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Interaction of High Energy Muons and Hadrons with a Large Aluminium Spherical Resonant Detector

G. Mazzitelli
INFN – Laboratori Nazionali di Frascati, P.O.Box 13, I–00044 Frascati, Italy

M.A. Papa
Università di Roma II, INFN – Sezione Roma II, Tor Vergata, Via Orazio Raimomdo, I–00173 Roma, Italy

Abstract

The aim of this work is to evaluate the effects of high energy hadrons and muons on a large spherical aluminum detector of 3 m of diameter. The interaction of single hadrons and muons has been simulated and the average counting rate has been calculated. Analytical estimation of Extensive Air Shower and Multihadron Shower effect is also reported.

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1 Introduction

The achieved spectral amplitude sensitivity[1] $\leq \frac{10^{-21}}{\sqrt{Hz}}$ makes resonant detectors the main tools in the detection of gravitational waves nowdays. Next generation resonant detectors, more sensitive and less "direction and polarization-state" dependent, are now being studied and, among these, large spherical antennas seem to be the favoured candidate.
In order to asses the real sensitivity performance of a, say, 3m sphere detector, it is necessary to consider the effects of the interaction of high energy cosmic rays with such detector. In fact, this question was already investigated for standard bars[2] and lead to the conclusion it would be necessary, already for NAUTILUS[3] class antennas, to be placed in underground laboratories screaned against cosmic rays.
A cosmic ray crossing the sphere causes, along its path in the medium, a local overheating phenomenon which can be related to a local overpressure. Such perturbations propagate acoustically to all the detector and the net effect on each mode can be estimated. The relation between the particle energy loss dE along a path dX and the energy E_n obseved by the $n-th$ vibrational mode[4] is:

$$E_n = \frac{1}{2}\frac{l_0^2}{V}\frac{G_n^2}{\rho v^2}\gamma^2\left(\frac{dE}{dX}\right)^2.$$

where l_0 is the total track length of the cosmic ray in the detector and V its the volume; γ, ρ and v are, respectively, Gruneisen's dimensionless parameter, the mass density and the speed of sound in the medium. The "form factor"

$$G_n = \frac{v}{\omega_n}\frac{1}{l_0}\int_{l_0} div_{\perp} u_n dl$$

is related to the geometry of the detector through the eigenmode u_n, and it is expected to be of order unity for a large number of modes and paths[4]. So, if we take $G_n = 1$ and assume that $\frac{dE}{dX}$ is the same along all the path, the relation between the energy released by the cosmic ray (ΔE) and the vibrational energy in the mode (E_n) can be easily estimated:

$$E_n\,(Kelvin) = 2.1\times 10^{-9}\,(\Delta E\,(GeV))^2$$

To estimate the energy released by particles in the detector, we have performed a Monte Carlo simulation based on the GEANT package improved with single hadron and muon cosmic rays generator. The counting rate as a function of the resonant detector sensitivity has been evaluated. An analytical estimation of the event rate due to Extensive Air Shower, as well as Multihadron Shower, is also reported.

2 Single Hadrons and Muons Simulation

A full simulation of the interaction of single hadrons and muons with a spherical detector has been performed by improving the existing simulation[3] based on the GEANT3 package[5]. The simulated geometrical structure consists of a 3 m diameter aluminum sphere. The sphere center is placed 190 cm above a vacuum box, that simulates an undefined particles detector. This detector has been chosen larger then the geometrical dimension of the sphere (3 cm high, 20×20 m large) in order to compute any particle outgoing from the resonant detector.
Hadron interactions are the most important when one evaluates the expected number of detectable events as a function of the detector sensitivity. The hadron generator uses two different parametrizations for the experimental data: for hadrons with energy greater than 300 GeV, we have used the differential vertical spectrum at sea level given by Sihoan et al.[6] up to a maximum energy of 10 TeV:

$$\frac{dN}{dE} = 1 \times 10^{-10} \left(\frac{E}{300}\right)^{-2.6} \quad \frac{hadrons}{s\ cm^2\ sr\ GeV}$$

Below this energy, we have used the Arvela et al.[7] parametrization with a minimum energy cut of 1 GeV:

$$\frac{dN}{dE} = 3 \times 10^{-4}\ E^{-2.5} \quad \frac{hadrons}{s\ cm^2\ sr\ GeV}$$

A factor of $e^{-\frac{h}{\Lambda_N}}$, where h is the atmospheric depth crossed by the particle and $\Lambda_N \simeq 140\ \frac{g}{cm^2}$, accounts for the hadron angular distribution. A 1.25 factor was also introduced, as suggested by Cowan et at.[8], to evaluate the hadron growth rate due to neutrons. The muon interaction contribution has been evaluated using, for the flux, the theoretical estimation of Dar[9] which

is in good agreement with the available experimental data and a μ^+/μ^- charge ratio of 1.25.
Particle interaction and tracking in the detector has been performed using the GEANT 3.15 package, including the GEISHA simulator for the interaction of the hadrons in a shower. We have used the default energy cut values for secondary particles with the only exception being the kinetic energy cut for delta rays set to 100 KeV. The appropriate corrections are applied to the particle fluxes to account for zenith angle distribution and the Laboratori Nazionali di Frascati location.

3 Analytical Estimation

We would like to point out that Extensive Air Shower (EAS) (as well as Multihadron or Multimuon showers) are events of particular interest because of the squared dependence of the mode energy to the energy released.
The EAS are mainly composed by electrons and photons. At sea level we can assume an average energy of 100 MeV that is the critical energy in air[2]. The integral density of charged particles is [10]:

$$H(>\Delta) = 0.124\ \Delta^{-1.46}\ sec^{-1}$$

assuming that the photon density is three times greater then the electron density, and that all the energy of the particles is released in the detector, we have obtained the result reported in Table 1.

To evaluate the effect due to Multihadron shower we used the result of the Monte Carlo simulation performed by Arvela et al.[7] where the flux of hadron shower is estimated as a function of the detector surface. Assuming a detector surface of 7 m^2, the rate of one TeV hadron is roughly 8 times greater then the 10 hadron rate of the same total energy. From the simulation that we have reported in the previous paragraph it is possible to estimate the energy released by an hadron of 100 GeV (assuming the 1 TeV total energy is divided into 10 hadrons of 100 GeV). The results are reported in the Table 1.

4 Conclusions

In Table 1 we have reported the expected integral day rate of events as a function of the mode energy threshold.

Mode energy threshold (K)	events/day (muons)	events/day (hadrons)	events/day (EAS)	events/day (multi had.)	events/day (total)
10^{-7}	126150	63770	2870	—	192800
10^{-6}	10870	8200	535	—	19600
10^{-5}	940	1110	100	22	2180
10^{-4}	84	120	19	20	245
10^{-3}	10	12	4	17	43
10^{-2}	0.5	1.3	0.6	2	4.4

From our calculations, we do not expect any significant correlation, for single muons and hadrons, between the energy released in the resonant detector and the particle counted in the volume below the sphere. Thus a "simple" cosmic ray veto system in coincidence with the gravitational detector, such as the one now in operation with the NAUTILUS antenna[3], cannot be easily designed. In our simulation we did not take into account the real distribution of the energy over the five quadruple mode due to the "form factor". Moreover, we know that form factor should be of order of one and we are evaluating it in order to improve our simulation. We are planning to study the cosmic ray mode signature, if any, in order to eventually use it to distinguish the cosmic ray signal from other excitations.
The analytical estimation performed for Extensive Air Shower and Multi-hadron Shower could be affected by large errors due to the uncertainty on experimental information available on the rate of such events in the energy range of interest. Furthermore, Multimuon shower could also be events of interest and we are going to include in our simulation a full generator of shower events. Finally, the GEANT package may, in certain conditions, underestimate the real energy loss.

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