The integral distribution of the event rate after the background unfolding, compared with the expected distribution (continuous line). The prediction is computed using the data of Table 1 and using the appropriate value $\alpha_s = 3.7$.

$\bar{E}$ by a factor 4.1, as found, with a statistical dispersion of a few percent, by numerically averaging the data sample of big events where the signal is much larger than the background, so that noise effects can be neglected.

4. We obtain several thousands stretches of filtered data in coincidence with EAS. The NAUTILUS average noise level in the 1998 run was $T_{eff} \sim\ 10\ mK$, while in the NAUTILUS 2003-2006 run the noise was $T_{eff} \sim\ 4\ mK$. In order to perform a more meaningful comparison of these data with the NAUTILUS 2003-2006 run we have considered only those stretches with $T_{eff} \leq 5\ mK$.

In order to verify the TAM model, we eliminate large signals with energy $E_{exp} \geq 100\ mK$ and we bin the remaining in five ranges according to the particle density Λ, measured by the streamer tubes under the cryostat with an upper cut to $\Lambda =\ 1000\frac{particles}{m^2}$ to avoid the saturation effects in the cosmic ray detectors.

The plot of excitation energy E_{exp} vs particle density Λ is shown in Fig.2. In this figure we show both the measurements with NAUTILUS at 140mK and 2.6K, as well as EXPLORER at a temperature of about 3 K (see discussion in the following sections). We clearly see a difference of almost an order of magnitude between the measurements taken with aluminum in the (s) state and those in (n) conduction state.

We have also measured the rate of events producing signals in the bar. The event rate per day after the unfolding of the background distribution is shown in Fig.3. The agreement with the predictions, computed from Table 1 modified by using the correct value of α_s, appears very good (taking into account the very large uncertainties

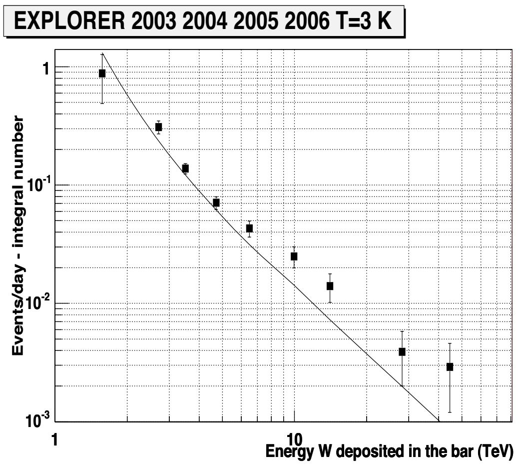

Figure 4. EXPLORER 2003-2006 : The integral distribution of the event rate after the background unfolding, as in Fig.3, compared with the expected distribution (continuous line). The prediction is computed using Table 1 multiplied by a factor 2.8 (see text).

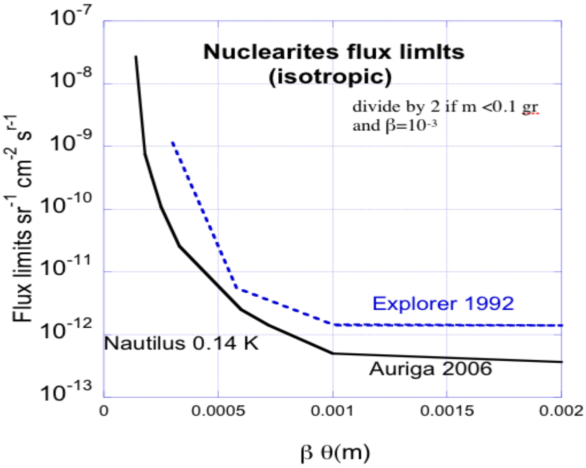

Figure 5. Nuclearites flux upper limits from gravitational wave bar detectors. Other detectors have much better sensitivities, but the detection techniques are completely different. The bar detectors are like "calorimeters" for this search

in the expected rates). A good agreement is also fount in the NAUTILUS data from 2003 to 2006, when NAUTILUS was operated in normal conducting state.

The EXPLORER detector has been in almost continuous operation at CERN since 1991, and it has undergone over the years several upgrades that progressively improved both its sensitivity and its operation duty cycle. EXPLORER has a bar similar to NAUTILUS, while the cryostat is sligthly different (three steel containers, one aluminum shield and a thin copper vessel). Data acquisition, readout and operation are very similar to NAUTILUS. The operating temperature is $T \sim 2.6\ K$. A detailed description of the apparatus and its main features (including data taking and analysis) can be found in ref [20]. In 2001 EXPLORER has been upgraded with a new read-out allowing for the first time "wide band" operation of a gw bar detector[27]. Explorer operation was suspended in August 2002 due to a cryogenic failure. We took advantage of this stop to recondition the transducer and complete installation of the cosmic ray shower detector described in section 4.

We also repeated the large event analysis and measured the rate of the large events. The results are in Figure 4, The event rate in EXPLORER is higher that in NAUTILUS. We expect a higher rate due the different altitude of Frascati and CERN and to the effect of the roof in the CERN building. The continuous line in Fig.4 shows the predictions computed from Table 1 scaled by a factor 2.8 that accounts for the difference in the EAS rates as measured by the cosmic ray detectors and discussed in section 4 .

The agreement between measurement and expectations is again quite good, considering the large uncertainties in the calculation of the predicted rates. It is important to note that acoustic gw detectors have no large signal limitations due to saturation effects and can detect very high energy events.

Indeed the largest event detected up to now has an energy in the first longitudinal mode of ~ 670 K corresponding to ~ 360 TeV in the bar. The event occurred in EXPLORER on Nov 10 2006 9:40 UT.

6. Conclusions

We have shown that the unexpected large events detected in 1998 with NAUTILUS at T=0.14 Kelvin were due to the superconductive state.

Cosmic rays noise could become an important noise in higher sensitivity detectors, namely in superconductive state, and this noise should be taken into account in possible future detectors of improved sensitivity, both acoustic [29][30] and interferometric. As shown in this paper, cosmic rays can provide an useful tool to have a continuous monitor and calibration of the acoustic gravitational wave detectors.

GW detectors when used as particles detectors are different from the usual detectors. They are similar to calorimeters with no threshold in the speed. So they could be able to detect large mass slow particles like nuclearites[10] or mirror micrometeorites[31]. An example of a such possibility is shown in Fig.5 with an updates of the limits of ref[10].

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