Geant4 simulation of cosmic ray particle interaction with the Mario Schenberg gravitational wave detector

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Abstract: Among the noises present in gravitational wave detectors that use the resonant mass technique stands out one from the cosmic ray interaction with the resonant mass. Therefore one of the systems coupled with the detector with the purpose to minimize the noise from cosmic ray particles is the veto system of cosmic rays, as the one installed at the gravitational detector NAUTILUS, in Italy. When the cosmic rays interact with the sphere, this interaction generates a thermal expansion of the material that composes the detector through energy deposition, making the detector normal modes vibrate, camouflaging a possible signal produced by a gravitational wave. Thus, this work aims to determine the energy deposited by particles as protons and muons in the gravitational detector Mario Schenberg, located at the IF-USP São Paulo, using the toolkit Geant4 developed by CERN.

Keywords: gravitational wave detector, cosmic ray, Geant4.

1 Introduction

The direct detection of gravitational waves is one of the main objectives of science of the XXI century. To increase the chance of this detection we need to increase the experimental apparatus detection sensitivity to measure the spacetime deformation and learn about the different noises present in these complex experiments. Among them there are those from cosmic rays in mass resonant gravitational wave detectors. These particles reach continuously our planet with an energy spectrum of up to 10^{20} eV/particle. Secondary particles produced by cosmic ray interactions reach the Earth's surface and some, such as neutrinos and muons, reach deep underground area.

The next generation of gravitational wave detectors will reach a sensitivity of h$\sim 10^{-23}$ Hz$^{-1/2}$ and thus the frequent cosmic ray events will grow to hundreds of events every day. Therefore it becomes important the study and installation of cosmic ray vetoes in gravitational wave detectors. The cosmic ray veto does not only identify the signals due to cosmic rays, but also allows the study of gravitational detector performance through acoustic signals produced by cosmic radiation, aiding the development of more accurate detection systems.

This work aims the study of cosmic ray flux in São Paulo city and the effects of this radiation on the Mario Schenberg gravitational detector. It is made a Monte Carlo simulation of the passage of cosmic radiation through the detector and the building where it is installed using the Geant4 toolkit from CERN, in order to determine the energy deposited in the gravitational wave detector and to get a better knowledge of the cosmic ray interaction with gravitational wave detectors.

2 Mario Schenberg detector

The Mario Schenberg detector has a spheroidal gravitational wave antenna, located at the USP Physics Institute in São Paulo. This antenna has diameter of 65 cm and was designed to achive a higher sensitivity than h$\sim 10^{-21}$ Hz$^{-1/2}$ at 3.2 kHz which has astrophysics importance. The sphere has a mass of 1150 kg, being twice less massive than other existing detectors, however it has more effective mass, a total of 1438 kg, involved in the gravitational wave detection and it is going to be cooled to 2 mK, reaching a very internationally competitive sensitivity [1], [2] and [3].

The sphere material is an alloy of cooper and aluminium (94%-6%) which has a high figure of merit, $Q_m > 10^7$ in 20 mK [4]. In Figure 1 it is shown the Mario Schenberg detector with its cryogenic chambers open.

The used vibration isolation system is the result of the experience of several research groups in gravitational waves in recent years. The designed system is free of resonances in the region from 3.0 to 3.4 kHz and is located inside the cryogenic chambers.

Figure 1: Mario Schenberg detector with the cryogenic chambers open.

3 Cosmic rays

Cosmic rays are stable particles and atomic nucleus which reach the Earth from our galaxy and others. They are mostly light atomic nuclei and their energy spectrum extends from some GeV to higher than 10^{20} eV [5]. The primary cosmic radiation intensity in the energy range from a few GeV up to about 100 TeV can be represented by [6]

$$I_N(E) \approx 1.8 \times 10^4 (\frac{E}{1GeV})^{-\alpha} \frac{nucleons}{m^2 s\, sr\, GeV} \quad (1)$$

where E is the energy per nucleon and α = 2.7 is the differential spectrum index of the cosmic ray flux.

This primary radiation interacts with the atmosphere nucleis producing neutral and charged secondary particles. The first interaction depends on the energy and mass of the primary particle and initiates a cascade process of secondary particle production called Extensive Air Shower (EAS). Part of the secondary cosmic radiation reaches the planet's surface. The particle energy and density in an EAS is greater in the central region of the shower, which is the region that generates more noise in the gravitational wave detector.

The cosmic rays, which reach the gravitational wave detector and can produce detectable signals in the detector, are those that, when interacting with the gravitational detector and also with the matter surrounding it, generate events which deposit a large amount of energy, $\sim$ hundreds of MeV, in the detector.

Events produced by cosmic rays which can generate an acoustic signal in the gravitational detector are:

Extensive Air Showers - there are million particles (e$\pm$, photons, $\pi\pm$ and hadrons) with relativistic speeds which reach the Earth's surface in the form of a disc (thickness of the order of meters and radius of hundreds of meters).

Muons - they are products of charged meson decay originated in the hadronic interaction in the higher atmosphere. The production of secondary photons and electrons through the interaction of muons around the sphere or in itself initiates electromagnetic showers which are largely absorbed by the sphere itself. These effects are mainly due to four different interaction processes: production of *knock-on* electrons, *bremsstrahlung*, pair production and photonuclear interaction.

Hadrons - they are mostly protons, neutrons, isolated pions and residual multi-hadrons generated from the primary hadronic interaction which can interact with the detector and the matter around it producing a hadronic cascade.

4 Hadron and muon flux in São Paulo city

Due to the difficulty in finding experiments which calculate the cosmic ray flux near and at the same altitude of São Paulo city, it was used the single hadron data from KASCADE calorimeter located at Karlsruhe, Germany, [7] to determine the hadron flux in São Paulo city. This calorimeter has been operating continuously and steadily for many years.

The hadrons have been detected with the central calorimeter of the KASCADE experiment measuring cosmic rays near sea level ([8]). This is a sampling calorimeter consisting of layers of lead, iron, concrete absorbers interspersed with nine layers of warm-liquid ionization chambers with an acceptance area of 304 m^2 ([9]). The calorimeter is surrounded by an array of stations equipped with scintillators in which the electromagnetic and muonic components of an air shower are detected. The description of the experiment can be found in [10].

The data for the flux of single hadrons from the KASCADE calorimeter is shown in Figure 2. The energy spectrum has a power-law like behaviour ($\propto E^{-\alpha}$, with $\alpha \approx$2.5).

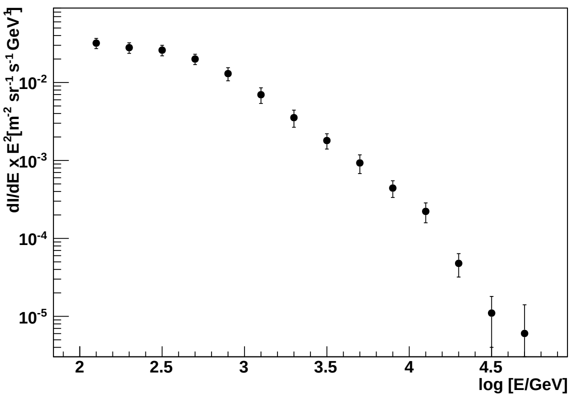

Figure 2: Single hadron spectrum: flux multiplied by the energy squared vs. single-hadron energy.

These data were used to estimate the particle flux in São Paulo city which is at an average atmospheric depth of 940 g/cm^2, therefore it was used the following equation:

$$I(x) = I_0 e^{\frac{-(\Delta x)}{\lambda}} \quad (2)$$

where I(x) is the particle flux in the interested region, I_0 is the flux in the region where the measurements were taken, Δx is the difference between the atmospheric depth of the interested region and the region where the measurements were taken and λ is the attenuation coefficient. Considering λ=110 g/cm^2 for hadrons, it was obtained the following results which are shown in Figure 3.

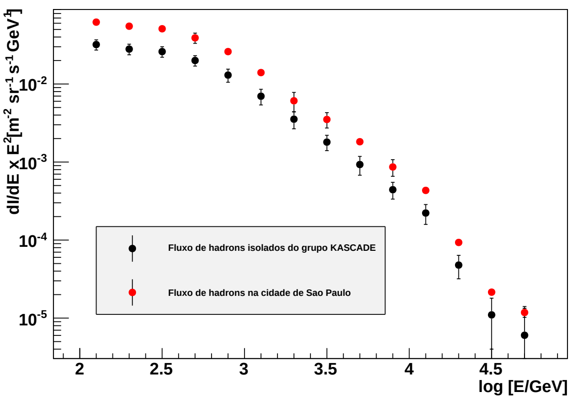

Figure 3: Particle flux in São Paulo city.

According to these energy spectra it can be seen the higher the energy the lower is the flux of particles which reaches the Earth's surface. The obtained spectrum for the São Paulo city is going to be used as an input in the Geant4 simulation which is described in the following section.

5 Geant4 simulation

The impossibility of studying the interaction of these particles with matter analitycally, due to the large amount of different particles and involved processes and phenomena, makes use of Geant4 Monte Carlo method. This software is used for the purpose of simulating the passage of particles through the detector and the building where it is located and obtain information about the interactions occured and produced particles, cross sections, mean free path, energy loss per unit lenght (dE/dX) and others.

5.1 Geometry and Materials

The Geant4 is a platform which uses object-oriented programming in C++. Based on this, it was initiated the simulation from a ready example and performed numerous code changes. These changes were made in order to build a simplified geometry of the USP building where the gravitational detector Mario Schenberg is. Among these changes there are the creation of the sphere damping apparatus, the physical interactions which occur through particle-matter interaction and determination of the energy loss (dE/dX) in the sphere per event.

The construction of the whole geometry used in the simulation was based on images of the building and figures with the exact dimensions of the structure where the sphere is (see Figures 4 and 5).

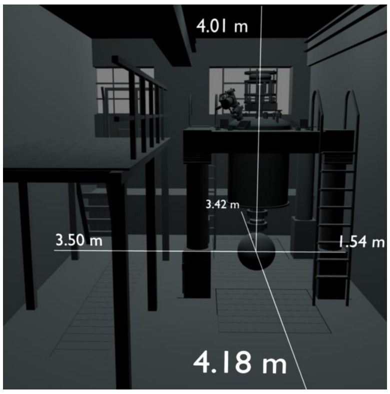

Figure 4: Internal structure of the room where the Mario Schenberg antenna is located with the detailed dimensions.

Figure 5: Mario Schenberg building at USP in São Paulo.

For each built structure it was used different materials and dimensions. The result of the construction can be seen in Figure 6.

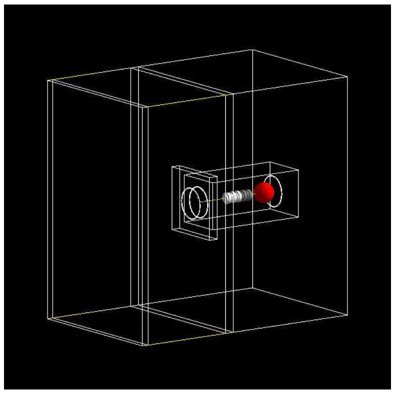

Figure 6: Rotated simulator vision.

5.2 Energy deposition in the Mario Schenberg detector

Set the characteristics of the building and the validation of the used models for the electromagnetic and hadronic interaction processes, it was initiated the simulation by inciding particles over the top surface of the building. The incidence of particles was based on the obtained energy spectrum for São Paulo city and was used the Geant4 reference class G4GeneralParticleSource (GPS) which allows to specify the spectral, spatial and angular distribution of the primary particle source. The source represents a circular beam of protons and muons with radius equal to the sphere (32.5 cm) centralized in (-4.000 -0.410 -0.975)m over the top surface of the building. The set angular distribution was focused on the sphere in order that all particles described a trajectory toward the sphere. The spectrum emitted by the source follows a power-law like behaviour, as the one obtained in São Paulo city, of y=AE$^{\alpha}$, where A is constant and E extends from 1 GeV to 1 TeV. The simulated energy spectrum of the incident particles, protons and muons, are shown below (Figures 7 and 8). It was simulated 20000 proton and muon particles interacting with the sphere and the building.

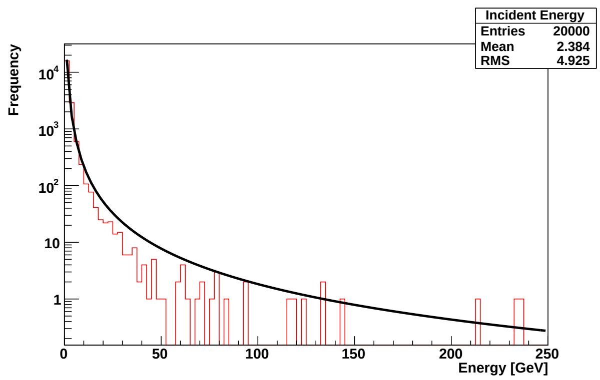

Figure 7: Simulated proton spectrum.

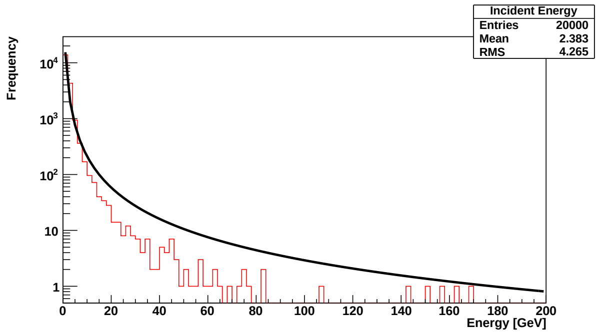

Figure 8: Simulated muon spectrum.

In order to analyze the shielding effect exerted by the building over the sphere, it was simulated the incidence of these same particles focusing directly over the sphere. Figure 9 shows the energy deposited in the sphere by protons inciding directly over the sphere and building.

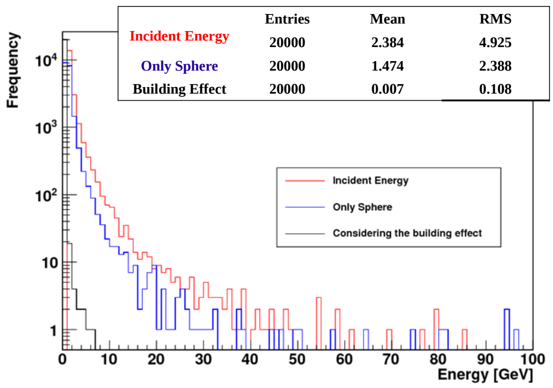

Figure 9: Simulated spectra of the deposited energy by protons inciding directly over the sphere and over the building.

In this Figure it can be seen how relevant is the shileding effect of the building over the sphere. Firstly, it is important to note that protons lose large amount of their initial energy through inelastic collisions with electrons in the outer atomic layers through ionization and excitation processes. Due to the large amount of matter that proton will have to cross to interact with the sphere, it suffers along its path numerous deflections in its trajectory. This deviation in its original trajectory occurs through small-angle multiple scattering by the nuclei of the target material. Thus, an amount of energy much lower than the initial is dissipated in the sphere. Therefore the interaction of the particles with the sphere produces a small thermal expansion of the material medium, i.e., generates a low vibration of the material medium, wherefore the noise generated in the sphere transducers will be low.

Moreover based on the average energy deposited in the sphere, it can be understood how a proton induced shower interacts with the building structure. In the spectra of Figure 9 it can be noticed a rather sharp peak in the energy range below 1 GeV, this is due to the large energy deposition in the sphere below this energy range.

Completing the simulation with protons, it was performed the simulation with muons, being the total number of muons, 20000, divided into $\mu+$ and $\mu-$. The results are shown in Figure 10 for muons inciding directly over the sphere and building.

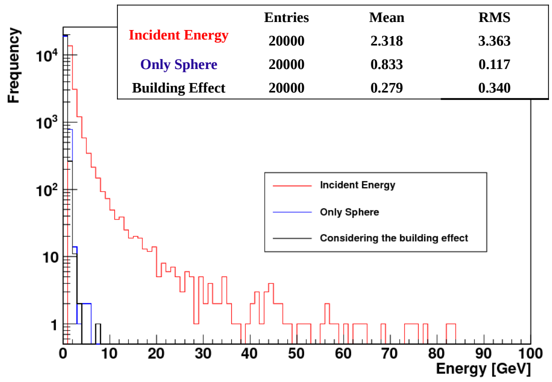

Figure 10: Simulated spectra of the deposited energy by muons inciding directly over the sphere and over the building.

According to the mean energy deposited in the sphere it can be concluded that the building shielding effect is not very significant to make the muons not interact with the sphere. The reason for this is the weak interaction of muons with matter and as they have larger mass than electrons, they describe a straigh trajectory along their path.

6 Conclusions

Through this study we better comprehend the interaction processes of protons and muons with the gravitational wave detector Mario Schenberg, the shileding effects of the building structure over the particles and how these particles behave. Moreover it is better understood the noise generated by cosmic rays in gravitational wave detector that can camouflage a possible signal produced by a gravitational wave.

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