Nuclear composition of primary cosmic rays around the knee region observed with GRAPES-3

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Abstract: We have measured the primary cosmic ray spectra of various nuclear groups by analyzing the relationship between muon multiplicity distribution and air shower size, and we have also estimated their mean mass as a function of primary energy. The shower data were obtained from the two years of observations with the GRAPES-3 air shower experiment, which has a high-density air shower array of plastic scintillation detectors and a large area muon detectors located at Ooty in southern India. We will present brief description about our experiment, data analysis and discuss the implications of the results.

Introduction

Power index of primary cosmic ray (PCR) energy spectrum changes from ~ -2.7 to ~ -3.1 at around $10^{15} \sim 10^{16}$ eV and it is called *knee*. Some models of *knee* expect change of PCR composition through this energy range. It is hoped to provide information on the origin of PCR.

Here we report GRAPES-3 observations of the nuclear composition and energy spectrum of PCR obtained from size and muon multiplicity distribution (MMD) of air showers.

Experiment

GRAPES-3 Experiment is located at Ooty in India at an altitude of 2,200 m above sea level. Figure 1 shows GRAPES-3 air shower array.

Shower detector array consists of nearly 300 plastic scintillation detectors (SDs), each contains 1 m^2 area, with 8 m separations as shown in figure 1. Signal for each SD is taken to ADC and TDC.

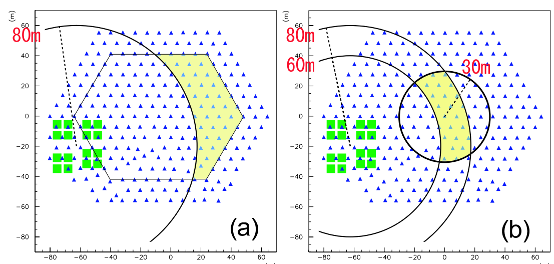

Figure 1: GRAPES-3 EAS Array. Shower detectors and Muon detectors are plotted with ▲ and ■.

Shower triggering requires more than 10 SDs firing. [1]

There are large area muon track detectors (total 560 m^2) to observe muons accompanying with EAS. Each detector consists of a 6 m long proportional counter with cross section of 10 cm $\times$ 10 cm. 58 counters are placed side by side on a concrete platform. Four layers of counters are arranged in crossed configuration to identify the track of individual muon and covered with 2 m thick concrete slab. Threshold energy of vertical through muons is about 1 GeV. The anode signal from each counter is shaped to an exponential form and discriminated at $\sim$ 0.2 mip. Width and timing of the pulse are recorded for each counter. [2]

Simulation

CORSIKA [3] EAS Monte Carlo (MC) code is used for interpretation of observations. To evaluate influence of hadronic interaction models on this analysis, MCs with SIBYLL 2.1 [4] (CORSIKA v6.50), QGSJET-II [5] (CORSIKA v6.50) and QGSJET01 [6] (CORSIKA 6.02) are performed for various primary nuclear groups namely H, He, N, Al and Fe. These results have been calculated and compared with the direct measurements obtained from balloon and satellite borne experiments. [7]

Shower Reconstruction

A total of 6×10^8 EAS collected over a live-time of 4.71×10^7s for two years, 2000 and 2001, have been analyzed. Each shower size is estimated from the lateral distribution of charged particles with fitting NKG function to them.

The followings are free parameters and estimated by NKG fitting using Maximum Likelihood Method with MINUIT [8].

- Shower Core Location $\mathbf{R}_{core} = (X, Y)$
- Shower Size N_e
- Lateral Age s

The linearity of the PMT response is studied with density spectrum of each detector. Detector has good response within $\sim$ 200 particles for each. After first NKG fitting, second is carried out with ignoring detectors where particle number exceed 200 particles in fitted function.

The detected number of muons is decided for each muon detector. In order to reject the accidental muons, pulse timings of proportional counters are considered and the number of tracks are counted to have the same direction to the shower. Effect of geometrical track overlapping has been considered through MC.

Muon Multiplicity Distribution

MMD analysis has been done for showers that satisfy the following conditions. Zenith angle of the air shower should be less than 25°. Core location should be inside areas as shown in figure 1 (a) for $N_e \geq 10^{5.2}$ and (b) for $N_e < 10^{5.2}$ to limit distance between shower core and muon detectors.

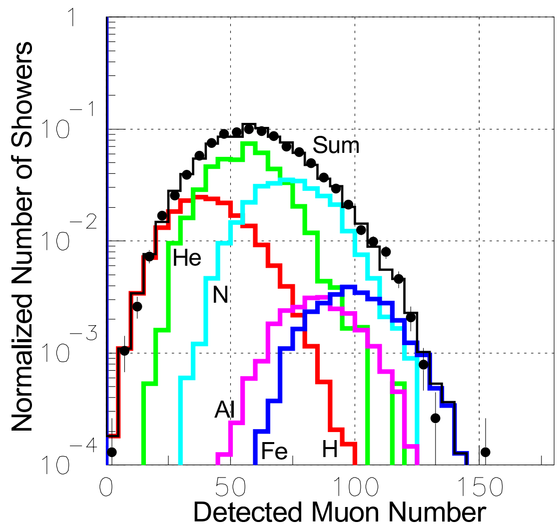

Figure 2: Observed and simulated (SIBYLL 2.1) distribution of multiple muons in size region of $10^{6.0} \leq N_e < 10^{6.2}$.

Selected showers are classified with N_e in intervals of 0.2 of $\log_{10}(N_e)$. MCs are also selected and classified with the same conditions. N_e has been converted to vertical value with considering of shower attenuation. MMDs of MC are fitted to observations using MINUIT to estimate relative abundance of each nuclear group in each size bin. Here, abundance ratio of Al to Fe is fixed to 0.8 based on direct measurements. Figure 2 shows MMDs of $10^{6.0} \leq N_e < 10^{6.2}$. Red, green, light-blue, purple and blue lines show MC results of H, He, N, Al and Fe respectively after fitting. Black point and line mean observation and sum of MC.

Energy Spectrum

Size spectrum initiated from each nuclear group is estimated with total size spectrum and relative abundance obtained from MMD fitting. Relations between shower size and primary energy are calculated on MC for each mass groups.

Energy spectra for each groups have been estimated with the above calculations using SIBYLL 2.1, QGSJET-II and QGSJET01 models. They are shown in figure 3. SIBYLL 2.1 and QGSJET-II have almost same results, though there are visible differences from QGSJET01. The Bent in proton spectrum can be seen around $1 \sim 3$ PeV for all models, though other spectra don't have this structure in our energy range.

All-particle energy spectra is also shown in figure 4. All the models give similar flux and have good agreement with direct observations here.

Mean Mass Number

Mean mass number $\langle \ln A \rangle = \Sigma(\ln A)/N$ of cosmic ray will be derived from energy spectra. Estimated $\langle \ln A \rangle = \Sigma(\ln A)/N$ is shown in figure 5.

$\langle \ln A \rangle$ with SIBYLL 2.1 is $0.1 \sim 0.2$ larger (e.g. 0.15 ± 0.03 larger at 10^{15} eV) than QGSJET-II. However, this difference is rather small and won't have much influence on study of composition.

Summary and Outlook

EAS data of GRAPES-3 of 2000 and 2001 are analyzed. With observed muons accompanying with showers, relative abundance in the size spectrum is estimated for each mass groupsH, He, N and Al+Fe with MMD fitting.

It was performed using three hadronic interaction models, SIBYLL 2.1, QGSJET01 and QGSJET-II. New model, namely QGSJET-II, and SIBYLL 2.1 have given very similar results in this analysis.

Proton spectrum becomes steeper at higher energy. An extension of the spectrum to higher energy side may show the break of the spectrum for heavier components. New scintillation detectors with dual PMT have been already installed to have large dynamic range (up to $2000 \sim 3000$ particles). These

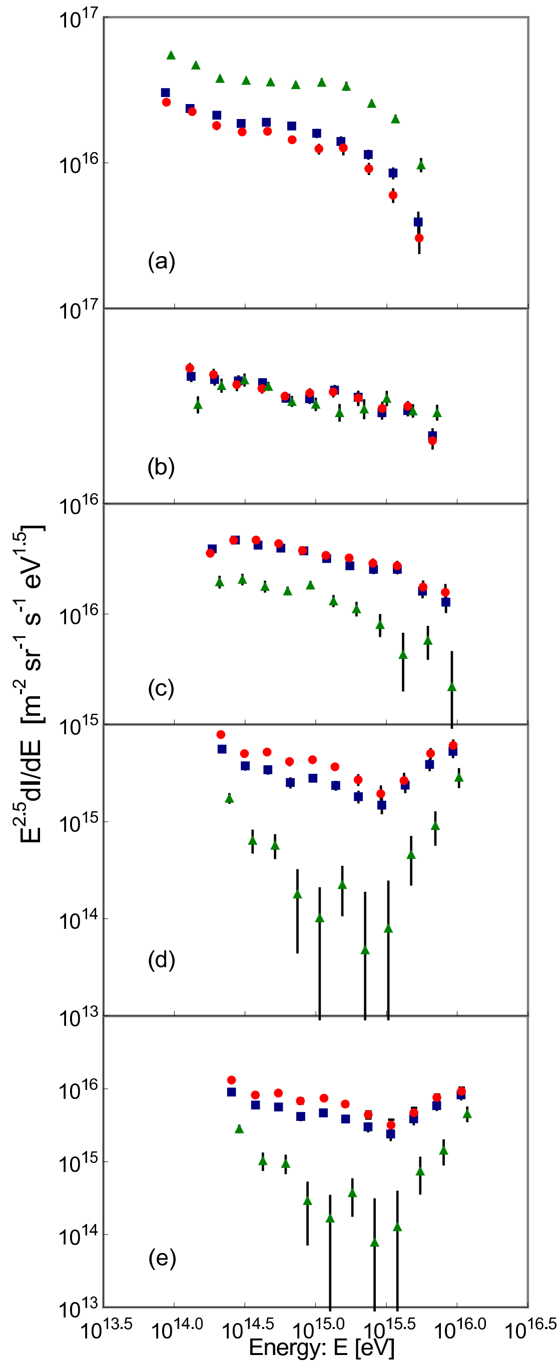

Figure 3: Energy spectra using SIBYLL 2.1 (●), QGSJET-II (■) and QGSJET01 (▲). (a) - (e) panels show H, He, N, Al and Fe spectra respectively.

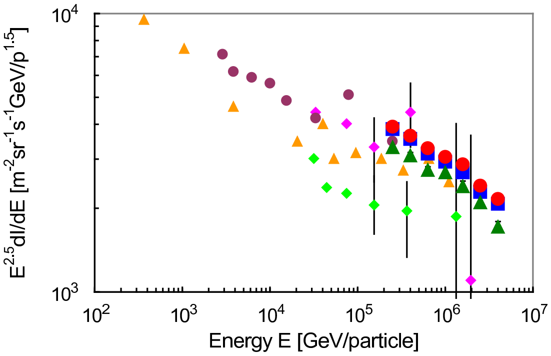

Figure 4: All-particle spectra from direct measurements ▲ Grigorov [9], ● SOKOL [10], ♦JACEE [11], ♦ RUNJOB [12] and GRAPES-3 (● SIBYLL 2.1, ■ QGSJET-II, ▲ QGSJET01).

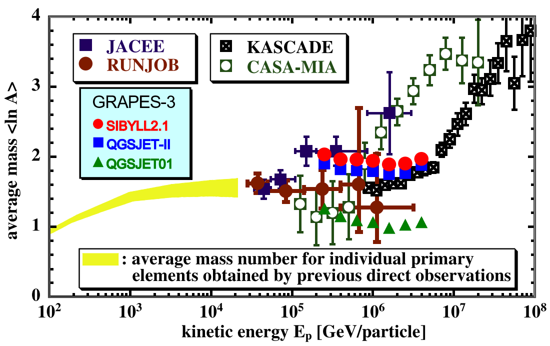

Figure 5: Mean Mass Number $\langle \ln A \rangle$ as a function of energy of PCR using SIBYLL 2.1 (●), QGSJET-II (■) and QGSJET01 (▲). JACEE [11], RUNJOB [12], KASCADE [13] and CASA-MIA [14] results are also shown.

are expected to provide more reliable estimate of the energy. It is also proposed to expand GRAPES-3 shower array over an area of 1 km^2. It would permit to study about nuclear composition to 10^{18} eV. [15]

Acknowledgement

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References

[1] S.K. Gupta et al. *Nuclear Instruments and Methods in Physics Research A*, 540:311–323, 2005.

[2] Y. Hayashi et al. *Nuclear Instruments and Methods in Physics Research A*, 545:643–657, 2005.

[3] D. Heck, J. Knapp, J.N. Capdevielle, G. Schatz, and T. Thouw. CORSIKA: A monte carlo code to simulate extensive air showers. Technical report, Forschungszentrum Karlsruhe, 1998. FZKA 6019.

[4] R. Engel, T.K. Gaisser, P. Lipari, and T. Stanev. In *26th International Cosmic Ray Conference*, volume 1, pages 415–418, Salt Lake City, Utah, 1999. HE 2.5.03.

[5] S. Ostapchenko. *Nuclear Physics B Proceedings Supplements*, 151:143–146, 2005.

[6] N.N. Kalmykov, S.S. Ostapchenko, and A.I. Pavlov. *Nuclear Physics B Proceedings Supplements*, 52B:17–28, 1997.

[7] H. Tanaka et al. In *30th International Cosmic Ray Conference*, Merida, Mexico, 2007. HE3.1, 1233.

[8] F. James. *MINUIT: Function Minimization and Error Analysis*. CERN, 94.1 edition, 1998. CERN Program Library Long Writeup D506.

[9] N.L. Grigorov et al. In *12th International Cosmic Ray Conference*, volume 5, pages 1746–1768, Hobart, 1971.

[10] I.P. Ivanenko et al. In *23th International Cosmic Ray Conference*, Calgary, 1993.

[11] Y. Takahashi for the JACEE Collaboration. *Nuclear Physics B Proceedings Supplements*, 60B:83–92, 1998.

[12] V.A. Derbina et al. *The Astrophysical Journal Letters*, 628:L41–L44, 2005.

[13] H. Ulrich et al. In *27th International Cosmic Ray Conference*, volume 1, pages 97–100, Hamburg, Germany, 2001.

[14] M.A.K. Glasmacher et al. *Astroparticle Physics*, 12:1–17, 1999.

[15] S.K. Gupta et al. In *30th International Cosmic Ray Conference*, Merida, Mexico, 2007. HE1.5, 1058.