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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

H. TANAKA[1], S.K. GUPTA[1], K. HAYASHI[2], Y. HAYASHI[2], N. ITO[2], A. IYER[1], P. JAGADEESAN[1], A. JAIN[1], S. KARTHIKEYAN[1], S. KAWAKAMI[2], H. KOJIMA[3], T. MATSUYAMA[2], M. MINAMINO[2], P.K. MOHANTY[1], S.D. MORRIS[1], P.K. NAYAK[1], T. NONAKA[2], S. OGIO[2], T. OKUDA[2], A. OSHIMA[2], B.S. RAO[1], K.C. RAVINDRAN[1], M. SASANO[2], N. SHIMIZU[2], K. SIVAPRASAD[1], S.C. TONWAR[1], T. YOSHIKOSHI[2]

[1]*Tata Institute of Fundamental Research*
[2]*Osaka City University*
[3]*Nagoya Women's University*
tanaka@tifr.res.in

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. In order to extract the spectra for various nuclear groups namely H, He, N, Al and Fe from these observations, Monte Carlo simulations using CORSIKA code have been performed. SIBYLL 2.1, QGSJET01 and QGSJET-II hadronic interaction models have been used for this investigation and our resultant spectra were compared with the direct measurements obtained from balloon and satellite borne experiments. Less of distinction was found between the results expected from SIBYLL and QGSJET-II.

Introduction

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

We noticed through Monte Carlo simulations (MC) that the muon multiplicity distribution (MMD) in large detectors can help in the studies on energy spectrum of various nuclear component of PCRs. The PCR energy spectrum can be estimated from EAS's size (total number of charged particles) spectrum. So, to obtain the precise size 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 nuclear components, such as Proton, Helium, N, Al and Fe groups.

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. Since we introduced dense array of scintillation detectors and large area muon detectors at the mountain altitude, it has become possible.

GRAPES-3 experiment

The GRAPES-3 experiment is being operated at Ooty (11.4°N, 76.7°E, 2200 m a.s.l.) in southern India. The EAS array consists 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 measurement 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 was about 13 Hz during this period. Various conditions (yellow shaded area) were imposed in selec-

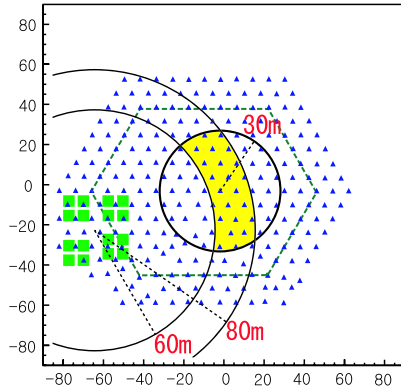Figure 1: 257 Scintillation Detectors ▲ (each 1 m^2) and 16 Muon Detectors ■ (each 35 m^2)

tion of EAS for getting size spectrum and MMDs in fig. 1.

EAS simulation

The EAS events were generated through COR-SIKA (v6.50) [3] MC simulation by using SIBYLL (v2.1) [4] and QGSJET-II (v03) [5] interaction models for high energy interactions and GHEISHA for interactions below 80 GeV in order to evaluate the composition of PCRs. MC EASs using QGSJET01 [6] (CORSIKA v6.02) model are also shown for comparison.
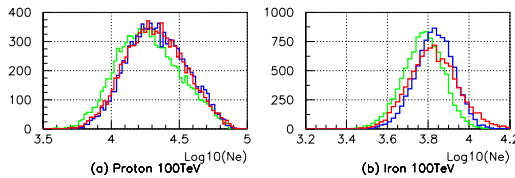

Figure 2: Red, blue and green lines show distributions of the numbers of electrons with SIBYLL, QGSJET-II and QGSJET01, respectively.

Figure 2 and 3 show distribution of the electron ($E_k > 1$ MeV) numbers and the muon ($E_k > 1$ GeV) numbers at the altitude of observatory. Left panels are results from vertical incidence proton primaries whose energies are 100 TeV and right panels are results from iron primaries in both fig-
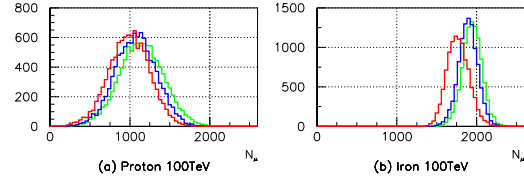

Figure 3: Red, blue and green lines show distributions of the numbers of muons with SIBYLL, QGSJET-II and QGSJET01, respectively.

ures. QGSJET-II model is seen to be similar to SIBYLL for the electron results and similar to QGSJET01 for the muon results.

Henceforth, MC data were generated from Proton, Helium, N, Al and Fe primaries whose energies followed power spectrum and whose incidence angles and core locations were determined randomly to compare with observed data.

Though NKG approximation is used for the electromagnetic component of EAS, differences between this approximation and full-MC with EGS4 [7] are considered including detector response [8]. 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 [9].

The muon track reconstruction efficiency was measured and incorporated into simulations. Generating EAS events with MC, one can get the 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 PCRs of various nuclear groups covering a relatively broader range of energies. Each nuclear group has its own MMDs,

as can be seen in fig. 4. Fig. 4 (a) and (b) shows examples of the relative abundance of nuclear components for different nuclear groups in two size regions.
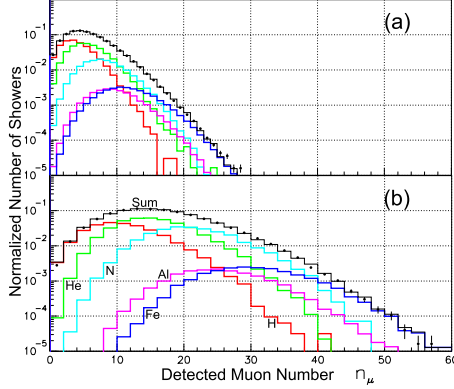

Figure 4: Observed and simulated (SIBYLL) distribution of multiple muons for two size bins. (a) $10^{4.2} \leq N_e < 10^{4.4}$, (b) $10^{5.0} \leq N_e < 10^{5.2}$

Since different nuclei 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 to the observed MMDs, relative abundance of each nuclear group can be estimated.

considering there is significant overlap between the MMDs for the Al and Fe groups, 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 by utilizing MMDs.

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

1. Generate showers through MC assuming PCRs energy spectrum with intensity of PCRs as $dI/dE_0 \propto E_0^{-2.7}$.

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

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

4. Multiply the amount of relative abundance with intensity of particular size bin in size spectrum.

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. 5.

There are obvious difference between spectra of QGSJET01 and others in spectrum of each nuclear group. However, obtained spectra from QGSJET-II are much closer to the spectra from SIBYLL. The energy spectra of protons based on SIBYLL and QGSJET-II models seems to well overlap with direct measurement like JACEE. But there is big discrepancy with QGSJET01's especially for 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 and QGSJET-II. SIBYLL and QGSJET-II seem to provide better description of particle interactions at energies $\sim 10^{14} - 10^{15}$ eV. One can see good agreement between the GRAPES-3 results and direct measurements of various nuclear groups.
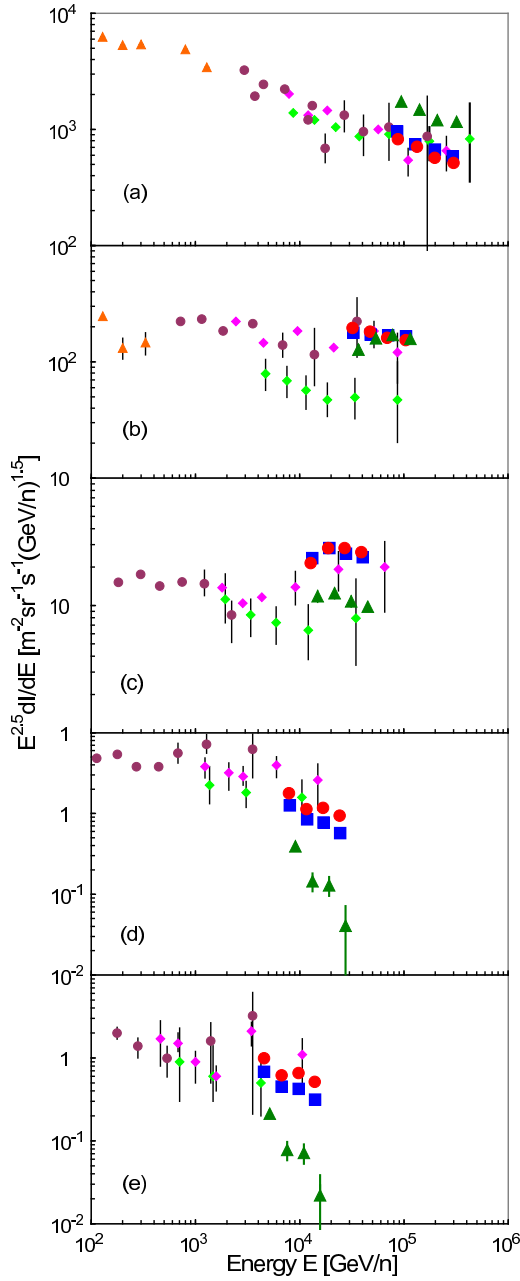
Figure 5: Energy spectra of H (a), He (b), N (c), Al (d) and Fe (e) groups from GRAPES-3 (● SIBYLL, ■ QGSJET-II, ▲ QGSJET01) and corresponding spectra from direct measurements, ▲Ryan [10], ●SOKOL [11], ◆JACEE [12][13] and ◆ RUNJOB [14].

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