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Influence of hadronic interaction models on the muon multiplicity distribution of air showers observed with the GRAPES-3 experiment at Ooty

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Abstract: The GRAPES-3 experiment observes extensive air showers using a high-density array of scintillation detectors and a large area tracking muon detector. We have studied the relationship between the muon multiplicity distribution and shower size for the GRAPES-3 data taken during the period of 2000 - 2001. Monte Carlo simulations using CORSIKA code were performed to extract the spectra for various nuclear groups namely H, He, N, Al and Fe from these observations. We have used SIBYLL and QGSJET2 hadronic interaction models and compared our spectra with the direct measurements obtained from balloon and satellite borne experiments. We also discuss the influence of these interaction models on various observables. Such a study is important for a better understanding of hadronic interactions at very high energies.

Introduction

There is a rather sudden change in index of energy spectrum of primary cosmic rays (PCRs) around the 10^{15} eV, so it is called the "knee". Some models of "knee" can claim that the composition of the PCRs should change in this energy region.

We noticed through Monte Carlo simulation (MC) that the muon multiplicity distribution (MMD) in large detectors can derive the energy spectrum of nuclear component of PCRs. The PCR energy spectrum can be estimated from EAS's size spectrum. So, to obtain the precise size (total number of charged particles) of EAS dense array of detectors is desirable. Since MMDs strongly depend on nuclear species of PCRs, one can utilize the MMDs to find out the relative abundance of primary's nuclear components, such as Proton, Helium, N, Al and Fe.

Different nuclear interaction models in MC yield different MMDs, so we have tried to find out the proper nuclear interaction model by comparing our observed data with the data of direct measurements. This is the first time that reliable comparison has been performed between EAS data and direct measurements. Since we introduced dense array of scintillation detectors and large area muon detectors, it has become possible. Details of this comparison is described later.

GRAPES-3 experiment

The GRAPES-3 (Gamma Ray Astronomy at PeV EnergyS Phase-3) experiment is being operated at Ooty in southern India. (11.4°N, 76.7°E, 2200 m a.s.l.). The EAS array consisting of 257 scintillators, each 1 m^2 in area with inter-detector separation of only 8 m (fig. 1), The 560 m^2 GRAPES-3 muon detector consists of 16 tracking modules (each 35 m^2 in area and energy threshold of 1 GeV for vertical muons), which provides reliable mea-

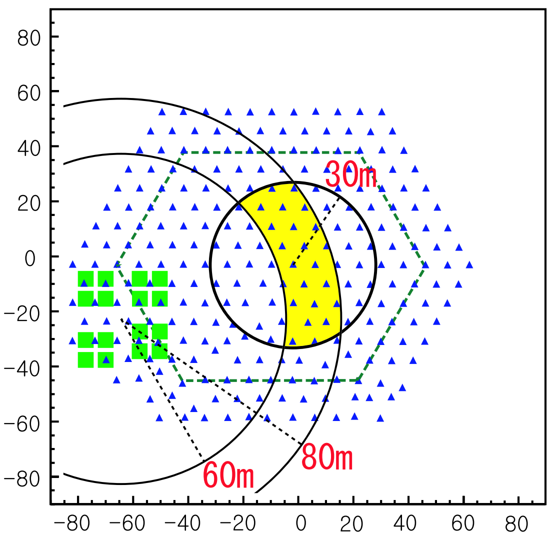

Figure 1: 257 Scintillation Detectors ▲(each 1 m^2) and 16 Muon Detectors ■(each 35 m^2)

surement of muon multiplicity even for low energy EAS. [1, 2]

A total of 6×10^8 EAS collected over a live-time of 4.71×10^7 s have been analyzed. Triggering rate is about 13 Hz during this period. Various conditions (yellow shaded area) were imposed in selection of EAS for getting size spectrum and MMDs in fig. 1.

EAS simulation

The EAS events were generated through CORSIKA(v6.50)[3] MC simulation using the interaction model SIBYLL (v2.1)[4] and QGSJET-II (v03)[5] for high energy interactions and GHEISHA for interactions below 80 GeV to evaluate the composition of PCRs. MC EASs using QGSJET01[6] (CORSIKA v6.02) model also are shown for comparison. NKG approximation is used for the electromagnetic component of EAS. Those generated EAS events were analyzed with the same manner as observed events.

EAS analysis

Various EAS parameters, size (N_e), core location (X_0, Y_0) and age (s) are estimated by fitting a NKG function to the lateral distribution, using the maximum likelihood algorithm with MINUIT[7].

The muon track reconstruction efficiency was measured and incorporated into simulations. Generating EAS events with MC, one can get a muon multiplicity in the muon detectors. Since the number of muons in a detector is counted by individual track of muon and not in terms of pulse height of the proportional counter, the accuracy in counting is very good. Effect of geometrical track overlapping has been corrected through MC. All the EAS are summed up with their size in intervals of 0.2 in $\log_{10}(N_e)$. Then we get the distribution of total number of detected muons for particular size bin.

Every one size bin contains various PCRs with different nucleus and different energy. Each nuclear group has its own MMDs, as you can see in fig. 2. Fig. 2 (a) and (b) shows examples of the relative abundance of nuclear components for different nuclear groups in two size regions.

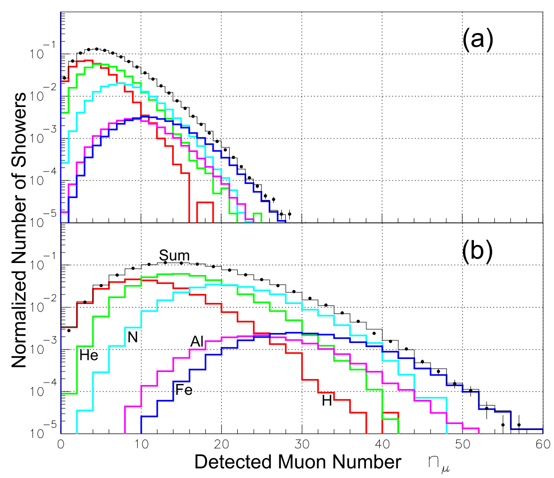

Figure 2: Observed and simulated (SIBYLL) distribution of multiple muons in two size region. (a) $10^{4.2} \leq N_e < 10^{4.4}$, (b) $10^{5.0} \leq N_e < 10^{5.2}$

Since different nucleus contribute different amount of muons, one has to adjust the contribution from every nuclear group to fit the observed MMDs. By fitting the MC MMDs into the observed MMDs, relative abundance of each nuclear group can be estimated.

There is significant overlap between the MMDs for the Al and Fe groups, thus these two distributions are combined assuming an abundance ratio (Al/Fe) of 0.8 based on direct measurements.

Using this relative abundance data, the energy spectrum of PCRs can be obtained from size spectrum.

Energy spectra

The PCRs' energy spectrum of each nuclear component can be estimated from the EAS's size spectrum with utilizing MMDs.

Relation between average PCRs' energy $\langle E_0 \rangle$ and average size $\langle N_e \rangle$ were calculated through MC. To obtain this relation we applied the same conditions as experimental one, triggering, core location etc. Size is converted to energy through this relation.

1. Generate showers through MC assuming PCRs energy spectrum with intensity of PCRs as $\mathrm{d}I/\mathrm{d}E_0 \propto E_0^{-\gamma}$, γ : 2.7. EAS samplings are obtained.

2. Classify these EASs in their size interval of 0.2 in $\log_{10}(N_e)$ and get MMDs in each size bin and in each nuclear group. MMDs in a size bin is obtained.

3. Using least χ^2 method, adjust the relative abundance for for groups (Proton, He, N and combination Al + Fe) by fitting the MC's MMDs to the observed MMDs. Relative abundance in a size bin is obtained

4. Multiply the amount of relative abundance with intensity of particular size bin in size spectrum. Intensity of each nuclear group for a size is obtained

5. Convert a size $\langle N_e \rangle$ to energy of PCRs using relation between $\langle N_e \rangle$ and $\langle E_0 \rangle$.

Now, intensity of a nucleus with an energy is obtained. Thus we obtain the energy spectra for each nuclear group. They are shown in fig. 3. All-particle energy spectrum is derived with summing up of them and shown in fig.4.

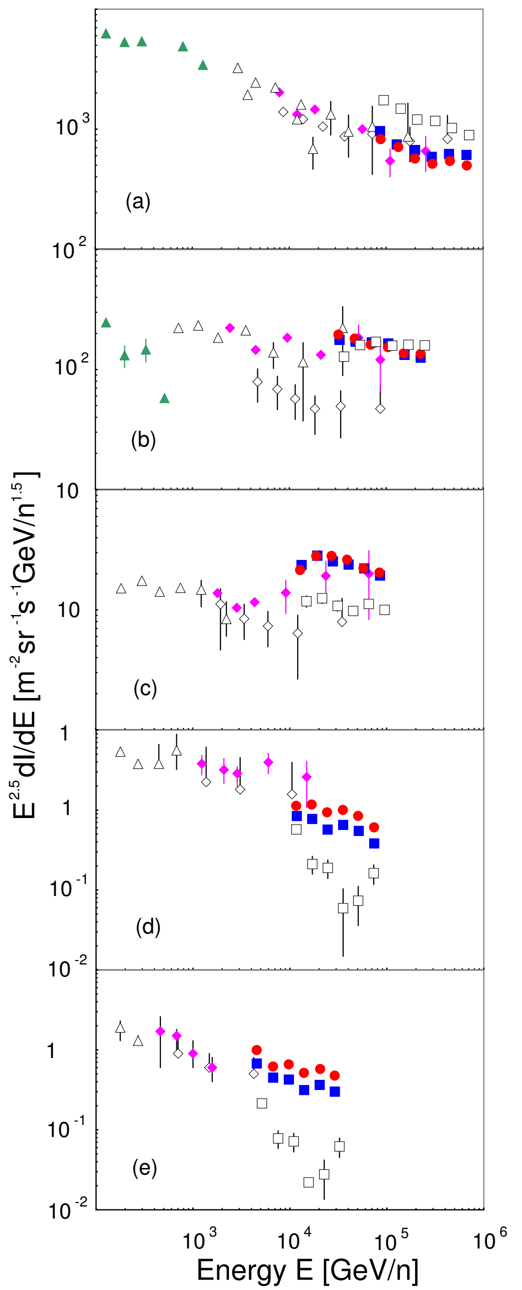

Figure 3: H(a), He(b), CNO(c), Middle(d), Fe(e) spectra from direct measurements ▲ Ryan [8], △ SOKOL [9], ♦ JACEE [10], ◇ RUNJOB [11], and GRAPES-3 ● SIBYLL 2.1, ■ QGSJET-II, □ QGSJET01.

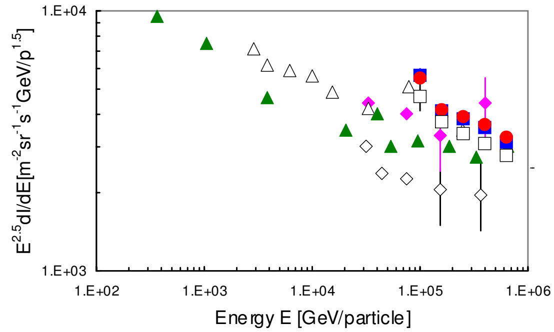

Figure 4: All-particle spectra from direct measurements ▲ Grigorov [12], △ SOKOL [9], ♦ JACEE [10], ◊ RUNJOB [11], and GRAPES-3 ● SIBYLL 2.1, ■ QGSJET-II, □QGSJET01.

Energy spectra with SIBYLL 2.1, QGSJET-II and QGSJET01 are not so much differect in all-particle. There are obvious difference between spectra of QGSJET01 and others in spectrum of each nuclear group. However, obtained spectra from QGSJET-II are much close to the spectra from SIBYLL. The energy spectra of proton based on SIBYLL and QGSJET-II models seems to well overlap with direct measurement like JACEE and there is big discrepancy with QGSJET01's especially in heavier nuclei.

Summary

An analysis of 6×10^8 EAS and their associated muon content in the GRAPES-3 experiment is used to study the muon multiplicity distribution as a function of N_e. The observed data were compared with the results obtained by simulation, using three hadronic interaction models, QGSJET01, SIBYLL 2.1 and QGSJET-II. SIBYLL and QGSJET-II seem to give better description in particle interactions. One can see good agreement between the GRAPES-3 results and direct measurements of various nuclear groups.

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