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Zenith angle dependence of the size spectrum of air showers around the knee observed with the Tibet air shower array

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Abstract: We present the shower size spectra of primary cosmic rays at different zenith angles in the energy region around the knee observed with the Tibet-III air-shower array. Each shower size is estimated using the modified NKG function which is optimized by the Monte Carlo simulation based on the QGSJET01c+HD and QGSJET01c+PD models. It is confirmed that the model dependence in estimating the shower size is smaller than 5%. The knee position of the shower size spectrum is located around 4×10^6 for vertical showers, while its position has a tendency to move to smaller size region with increasing zenith angle. It is also shown that the behavior of the shower size spectra observed at different zenith angles is wholly compatible with that expected from the heavy enriched composition in the knee energy region. The zenith angle dependence of the shower size spectra will give a unique information about the primary composition at energies around the knee region.

Introduction

The energy spectrum of observed cosmic rays is expressed by a power law from about 10^{10} to 10^{20} eV with a slight change of slopes between 10^{15} to 10^{16} eV. The break of the all particle spectrum at around 4 PeV is called the "knee". The chemical composition of the cosmic rays at the knee is considered as a key information to understand the cosmic-ray acceleration and propagation in the Galaxy [1]. We already reported the energy spectra of protons and heliums around the knee region observed with a hybrid experiment of air shower array and burst detector array [2], [3]. These results obtained suggest that the heavy components are superior in the primary cosmic rays around the knee. Thanks to the high altitude, the Tibet-III air shower array is able to measure the shower size and the arrival direction of each primary particle in the wide energy region over about three decades, as well as in the wide zenith angle region up to about 60° with a good accuracy. It is noted that the primary mass dependence on the air shower development becomes strong as the zenith angle becomes large at Yangbajing level. In this paper, we discuss the primary cosmic ray composition around the knee based on the shower size spectra observed at different zenith angles.

Experiment

The Tibet ASγ experiment is located at the site of Yangbajing (Tibet) at a height of 4300 m above sea level (606 g/cm^2). The details of the Tibet-III air shower array (AS) are described in the paper [4], The Tibet-III AS array (36,900 m^2) is used to measure the shower size and the arrival direction of each air shower. The primary energy of each event is determined by the shower size N_e, which is calculated by fitting the lateral particle density distribution to the modified NKG structure function. The air shower direction can be estimated with an inaccuracy smaller than 0.2° at energies above 10^{14} eV. We used the data set obtained during the period from 2000 November through 2004 October. The effective live time T is 805.17 days, and the total effective area $S \times \Omega$ is calculated to be 10410 m^2·sr for all primary particles with $E_0 \geq$ 100 TeV.

HD model	10^{14} eV	10^{15} eV	10^{16} eV
P	22.6%	11.0%	8.1%
He	19.2%	11.4%	8.4%
M	36.0%	38.5%	31.8%
Fe	22.2%	39.1%	51.7%
PD model	10^{14} eV	10^{15} eV	10^{16} eV
P	39.0%	38.1%	37.5%
He	20.4%	19.4%	19.1%
M	31.2%	32.6%	33.2
Fe	9.4%	9.9%	10.2%

Table 1: Fractions of the proton(P), helium(He), medium(M) and iron(Fe) components in the assumed primary cosmic-ray spectrum of the HD and PD models

Simulation

A full Monte Carlo (MC) simulation has been carried out on the development of air showers in the atmosphere and also on the detector response of the Tibet-III array. The simulation code CORSIKA (version 6.204) including QGSJET01c and SIBYLL interaction models [5] is used to generate air shower events. In order to discuss the composition dependence on the size spectra at various zenith angles, two primary composition models are examined as the input energy spectra, namely a heavy dominant (HD) and a proton dominant (PD) ones [2]. The fractional contents of the assumed primary cosmic-ray flux models are listed in Table 1. The incident zenith angles of primary particles are isotropically sampled within 60 degrees at the top of atmosphere.

All secondary particles are traced until their energies become 1 MeV in the atmosphere, and the simulated air-shower events are reconstructed with the same detector configuration and structure as the Tibet-III array. That is, all detector responses including the materialization of photons inside the detector are taken into account in this simulation.

In our experiment, the number of charged particles detected by each scintillation detector is defined as the PMT output (charge) divided by that of the single peak, which is determined by a probe calibration using cosmic rays. According to the MC, the peak value of the energy deposit for a single particle in each detector is calculated as 6.11 MeV. Based on this result, we can estimate the number of charged particles from the observed ADC value for each hit detector. The number of charged particles of each event (hereafter, we call this a " shower size (Ne)") was estimated using the modified NKG function which is optimized by the Monte Carlo simulation using the QGSJET01c+HD model and QGSJET01c+PD model independently. For the model dependence on the shower size estimation, it is confirmed that the difference between QGSJET+HD-fit and QGSJET+PD-fit is within 2%, and that between QGSJET+HD-fit and SIBYLL+HD-fit is within 5%. The details of the shower size estimation method are written in the paper [6]. The shower size resolutions estimated are summarized for the events with different zenith angles in Table 2.

Zenith angle (sec(θ)) range	HD model	PD model
$1.0 \leq \sec(\theta) < 1.1$	7%	9%
$1.1 \leq \sec(\theta) < 1.2$	9%	11%
$1.2 \leq \sec(\theta) < 1.3$	15%	16%
$1.3 \leq \sec(\theta) < 1.4$	16%	19%

Table 2: The shower size resolution.

Analysis

The following conditions are imposed on the data set to select the events to be used in the present analysis; 1) more than 10 detectors should detect a signal of more than five particles per detector, and 2) the central positions weighted by the 8th power of the number of particles at each detector should be inside the innermost 135 m $\times$ 135 m area. This area is chosen with use of MC events so that the following two cases are just canceling out each other, namely the number of events originally inside of this area but falling outside after event reconstruction equals to the number of events in the opposite case.

Results

In order to obtain the shower size spectrum at respective zenith angle, the events are accumulated for different angular bins in such a way that the zenith angle (cosθ) increases by a constant amount (0.07). We are then able to obtain the differential flux of cosmic rays in terms of the

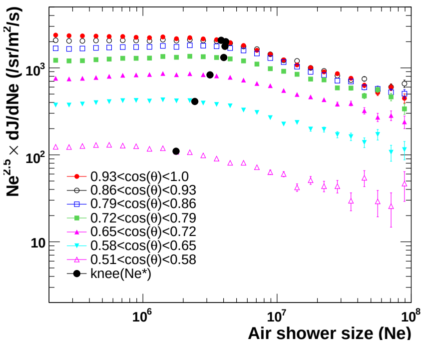

Figure 1: Differential shower size spectra of cosmic rays at various zenith angles around the knee. The black closed circle denotes the knee position.

shower size at different zenith angle. The result is shown in Fig. 1, where the black closed circle denotes the knee position of each shower size spectrum. The knee position is calculated using the fit-functions including the knee parameters proposed by Hörandell [7].

It is important to see that the knee position seems to shift to smaller size region and to become unsharp with increasing zenith angle, while stopping at the almost same place for the size spectra at the zenith angles smaller than about 40°. This tendency will reflect the composition of primary cosmic rays and support the heavy dominant primary composition around the knee region. The reason is as follows; the Tibet altitude is close to the maximum development of air showers induced by primary cosmic rays around the knee region, so that the change of the knee position of the size spectrum is small around vertical directions while becoming larger with increasing zenith angle, where the difference of the shower development for different primary mass becomes large. If the primary, however, is dominated by light nuclei such as protons and heliums at energies around the knee (PD model), the change of the knee position should then be very small and almost independent of the zenith angle due maily to their longer interaction mean free paths compared to heavy nuclei in the atmosphere and to small contribution from heavier nuclei. This tendency is incompatible with the experiment. Detailed MC simulation will provide

Zenith angle ($\cos(\theta)$)	Knee-position (Ne*)	Index of Ne spectrum
0.93-1.0	$(3.83 \pm 0.13) \times 10^6$	γ_1=2.53 $\pm$ 0.01 γ_2=2.99 $\pm$ 0.01
0.86-0.93	$(4.13 \pm 0.16) \times 10^6$	γ_1=2.49 $\pm$ 0.01 γ_2=2.99 $\pm$ 0.01
0.79-0.86	$(4.49 \pm 0.21) \times 10^6$	γ_1=2.46 $\pm$ 0.01 γ_2=3.00 $\pm$ 0.02
0.72-0.79	$(4.01 \pm 0.20) \times 10^6$	γ_1=2.44 $\pm$ 0.01 γ_2=2.91 $\pm$ 0.02
0.65-0.72	$(3.17 \pm 0.60) \times 10^6$	γ_1=2.42 $\pm$ 0.04 γ_2=2.88 $\pm$ 0.05
0.58-0.65	$(2.44 \pm 0.51) \times 10^6$	γ_1=2.41 $\pm$ 0.06 γ_2=2.91 $\pm$ 0.05
0.51-0.58	$(1.77 \pm 0.90) \times 10^6$	γ_1=2.38 $\pm$ 0.07 γ_2=2.77 $\pm$ 0.10

Table 3: The knee position and power index of the shower size spectrum observed at different zenith angle region. γ_1 is the best fitted-index for the shower size below 10^6, and γ_2 is that above 4×10^6.

robust information on the chemical composition at the knee because of small interaction model dependence for size estimation in Tibet air shower experiment (at most 5%). The characteristics of the shower size spectra at various zenith angles are summarized in Table 3.

We present the shower size spectrum of almost vertical events in Fig. 2(a) and that of large zenith angle in Fig. 2(b), comparing with the MC results. Fig. 2(a) shows that the observed shower size spectrum at small zenith angle is in good agreement with both composition models. As seen in Fig. 2(b), however, the observed shower size spectrum at large zenith angle favors to the HD composition in the knee energy region, though the the statistics of MC events is still not enough at high energies. It may be well seen that the size spectrum based on the PD model deviates from the experiment at large zenith angle considerably. Such behavior is consistent with that of the knee position of the shower size spectrum as discussed above.

Summary

We observed the shower size spectra of cosmic rays at various zenith angles with the Tibet-III air shower array and compared these with the MC results. The behavior of the shower size spectrum

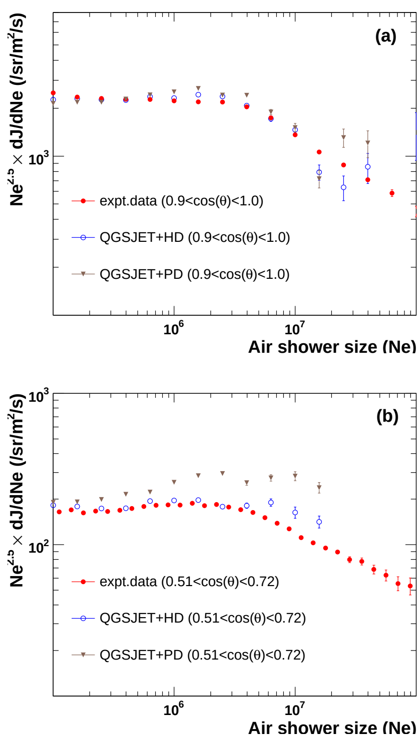

Figure 2: Comparison of the observed shower size spectra with th MC data at different zenith angles : (a): vertical events, (b): large zenith angle events.

at large zenith angle was shown to depend on the primary composition strongly, and found that the observed shower size spectra are wholly consistent with those expected from the heavy enriched primary composition around the knee region. A careful estimation of the systematic errors is under way. We need more MC data to reach a definite conclusion.

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