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## Performance and Preliminary Results of the Cosmic-Ray Detector Associated with NAUTILUS

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A cosmic-ray detector surrounds the gravitational wave antenna NAUTILUS operating at Frascati Laboratory. The expected number of events from the interactions of high-energy hadrons and muons and multihadron showers with the antenna are shown together with preliminary results of the search for coincidences between the two detectors.

### 1 Introduction

The ultracryogenic antenna NAUTILUS<sup>1</sup>, operating at Frascati INFN National Laboratory, is at present one of the most advanced detector for the detection of gravitational radiation caused by a variety of events: the coalescence of binary black holes or neutron stars, the collapse of white dwarfs or neutron stars and supernova explosions. The detector consists of a resonant Al 5056 cylindrical bar ( $L=3$  m.  $\varnothing=0.6$  m.), whose vibrational normal modes should be excited by gw bursts. While the sensitivity reached at present by this kind of detector is at the level of  $h \approx 7 \times 10^{-19}$ , corresponding to our galaxy and the local group of galaxies, the final goal of NAUTILUS is to extend the range of observable distances up to the Virgo Cluster and at gw amplitudes of the order of  $h \approx 10^{-21}$  that require a noise temperature near the quantum limit ( $T_n \approx 10^{-7}$  K). In order to clearly assign the signal detected by the antenna to gw bursts, the usual strategy is to make coincidences between similar detectors and use seismic and electromagnetic veto systems. NAUTILUS also has been equipped with a cosmic-ray veto system.

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## 2 Cosmic-Ray Detector and Montecarlo Simulation

The cosmic-ray detector is described elsewhere<sup>3</sup>. It was designed to maximize acceptance for high-energy particles and extensive air showers (EAS), taking into account the severe space constraints. It consists of seven layers of limited streamer tubes (LST's), three ( $6 \times 6 \text{ m}^2$ ) above the cryostat and four ( $6 \times 2.75 \text{ m}^2$ ) at ground level. The analogic readout of the LST wires allows measurement of the multiplicity of the particles impinging on the detector. Three triggers can be selected:

1) MUONS used for periodic calibration of the detector.

2) INTERACTING PARTICLES here we require one or more particle in the top module and more than 20 particles in the bottom module. (Rate about 2 Hz).

3) NEUTRAL PARTICLES here we require no particles in the top module and more than 20 on the bottom one.(rate about 2 Hz).

We performed a full simulation of the interaction of single hadrons and muons with the NAUTILUS bar. The energy lost by a cosmic ray is converted into a local expansion of the bar, due to the temperature increase. This effect was studied experimentally by Grassi et al.<sup>2</sup> using a 30 Mev proton beam. The relation between particle energy loss and the innovation of the vibrational energy of the bar can be found in<sup>3,4</sup>.

In simulating the effects due to hadron interaction, we used two different parametrizations for the experimental data: for hadrons of energy exceeding 300 GeV, we used the differential vertical spectrum at sea level given by Sihoan et al.<sup>5</sup>, up to a max. of 10 TeV. Below 300 GeV, we used the Arvela et al.<sup>6</sup> parametrization with a minimum energy cut of 1 GeV. A factor of  $e^{-\frac{h}{\Lambda_N}}$ , where  $h$  is the atmospheric depth crossed by the particle and  $\Lambda_N \simeq 140 \frac{\text{g}}{\text{cm}^2}$ , accounts for the hadron angular distribution. The muon interaction contribution was evaluated using, for the flux, the theoretical estimation of  $\text{Da}\bar{\nu}$ <sup>7</sup>, which is in good agreement with the available experimental data and a  $\mu^+/\mu^-$  charge ratio of 1.25. The following table gives the results on the expected number of events/day from hadrons and muons as a function of the minimum vibrational energy change detectable by the gravitational detector, expressed in kelvin. Also reported are an analytical estimation of the contribution due to EAS, as suggested by Amaldi and Pizzella<sup>8</sup>, and an estimation of multiple hadron events based on the Arvela et al. Monte Carlo results.

Mode energy threshold (K)	events/day (muons)	events/day (hadrons)	events/day (EAS)	events/day (multi had.)	events/day (total)
$10^{-7}$	1540	3310	137	— — —	4987
$10^{-6}$	155	463	35	— — —	653
$10^{-5}$	12.7	55.7	7	5.5	80.9
$10^{-4}$	1.2	6.2	1.3	3.7	12.4
$10^{-3}$	0.18	0.56	0.24	1.2	2.18
$10^{-2}$	0.002	0.035	0.04	0.1	0.18

Note that our evaluation at high energy is based on measurements affected by large errors.

### 3 Detector Performance and Preliminary Results

The NAUTILUS antenna is active at the Frascati Laboratory; a record thermodynamic temperature of 95 mK has been reached and many efforts have been made to search for any source of excess noise, mainly nonstationary, so as to operate the antenna at a stable noise temperature. Meanwhile, data have been collected from the cosmic-ray detector. When we compare our measured EAS multiplicity rate with the best fit<sup>9</sup> to the results of some sea-level cosmic-ray detectors, the agreement is very good; only a small discrepancy is present in the low range of particle density due to the trigger request of at least 20 particles in the bottom module; while at high density the data are affected by the ADC saturation effect.

Since the basic problem of gravitational-wave research is the detection of short bursts and extremely small signals due to gravitational collapses embedded in an ideally flat noise spectrum, different filtering procedures are applied to the antenna data. However, details about the data processing procedures can be found in<sup>10,11</sup>. Here, we report preliminary results of the search for coincidences between the gravitational and cosmic-ray detectors based on the analysis of 129 hours of stable conditions and good antenna sensitivity. A threshold of 100 mK was applied to the useful gravitational data sampled at a rate of 3.44 Hz and processed following the the so-called "slow" procedure<sup>11,12</sup>. We used a  $\pm 1$  s coincidence time window and considered two samples of cosmic-ray events: a) EAS selected with the requirement of more than  $50 \frac{\text{particles}}{\text{m}^2}$  on the top module; b) single interacting particles with the requirement of zero or one particle in the top module and more than 500 particles in the bottom module. For a) we found no coincidences with an expected number of accidentals  $\langle n \rangle_{acc} = 2.4$

corresponding to an upper limit at 90% CL of 0.7 coincidences per day; for b) 11 coincidences with  $\langle n \rangle_{acc}=8.2$  corresponding to an upper limit at 90% CL of 1.6 coincidences per day. The  $\langle n \rangle_{acc}$  is obtained experimentally by random changes of the occurrence times of the cosmic-ray events.

The results obtained in coincidence with NAUTILUS are the first evaluating the effects due to cosmic rays (hadrons, muons and EAS) on a cryogenic antenna at sea level. The past experiments was sensible to EAS only.

The experiment of Ezrow et al<sup>13</sup> with a room temperature bar has given an upper limit for EAS of 1 ev/day at 90% confidence level with an antenna threshold of the order of 200 Kelvin. The Stanford cryogenic antenna<sup>14</sup> was under a 1-m concrete shield with an attenuation factor for EAS of about 20. The upper limit obtained scaling for a factor 20 the original Stanford limit is 4.2 events/day at 90% confidence level with an antenna threshold of the order of 0.25 Kelvin. So our preliminary results for EAS (with a very small data sample) are already better than the existing published limits.

From the Montecarlo simulation, at 100 mK, we expect of the order of  $10^{-2} \frac{events}{day}$  to give detectable signals in the antenna. Hence, higher statistics or better sensitivity are required in order to reach a significant excess of coincidences.

#### 4 Conclusions

The cosmic-ray veto system has demonstrated good performance, well in agreement with the physics requirements of the experiment and with the simulation results. A preliminary search for coincidences has been made. At a threshold of 100 mK no statistical excess for extensive-air-showers and hadron-like events has been found in a 129 hours interval. The analysis of more data is still in progress.

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