A Study of the Primary Composition at $\sim 10^{14} - 10^{15}$ eV with the GRAPES-2 array at Ooty

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Abstract

Several observations on the electrons, muons and hadrons in air showers at energies $\sim 10^{15}$ eV have suggested that the primary cosmic ray flux may be getting enriched in heavier nuclei with increasing energy. This conclusion, though in conflict with some other observations, particularly, on the characteristics of the Cherenkov radiation in showers, has very significant implications for the nature of galactic sources generating and accelerating particles to ultra-high energies. We present here the results from the analysis of data on the muon multiplicity distributions from observations made with the large 192-module 200 m^2 area muon detector operating in association with the 100-detector air shower array of the GRAPES-2 experiment. Our observations also provide support to the hypothesis that the energy spectra for the heavier elements in the primary flux seems to be flatter relative to spectra for lighter nuclei at energies $\sim 10^{15}$.

1. Introduction

The presence of ultra high energy ($\geq 10^{14}$ eV) particles in primary cosmic rays invites speculations on the nature of very energetic astrophysical sources which are capable of producing and accelerating particles to energies as high as 10^{20} eV. Due to the scattering of particles by the chaotic magnetic fields pervading most of the interstellar space in our galaxy, it has not been possible to identify these sources directly. While some success [1] has been achieved in identification of a few sources emitting TeV γ-rays, similar success at PeV and higher energies continues to elude us as it is very difficult to identify showers initiated by primary γ-rays in the presence of the huge background of showers due to charged cosmic rays. Therefore, presently, detailed studies on the charged component of cosmic rays offer the only means to understand the astrophysics of high energy cosmic rays.

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At energies above 10^{14} eV the flux of cosmic rays is too small to be detected by satellite or balloon borne detectors flying above the atmosphere due to constraints on achieving very large exposure factors with moderately heavy payloads. For example, even a detector with a large exposure factor of $\sim 10^{10} cm^2 ssr$ would detect only ~ 1 event above 10^{15} eV. Though the energy spectra for various nuclear groups have been well measured with detectors flown aboard long-flying balloons [2,3] at energies around $\sim 10^{12}$ eV, the statistics at energies above 10^{14} eV are inadequate to extrapolate the measured spectra to the energy of the *knee* in the energy spectrum of primary cosmic rays at energy $\sim 3 \times 10^{15}$ eV . Therefore, measurements on the energy spectra of various nuclear groups at energies above $\sim 10^{14}$ eV have to rely presently on indirect observations on the products of interactions of primary cosmic ray particles in the atmosphere.

Detailed simulations show that measurements on the distribution of the number of muons incident over a very large area detector, usually called the muon multiplicity distribution, along with good measurements on the electron component of the shower accompanying the muons, offer a very promising means to study the energy dependence of the composition of primary flux at energies above 10^{14} eV. The **G**amma **R**ay **A**stronomy at **P**eV **E**nergie**S** **- Phase 2 (GRAPES-2)** experiment has been designed with this objective in mind.

2. The GRAPES-2 Experiment

The GRAPES-2 experiment is located within the city of Ooty ($11^o.4$ N latitude, $76^o.3$ E longitude and 2200 m altitude), a popular mountain resort town in southern India. It consists basically of 100 unshielded 'electron' detectors and a 192-module 200 m^2 area shielded 'muon' detector, shown schematically in the left panel of Fig. 1. Due to the limitations imposed by the ground topography, the placement of electron detectors, with inter-detector spacing of $\sim$ 10 m, is hexagonally symmetric only upto about 40 m from the center, that is, for 61 detectors placed within the inner 4 rings. However, outer detectors, 62-85, provide good sampling of particle density for core distances upto $\sim$ 80 m for showers whose cores are located within $\sim$ 30 m of the array center. The very compact nature of the GRAPES-2 array is a unique feature which yields a relatively lower energy detection threshold and more accurate reconstruction of shower characteristics including arrival direction.

The large (200 m^2) area muon detector of the GRAPES-2 array consists of 192 modules, each 1.04 m^2 in area. The center of the muon detector is located at a distance of $\sim$25m from the array center and the distance of individual muon detector modules from the array center varies from $\sim$15 m to $\sim$40 m. A total of 16 tunnels, each 22 m deep, were made by digging into the hillside to accommodate the 192 muon detector modules. The tunnels are covered by a 0.3 m thick reinforced concrete slab which takes the load of 3.5 m thick layer of packed soil

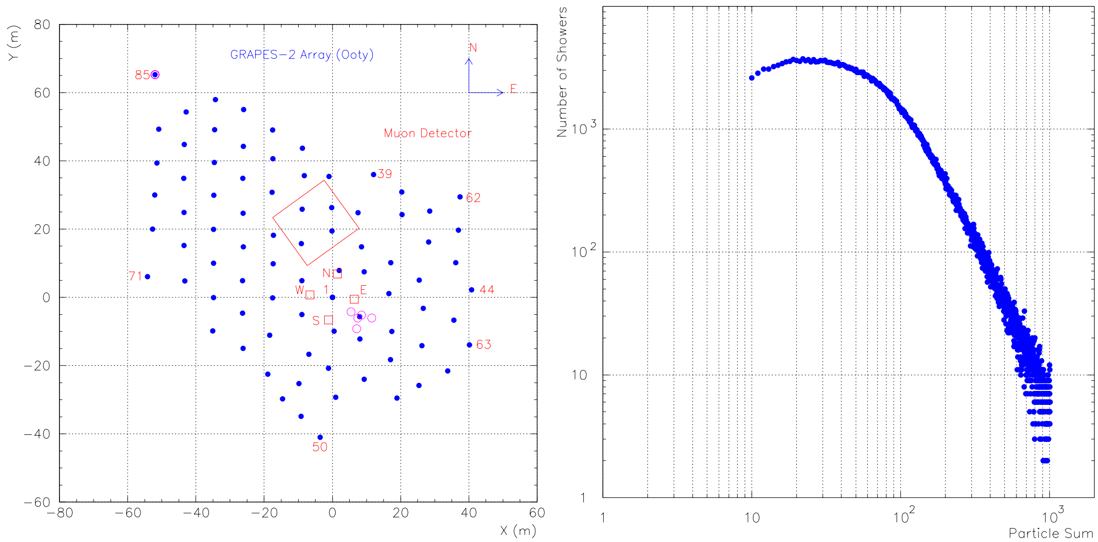

Fig. 1. Schematic layout of electron detectors and the muon detector in the GRAPES-2 array located within the Raj Bhavan campus at Ooty (left panel) and distribution of 'Particle Sum' for showers satisfying the software selection conditions' (right panel).

placed above it. The total thickness of the absorber above the detector modules is $\sim 600gcm^{-2}$ which sets the energy threshold of 1 GeV for vertical muons to be able to give signal in the 20 cm deep water Cerenkov detector modules.

3. Observations

A special feature of the GRAPES-2 experiment is the requirement for the cores of most of the selected showers to lie in the central area of the array. For this purpose, only a 4-fold coincidence between signals from each of the four centrally placed detectors, N, E, W and S, is required for generating a shower trigger. The signal from each detector is required to be larger than ~ 0.3 times the mean signal I^{min} expected for the passage of a minimum ionizing particle (MIP) through the detector. However, the trigger has been designed to disfavor the selection of very small local showers by imposing the additional requirement that one of these 4 detectors should have a signal ≥ 3 MIPs.

The average rate of the shower trigger has been observed to be 5.69 min^{-1}. However it was decided during data analysis to put additional software selection conditions which required (a) a 4-fold coincidence between signals ≥ 1.0 MIP from the detectors, N, E, W and S and (b) a signal ≥ 6 MIP from any one of these 4 detectors. The shower rate using these additional selection conditions is 3.55 min^{-1}.

There is considerable uncertainty in the reconstruction of lateral distribu-

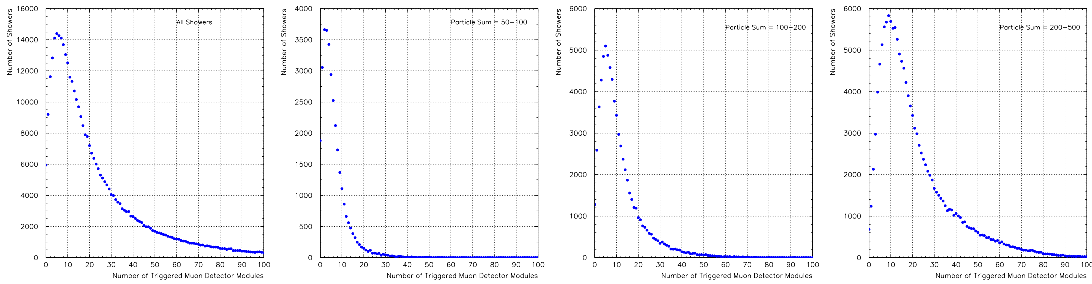

Fig. 2. Distribution of the number of triggered muon detector modules for all showers satisfying the 'software' trigger conditions and for three ranges of 'Particle Sum' values.

tion and determination of shower parameters for small size showers. However, information from these showers can provide information on composition for the energy range which partially overlaps with the range covered by direct measurements. Therefore it is convenient to use the quantity, 'Particle Sum', as the measure of shower size by summing the number of particle measured in detectors of the inner 3 rings, that is, detectors numbered 1 to 37. The observed distribution of 'Particle Sum', is shown in the right panel of Fig. 1 for showers satisfying the 'software' trigger conditions.

Fig. 2 shows the distribution of the number of triggered muon detector modules for showers satisfying the 'software' trigger conditions and also for three ranges of 'Particle Sum' values. Detailed simulations are being carried out, using semi-Monte Carlo procedure, discussed in detail elsewhere [4,5], to obtain information on primary composition from data shown in Fig. 2.

4. Summary

The GRAPES-2 experiment has been described briefly and some observational data on 'Particle Sum' and muon multiplicity distributions has been presented. Detailed results from the comparison of observations with expectations from simulations would be discussed at the conference.

5. References

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