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Muon Flux Measurements and their angular distribution with the new muon telescope at GRAPES-3 experiment

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The GRAPES-3 experiment consists of a large area (560m^2) muon telescope consisting of 3712 proportional counters of each dimension of 6m $\times$ 0.1m $\times$ 0.1m. A similar muon telescope next to the existing one is under construction. The new muon telescope is designed to have a 70% larger field of view (2.3 sr to 3.9 sr) as compared to the existing one. One of the 16 modules of the new muon telescope has been made operational. The energy threshold is 0.5 GeV for vertically incident muons. In this paper, we present our GEANT-4 simulation results of muon energy deposition and angular distributions using the new muon telescope of GRAPES-3, as well as the results of the muon module rate for incoming muons with GRAPES-3 data.

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1. Introduction

Cosmic Rays are high-energy charged particles originating from outer space and extragalactic sources. Their energy ranges from 10^8 eV to 10^{20} eV [1, 2]. The energy spectrum of Primary Cosmic Rays (PCRs) has been investigated across the energy range spanning from 10^8 eV to 10^{14} eV [3]. Traveling at high energies, cosmic rays interact and undergo deflection by interstellar radiation fields and matter. This complexity makes determining their sources incredibly challenging, and by the time they reach our solar system, they have lost all information about their origins. This emphasizes the significance of studying various parameters, such as their energy spectrum, flux, angular distributions, and chemical compositions. These parameters offer us valuable information that is essential for understanding cosmic rays and, on a fundamental level, the universe itself.

PCRs consisting mainly of protons, upon entering the Earth's atmosphere undergo interaction with charged nuclei present in the atmosphere and decay further into energetic hadrons. These inherently unstable hadrons then go through further decay. This sequence of subsequent decays is referred to as the Extensive Air Shower (EAS). One of the daughter particles of this cascade are muons. Muons travelling at relativistic speeds cover long distances to reach the Earth's surface despite their incredibly small lifetime of $\sim 2\mu$s being a direct example of the special theory of relativity. Accompanying muons, other hadronic particles, gamma rays and electrons are also produced. The atmosphere has more than 10 interaction lengths, which is sufficient for these particles to lose most of their energy by the time they reach sea level.

It has been observed that PCRs are direction dependent and come mostly from the West. The positively charged particles coming from the West, bend towards the earth, and the ones coming from East, bend away. This asymmetry is known as the East-West effect [4]. The heliospheric magnetic field also plays a role in deflecting the Galactic cosmic rays. Facing the turbulent solar winds leads to change in their intensity and energies with respect to their positions in the heliosphere. This process, known as Solar Modulation and takes part in the low energy spectrum of the radiation [5].

2. GRAPES-3 Muon Telescope

The GRAPES-3 (**G**amma **R**ay **A**stronomy at **P**eV **E**nergie**S** phase - 3) experiment is a large area (560m^2) ground based experiment, located in Ooty, Tamil Nadu, India. The experiment operates at an altitude of 2200 meters above mean sea level, with geographical co-ordinates 11.4°N latitude and 76.7°E longitude. The GRAPES-3 Muon Telescope (G3MT) investigates the muonic component of PCRs using a large array of gaseous Proportional Counters (PRC). One of the 16 modules of the new muon telescope has been made operational recently. The new muon telescope is similar to the old muon telescope but with a larger field of view (2.3 sr to 3.9 sr), 70% more than that of the old muon telescope. It has a threshold energy of 0.5 GeV $\times \sec\theta$ for muons at θ angles.

The 16 independent modules house a total of 3,776 PRCs, each module containing 4 layers of 59 PRCs. Placed on a 50 cm thick concerete slab, the bottom most PRC layer is termed as layer 0 and the topmost as layer 3. These layers are placed orthogonal to each other in order to maximise the detection of the cosmic muons. Between each layer of the PRCs, a 15 cm thick layer of concrete is placed. A concrte slab of 2 m thickness is placed above layer 3 in an inverted pyramid shape with an angle of 60° with the vertical direction. The top concrete slab is termed as the absorber. The role of this absorber is to shield other electromagnetic components and muons with less than the above mentioned threshold energy. Hadrons passing through the absorber interact with the concrete leading to a hadronic EAS depending on the hadronic energy. These hadrons leave their signature in the form of a cluster hit inside the PRC [6].

The PRCs are galavnised mild steel tubes, each having dimensions 600cm × 10cm × 10cm, containing a 600cm long Tungsten wire with a diameter of 100 microns and P10 gas (90% Argon, 10% Methane). The gas is kept at a pressure 1.09 bar and temperature 295K with a density of 1.67 kgm^{-3}. The PRC operates at 3000 V, where the the Tungsten wire acts as the anode and the PRC steel body as the cathode. A metal-to-glass hermetic seal is used on the 10 × 10 cm face of the PRC to separate the anode and the cathode [7].

3. GEANT4 Simulation of one module of the G3MT

GEANT4, **GE**ometry **AN**d **T**racking is the simulation toolkit version (v-4.10.07) [8] is used to prepare the detector geometry of the G3MT module starting with creating one PRC with the above mentioned parameters. Each of the 600cm × 10cm × 10cm PRC has a 0.23 cm thick Iron coating, within it lies the P10 gas and the Tungsten wire along the axis of the tube. The desired geometry is achieved by using G4Box and G4Tubs classes, and the materials are defined using the G4NistManager class. The geometry of one PRC can be seen in Figure 1.

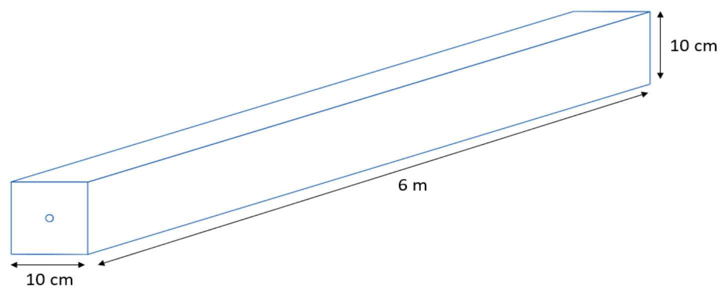

Figure 1: Geometry of one PRC; blue body represents the PRC tube and the circle represents the Tungsten wire.

The 4 layers of PRCs consisting of 59 counters each are then constructed, placed orthogonal to each other. Between each PRC layer, 15cm thick concrete layers were inserted and the 2m absorber above the PRC layers was constructed. The GEANT-4 simulation result of one new G3MT module is shown in Figure 2. The muons are then injected vertically on one of the individual PRC to study their energy deposition. The hits stored in the counters is done by defining a Scoring Volume which

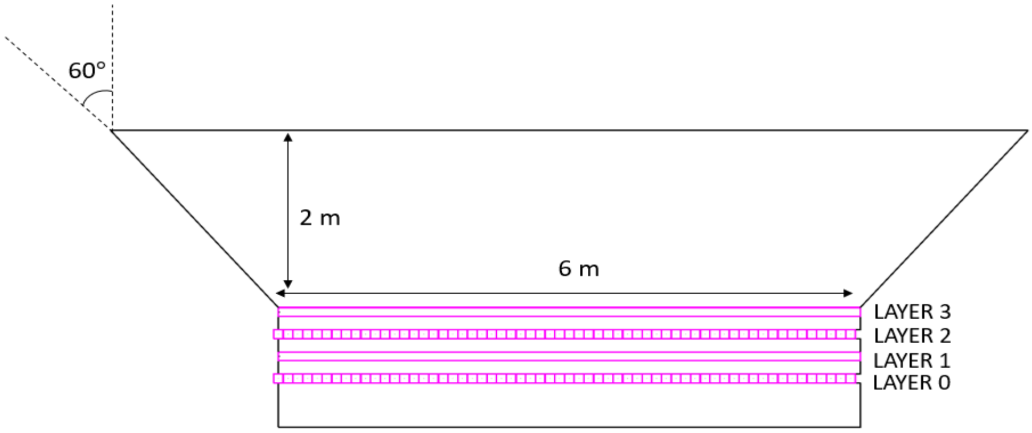

Figure 2: Reconstruction of one new muon module at GRAPES-3.

makes the detector volume sensitive, such that the information of the incident particles like their energy deposition, track length, momentum direction etc. can be measured. The relevant parameters can subsequently be extracted for the specific purpose of analysis. The energy deposition was extracted by making a user defined stepping action inherited from the class G4UserSteppingAction. Particles other than muons have also been injected on the module to study their energy deposition. These particles were defined using the G4ParticleGun class. At a height of 3m above the PRC the particle gun was positioned, while both the PRC and Particle Gun was surrounded by air using the G4NistManager class.

We have fired 100K muons, each having energy of 4 GeV on a PRC and plotted the energy deposition curve. The curve peaks at 24.35 KeV. Further, we have fitted the energy deposition curve with the Gaussian function in the range from 16.7 keV to 25.65 keV and obtained the fitted mean value as 21.13 KeV. This is shown in Figure 3.

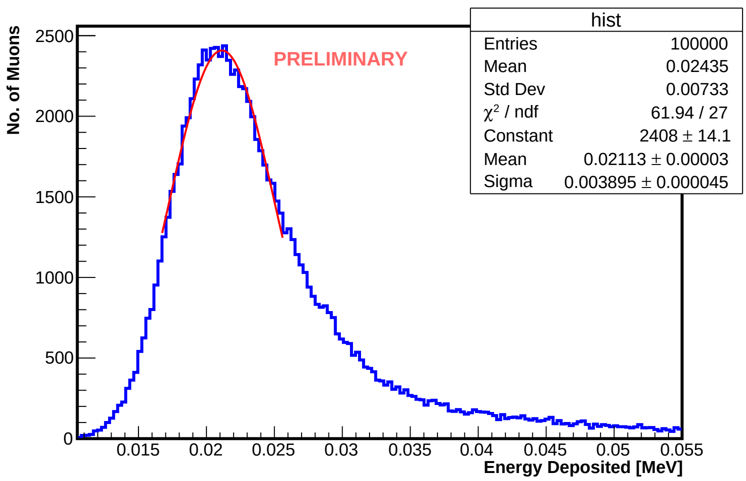

Figure 3: Energy deposition by muons in one PRC is 21.13 keV with Gaussian fit.

4. Flux and Angular Distributions

The flux and angle parameters of cosmic rays prove to be extremely useful to study because they provide us with vital information about their chemical compositions, energy range and also about the extra galactic bodies from which they originate. We can understand the behaviour of these bodies which can otherwise be difficult to determine. We can also gain information about the Earth's atmosphere how charged particles interact with it. Particle interaction with the Heliosphere and the solar winds can also be studied, giving us more information about the sun.

The flux of cosmic rays is measured as the number of particles per unit area per unit solid angle per unit time ($m^{-2}sr^{-1}s^{-1}$). The higher energy Cosmic Rays have a lower flux and the lower energy rays have a higher flux, this is due to the nature of the EAS. Cosmic Ray muon flux is subject to changes, depending on their energies and the radiation fields they interact with. Low energy rays are effected by the solar winds as mentioned in Section 1 along with the Earth's magnetic field causing a change in their intensities and flux [9, 10]. The differential flux is calculated as: $\frac{dN}{dAdtd\Omega} = I_{\circ}\cos^2\theta$, where θ is the zenith angle and $I_{\circ}$ is the intensity when $\theta = 0$. The integral flux is calculated by taking the integral of the cosine distribution. The flux for muons having energy greater than 1 GeV is observed to be $\sim 70m^{-2}sr^{-1}s^{-1}$[10, 11].

Study of the angular distributions of Cosmic Rays is necessary because it helps us understand the direction of incoming rays. In this paper, we present a study of the Zenith angle (θ) and Azimuthal angle (ϕ) measurements. The θ angle is measured with respect to the vertical axis and ϕ angle is measured with respect to the horizontal axis. θ is an important parameter that effects the intensity and flux of the rays. Greater values of θ indicate that the rays have traversed more extensive distances in the universe when compared to the smaller θ angles.

The GEANT-4 study of angular distributions of muons with new G3MT is done using the G4GeneralParticleSource. 100K muons were fired normally from above the G3MT module with energy ranging from 0.5 to 10 GeV. Their zenith angle (θ) and azimuthal angle (ϕ) were then plotted by using a user defined tracking action where the particle directions were tracked using their momentum and the distributions are shown in Figure 4.

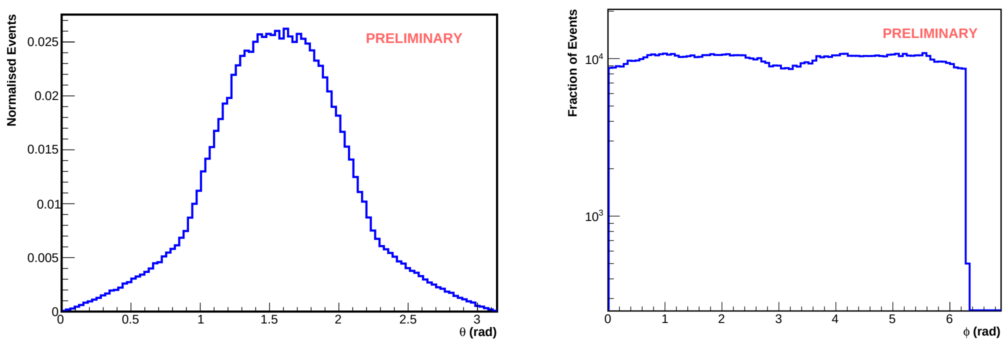

Figure 4: The zenith angle (θ) and azimuthal angle (ϕ) distributions for the vertically incident muons.

We only plotted the angles of the muons that make it through the entire module of new G3MT. For this purpose, Layer 0 in the module has been made the Scoring Volume in GEANT-4. We have observed that the Zenith angle (θ) peaks at 1.596 rad ($\sim 91°$). As the the θ angle deviates from 90 degrees, the number of incident muons diminishes, resulting in a gradual decrease in the distribution. The Azimuthal angle (ϕ) distribution is found to be relatively flat and symmetric, with an approximately equal likelihood of muons arriving from all azimuthal directions around the new G3MT module.

5. GRAPES-3 Data Analysis

The data collected by GRAPES-3 is done by reconstruction of muon tracks in two planes, the X - Z plane for Layer 1 and 3 and the Y - Z plane for Layer 0 and 2. The arrival direction of muons are binned into 225 directions in the $\theta - \phi$ space, taking a live time of 10 seconds. The projection of secondaries are calculated in the two planes, considering the θ and ϕ angles [6, 7].

For our analysis, we have taken 'one day' data from the old G3MT. We have plotted the rate of muons against time to understand the number of incoming muons. We studied the muons incident on one module of Station 1. Using the rate of muons binned in 225 directions in the $\theta - \phi$ space, we first calculate the rate of muons for every 10 seconds which gives the Module Rate. We observed the Module Rate to be 2,942 muons every 10 seconds. The total operation time of module is then converted to Day Number. We plotted the Module Rate with respect to Day Number which can be seen in Figure 5. In this plot one bin represents the average rate of muons in one minute. This analysis is under progress and our aim is to calculate and plot the flux ($m^{-2}sr^{-1}s^{-1}$) of the muons with new G3MT data.

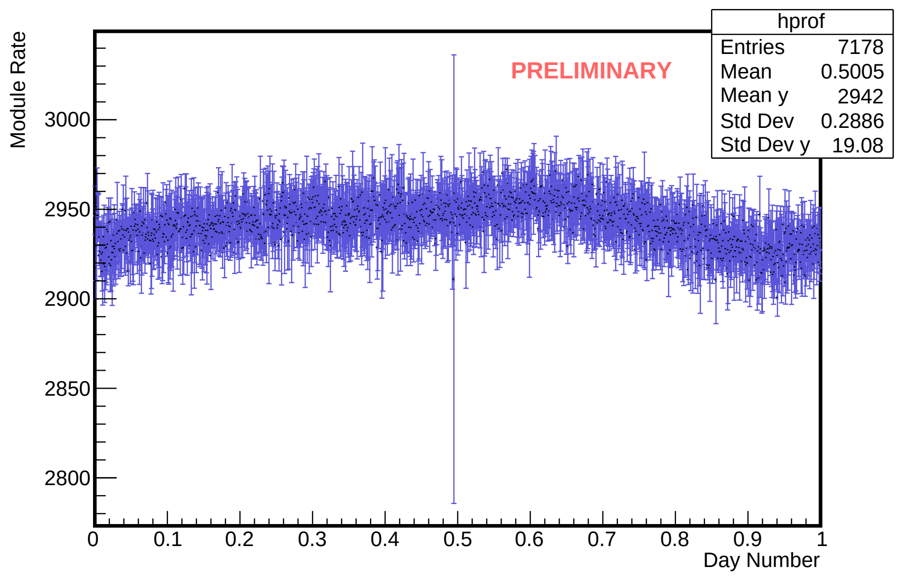

Figure 5: The Module Rate as a function of Day Number for one muon module.

6. Summary and Discussions

In this paper, we present GEANT-4 simulation results for a single module of the new muon telescope at GRAPES-3. The mean energy deposition on one PRC with 100K normally incident muons, each having 4 GeV energy, is observed to peak at 21.13 keV with a Gaussian fit. We studied the Zenith angle, θ, and Azimuthal angle, ϕ, of normally incident muons with energies ranging from 0.5 to 10 GeV on one module of the new muon telescope. The θ value peaked at 1.59 radians (approximately 91°), and the ϕ distribution was found to be flat and symmetric. Additionally, a preliminary study of the incoming muon rate is conducted using 'one-day' GRAPES-3 data from a module in the first station. A correlation between the Module Rate and Day Number is reported. Furthermore, we project the calculation of the integrated muon flux and carry out a data-simulation comparison by employing the CORSIKA[12] shower simulation along with the low-energy interaction model of FLUKA [13].

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