Proceedings of the 30th International Cosmic Ray Conference
Rogelio Caballero, Juan Carlos D'Olivo, Gustavo Medina-Tanco,
Lukas Nellen, Federico A. Sánchez, José F. Valdés-Galicia (eds.)
Universidad Nacional Autónoma de México,
Mexico City, Mexico, 2008

Vol. 4 (HE part 1), pages 103–106

30TH INTERNATIONAL COSMIC RAY CONFERENCE

ICRC'07
Mérida, México

The cosmic ray all-particle spectrum in the wide energy range from 10^{14} eV to 10^{17} eV observed with the Tibet-III air-shower array

THE TIBET ASγ COLLABORATION

chen@icrr.u-tokyo.ac.jp

Abstract: We present an updated all-particle energy spectrum using data set collected in the period from 2000 November through 2004 October by Tibet-III air-shower array. The energy determination of the air showers is made by fitting the lateral density distribution of the shower particles to the modified NKG function which is optimized by simulation calculation using interaction models of QGSJET01c and SIBYLL2.1 taking into account of the detector configurations. It is shown that the model dependence in the energy determination is not significant being less than 5% in the absolute flux value and we obtained the cosmic ray energy spectrum in a wide range over 3 decades between 10^{14} eV and 10^{17} eV, in which the position of the knee is clearly seen at around 4 PeV. Based on these calculations, we briefly discuss the systematic errors involved in our experimental results due to the Monte Carlo simulation.

Introduction

The energy spectrum of primary cosmic rays is well described by a power law over a wide energy range, while its slope becomes steeper in the energy range between 10^{15} and 10^{16} eV, which is called "knee". It has been discussed that the knee is closely related with the origin, the acceleration and the propagation of high-energy cosmic rays in the Galaxy. One of the possibile understanding may be that almost all cosmic rays below the knee are accelerated at supernova remnants (SNRs), since the maximum energy gained by shock acceleration at SNRs is of the order of 10^{14} eV per unit charge [1], the cosmic-ray spectrum is expected to become steeper at energies around and beyond the knee. Another possibility is that the break of the spectrum around the knee represents the energy at which cosmic rays can escape more freely from the trapping zone in the Galactic disk [2].

Tibet-III air shower array and detector response

The Tibet air shower (AS) experiment has been successfully operated at Yangbajing (90.522° E, 30.102° N, 4,300 m above sea level) in Tibet, China, since 1990. The experimental set-ups of the Tibet-III air shower array are described in the previous papers [3]. The Tibet-III air-shower 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 (see sec. 4).

Simulation

An extensive Monte Carlo (MC) simulation has been carried out on the development of air showers in the atmosphere and also on the response in the Tibet-III array. The simulation code CORSIKA (version 6.204) including QGSJET01c and SIBYLL2.1 hadronic interaction models [4] are used to generate air shower events. For the primary particles, the heavy dominant model (HD) and proton dominant model (PD) [5] are used. All shower particles are traced until their energies become 1 MeV in the atmosphere. Simulated air-shower events were input to the detector with the same detector configuration as the Tibet-III array with use of Epics code (ver. 8.64) [6] to calculate the energy deposit of these shower particles.

In this experiment, ”one particle” is defined as a peak position of the ADC distribution by singly charged particles passing through the detector. 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 shower particles from the observed ADC value for each hit detector.

Analysis

As shown in the previous paper [7], the size of the air showers observed at Yangbajing with small zenith angle is almost independent of the nature of the primary particles when their primary energies are higher than 100 TeV. Thus, the following criteria are applied to select the events for the analysis.

1) The zenith angle (θ) of each air-shower event should be smaller than 25°, or $\sec\theta \leq$ 1.1 to minimize the primary mass dependence on the air shower size at Yangbajing altitude.

2) More than 10 detectors should detect a signal of more than five particles per detector. 3) 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.

It is confirmed by simulations that the air showers induced by primary particles with $E_0 \geq$ 100 TeV and $\sec\theta \leq$ 1.1 can be fully detected without any bias under above mentioned criteria. The total effective area S $\times$ Ω is calculated to be 10410 m^2·sr for all primary particles with $E_0 \geq$ 100 TeV. For the operation period from 2000 November through 2004 October, the effective live time T is 2.21 years. The total number of air showers selected under the above conditions is 4.1 $\times$ 10^7 events.

The shower size of an event is estimated by fitting the lateral distribution of the shower particles using the following modified NKG functions, which are optimized by Monte Carlo simulation using QGSJET+HD, QGSJET+PD and SIBYLL+HD models independently,

$$f(r,s) = \frac{N_e}{C(s)}(\frac{r}{{r_m}'})^{a(s)}(1+\frac{r}{{r_m}'})^{b(s)}/{r_m}'^2 \quad (1)$$

$$C(s) = 2\pi B(a(s)+2, -b(s)-a(s)-2) \quad (2)$$

where ${r_m}'$ = 30 m, and the variable s corresponds to the age parameter, N_e the total number of shower particles and B denotes the beta function. Other details are described in ref.[3].

It is confirmed by simulations that the difference of the size estimation between QGSJET+HD-fit and QGSJET+PD-fit is within 2%, and the difference between QGSJET+HD-fit and SIBYLL+HD-fit is within 5%. We obtained a good correlation between the true shower size and the estimated shower size, where the true shower size (Ne_{true}) means particle number calculated for infinitely large carpet array while the estimated shower size (Ne_{est}) does the fit value for real Tibet-III array using the modified NKG function described above (Eq.(1),(2)). We found that the shower size is well reproduced with standard deviation of 7%, 9% and 9% for the size N_e above 10^5 in the case of QGSJET+HD, QGSJET+PD and SIBYLL+HD model, respectively. In Fig. 1 we show the model dependence of the air shower size spectrum of nearly vertical air showers. One can see that the model dependence of the AS size is small (less than 3% in absolute intensity on the primary composition model, while less than 5% in absolute intensity on the hadronic interaction models).

Thus, we can obtain the correlation between the estimated shower size N_e and the primary energy E_0 for each interaction models and composition models. The conversion function from the shower size N_e to the primary energy E_0 can be expressed by the following equation for $\sec\theta \leq$ 1.1,

$$E_0 = a \times (\frac{N_e}{1000})^b \quad [\text{TeV}], \quad (3)$$

The energy resolution is estimated by our simulation as 36% and 17% at energies around 200 TeV and 2000 TeV in the case of QGSJET+HD model, respectively, corresponding values for

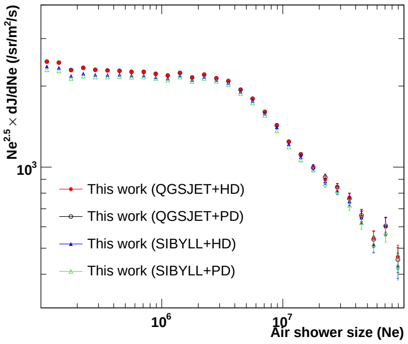

Figure 1: The model dependence of the size spectrum of nearly vertical air showers

Model	knee position (PeV)	Index of spectrum
QGSJET +HD	(4.0 ± 0.1)	γ1= -2.69 ± 0.01 γ2= -3.13 ± 0.01
QGSJET +PD	(3.3 ± 0.1)	γ1= -2.64 ± 0.01 γ2= -3.12 ± 0.01
SIBYLL +HD	(3.7 ± 0.1)	γ1= 2.68 ± 0.01 γ2= 3.12 ± 0.01

Table 1: The summary of the measured all-particle energy spectrum and knee region parameters are listted. γ1 is the best fitted-index for the energy below 1 PeV, and the γ2 is for the energy above 4 PeV.

SIBYLL+HD model are 38% and 19%, corresponding values for QGSJET+PD model are 39% and 19%.

Results and Discussions

On the basis of all the discussions above, we obtained the all particle energy spectrum between 1×10^{14} eV and 1×10^{17} eV based on the QGSJET+HD model, QGSJET+PD model and the SIBYLL+HD as shown in Fig. 2(a), where the black circle denotes the QGSJET + HD model, the red circle the SIBYLL + HD model, and the green star the QGSJET + PD model, respectively. Form Fig. 2(a), the position of the knee is clearly seen at around 4 PeV, and the interaction model dependence is less than 5% in absolute intensity, and the composition model dependence is less than 20% in absolute intensity. Fig. 2(b) shows our result compared with other experiments. This work is about 4% lower than old result [16] below 1PeV and 15% lower above 4 PeV. This difference is due to the upgrade of MC calculations. The summary of the measured all-particle energy spectrum and knee region parameters are listted in the Table 1, γ1 is the best fitted-index for the energy below 1 PeV, and the γ2 is for the energy above 4 PeV.

Conclusion

We present an updated all-particle energy spectrum using data set collected in the period from 2000 November through 2004 October by Tibet-III airshower array. Monte Carlo calculation has been upgraded using the new simulation codes, and we obtained the all-particle energy spectrum of cosmic rays in a wide range over 3 decades between 10^{14} eV and 10^{17} eV, and found that the knee of the spectrum is located around 4 PeV. The interaction model dependence in deriving the all-particle spectrum is found to be small (less than 5% in absolute intensity, 10% in position of the knee, and the composition model dependence is less than 20% in absolute intensity).

References

[1] Lagage, P.O., et al., Astron. Astrophys. **118**,223, 1983.

[2] Peters, B., Nuovo Cimento **22**, 800, 1961.

[3] M. Amenomori et al., Advances in Space Research 2006 (COSPAR) (2006).

[4] Heck, D., et al., Report **FZKA 6019**, 1998;

[5] M. Amenomori et al., Phys. Rev. D 62, 112002 (2000).

[6] Kasahara K., `http://cosmos.n.kanagawa-u.ac.jp/EPICSHome/index.html`.

[7] Amenomori, M., Cao, et al., ApJ. **461**, 408, 1996.

[8] K. Asakimori, et al., *ApJ*, 502, 278, 1998.

[9] A.V. Sukhadolskaya, et al., *Astropart. Phys.*,16, 13, 2001.

[10] N.L. Grigorov, et al., ICRC12. (Hobart), Vol.5, 1746, 1971.

[11] T. Antoni, et al., *Astropart. Phys.*, 24, 1, 2005.

[12] S. Ogio, et al., ApJ. 612, 268, 2004.

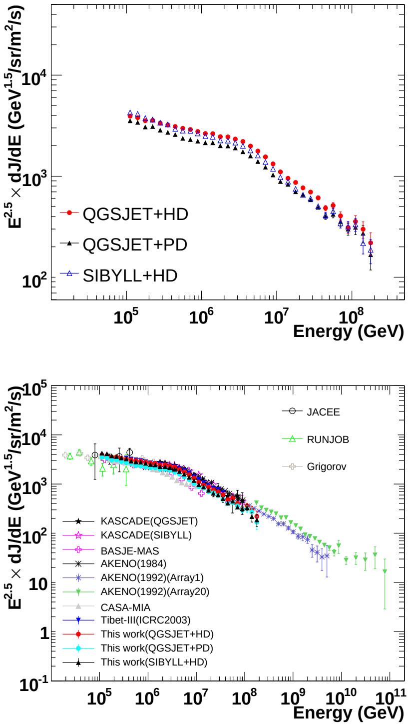

Figure 2: The differential energy spectra of all particle obtained by the present experiment (a), and they are compared with other experiments (b). JACEE [8],RUNJOB [9], Grigorov [10], KASCADE [11], BASJE-MAS [12], AKENO(1984) [13], AKENO(1992) [14], CASA-MIA [15], Tibet-III(ICRC2003) [16].

[13] M. Nagano, et al., *J. Phys. G*, 10, 1295, 1984.
[14] M. Nagano, et al., *J. Phys. G: Nucl. Part. Phys.*, 18, 423, 1992.
[15] M.A.K. Glasmacher, et al., *Astropart. Phys.*, 10, 291, 1999.
[16] M. Amenomori, et al., ICRC28, (Tsukuba), Vol.1, 143, (2003).