The energy spectrum of all-particle cosmic rays around the knee region observed with the Tibet air-shower array

The Tibet ASγ Collaboration
M. Amenomori,[1] S. Ayabe,[2] S.W. Cui,[3] Danzengluobu,[4] L.K. Ding,[3] X.H. Ding,[4] C.F. Feng,[5] Z.Y. Feng,[6] X.Y. Gao,[7] Q.X. Geng,[7] H.W. Guo,[4] H.H. He,[3] M. He,[5] K. Hibino,[8] N. Hotta,[9] Haibing Hu,[4] H.B. Hu,[3] J. Huang,[9] Q. Huang,[6] H.Y. Jia,[6] F. Kajino,[10] K. Kasahara,[11] Y. Katayose,[12] K. Kawata,[13] Labaciren,[4] G.M. Le,[14] J.Y. Li,[5] H. Lu,[3] S.L. Lu,[3] X.R. Meng,[4] K. Mizutani,[2] J. Mu,[7] H. Nanjo,[1] M. Nishizawa,[15] M. Ohnishi,[13] I. Ohta,[9] T. Ouchi,[13] S. Ozawa,[9] J.R. Ren,[3] T. Saito,[16] M. Sakata,[10] T. Sasaki,[8] M. Shibata,[12] A. Shiomi,[13] T. Shirai,[8] H. Sugimoto,[17] K. Taira,[17] M. Takita,[13] Y.H. Tan,[3] N. Tateyama,[8] S. Torii,[8] H. Tsuchiya,[13] S. Udo,[2] T. Utsugi,[8] B.S. Wang,[3] H. Wang,[3] X. Wang,[2] Y.G. Wang,[5] L. Xue,[5] Y. Yamamoto,[10] X.C. Yang,[7] Z.H. Ye,[14] G.C. Yu,[6] A.F. Yuan,[4] T. Yuda,[13] H.M. Zhang,[3] J.L. Zhang,[3] N.J. Zhang,[5] X.Y. Zhang,[5] Y. Zhang,[3] Zhaxisangzhu,[4] and X.X. Zhou[6]
(1) Dept. of Phys., Hirosaki Univ., Hirosaki, Japan (2) Dept. of Phys., Saitama Univ., Saitama, Japan (3) IHEP, CAS, Beijing, China (4) Dept. of Math. and Phys., Tibet Univ., Lhasa, China (5) Dept. of Phys., Shandong Univ., Jinan, China (6) Inst. of Modern Phys., SW Jiaotong Univ., Chengdu, China (7) Dept. of Phys., Yunnan Univ., Kunming, China (8) Faculty of Eng., Kanagawa Univ., Yokohama, Japan (9) Faculty of Ed., Utsunomiya Univ., Utsunomiya, Japan (10) Dept. of Phys., Konan Univ., Kobe, Japan (11) Faculty of Systems Eng., Shibaura Inst. of Technology, Saitama, Japan (12) Dept. of Phys., Yokohama Natl. Univ., Yokohama, Japan (13) ICRR, Univ. of Tokyo, Kashiwa, Japan (14) CSSAR, CAS, Beijing, China (15) NII, Tokyo, Japan (16) Tokyo Metropolitan Coll. of Aeronautical Eng., Tokyo, Japan (17) Shonan Inst. of Technology, Fujisawa, Japan

Abstract

The Tibet air-shower array was upgraded in 2000 by adding wide dynamic range PMTs to 221 sets of all detectors which are placed on a lattice of 15 m spacing in the area of the Tibet-III array. Using the data set collected in the period from 2000 November through 2001 October with this array, we obtained the energy spectrum of primary cosmic rays in the energy region above 5×10^{14} eV.

1. Introduction

It is well known that the energy spectrum of primary cosmic rays changes its slope at energies between 10^{15} and 10^{16} eV. This energy region is called as the knee and many arguments have so far been made about its origin. Such a steepening of the spectrum or the existence of the knee is considered to be deeply related to the breakdown of a cosmic-ray acceleration mechanism at sources or leakage of cosmic rays from the trapping zone in the Galactic disk. However, a general agreement is not reached yet about the shape of the knee and its position, although many measurements have been done on the energy spectrum around the knee.

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We presented the all-particle energy spectrum around the knee in 1996 with most accurate way at that time using the data obtained with a small air shower array (Tibet-I array) [1]. It is important to note that air showers induced by primary particles with energies $\sim 10^{15}$ - 10^{16} eV reach their maximum developments at Yangbajing altitude of 4,300 m so that their size fluctuations become a minimum. This fact enables us to estimate the primary energy spectrum around and beyond the knee with smallest ambiguity.

The Tibet-I array has been gradually improved to increase its sensitivity for high energy gamma-ray astronomy and then the Tibet-III array was constructed in the late fall of 2000. In this paper, we present a preliminary result on the energy spectrum of primary cosmic rays using the data set obtained with the Tibet-III array.

2. Experiment

The Tibet-III air shower array, consisting of 533 scintillation detectors of each 0.5 m^2 with the area of 22,050 m^2, has been successfully operating since 1999 with energy threshold of a few TeV. In the fall of 2000, this array was further improved for UHE cosmic-ray study by adding wide dynamic range PMTs to all 221 sets of detectors which are placed on a lattice of 15 m spacing in the detector covering area of 36,900 m^2. This PMT in each detector can be measured to the number of particles beyond 4,000, so that UHE cosmic rays with energy above the knee could be observed with sufficient accuracy.

3. Simulation

We have done an extensive Monte Carlo (MC) simulation to generate air showers induced by primary cosmic rays in the atmosphere using a Cosmos code with an ad-hoc model [2] which is expected to give a similar result by a CORSIKA code with QGSJET model [3]. All shower particles are followed untill their energies become 1 MeV in the atmosphere. We also used an Epics code [4] to calculate the energy deposit of these shower particles in the scintillator inside each detector under the same conditions as the experiment.

Primary particles are uniformly injected at the top of the atmosphere assuming a heavy dominant model [1]. Air shower events induced by these primaries in the atmosphere are uniformly thrown on the Tibet-III detector area. Each airshower event is observed with the Tibet-III array like the actual experiment.

In this experiment, the number of one particle is defined as a peak position of the ADC distribution recorded by singly charged particles passing through the detector. According to the MC, the peak value of energy deposit for a single particle in each detector is calculated to be 5.52 MeV. Based on these results, we can easily estimate the number of shower particles from the observed ADC value for each hit detector.

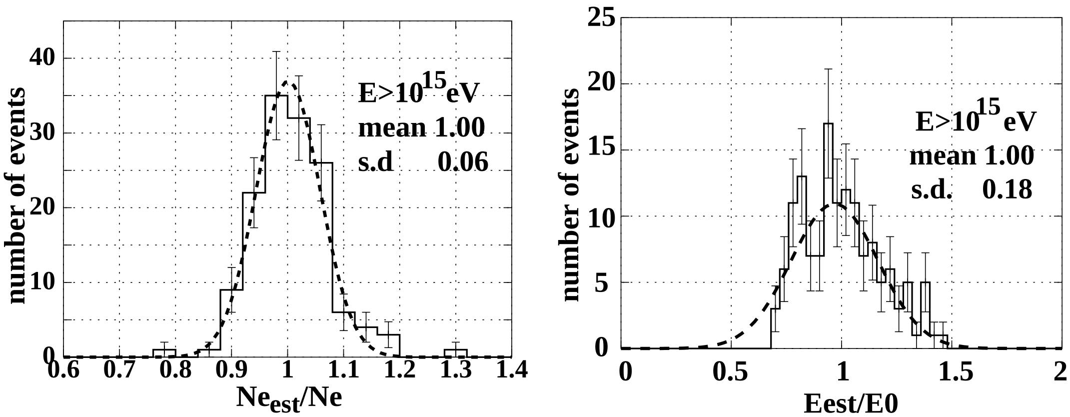

Fig. 1. Distribution of Ne_{est}/Ne and E_{est}/E_0 for MC events in the primary energy region over 10^{15} eV. For the estimation of size and primary energy, see text.

4. Data Analysis

As shown in the previous paper [1], the air showers observed at Yangbajing with smaller zenith angles are almost independent of the nature of the primary particles when their primary energies are higher than several $\times 10^{14}$ eV. Hence, we selected the high-energy shower data from the original data set by imposing the following conditions ; 1) The zenith angle (θ) of each shower event should be smaller than 25°, or $\sec\theta \leq 1.1$, 2) more than 10 detectors should detect a signal of more than five particles/detector, and 3) the center of positions weighted 8th power of the number of detected particles of each shower should be inside the innermost 135 m× 135 m area.

It is confirmed that this large power value is very useful for estimating the effective area of the array. For the lateral fitting of shower particles, however, a much smaller value of the power, say 2.0, is better to estimate the core position.

We used the data set obtained with the Tibet-III array in the period from 2000 November through 2001 October. Then, the total number of air showers selected under the conditions mentioned above was 2.73×10^8 events. Monte Carlo events are also selected under the same conditions as the experiment.

Each air shower size was calculated by fitting a modified NKG function [1] to the experimental data and MC data. A conversion factor from the air shower size to the primary energy was calculated as a function of air-shower size by the MC simulation.

In Figure 1, we compare the estimated shower size (Ne_{est}) and primary energy (E_{est}) with the true size (Ne) and energy (E_0), respectively, for MC events. Here, the size is estimated by using the modified NKG function and the primary energy is estimated by multiplying the conversion factor. It is seen that the estimation of size and primary energy is well done with a good accuracy in the knee energy region. However, there are still some problems when we apply the above method to the events with small size of $< 10^5$ ($E_0 < 3 \times 10^{14}$ eV) and its study is under way.

The total effective area $S \times \Omega$ is calculated to be $9.91 \times 10^3 \mathrm{m}^2\mathrm{sr}$ for all primary particles with energy greater than 3×10^{14} eV. In this experiment, the effective running time T of the array was 2.77×10^7 s.

5. Result and Summary

Figure 2. shows the differential energy spectrum of all-particle cosmic rays observed with the Tibet-III air shower array. Although the present result is still preliminary and systematic errors are under extensive study, it seems to be consistent with the Tibet-I data above 2000TeV and a small possible deviation seen below 2000TeV may be attributed to a better energy resolution of the Tibet-III array compared to the Tibet-I array.

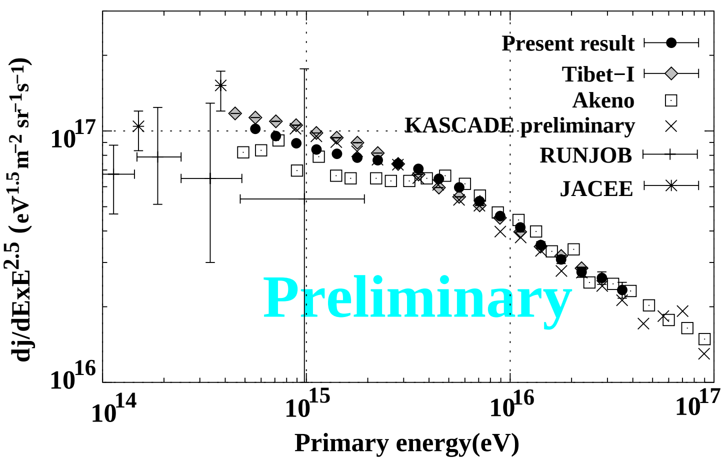

Fig. 2. Differential energy spectrum of primary cosmic rays between 5×10^{14} and 3×10^{16} eV. The present result is compared with other data.

Dependence of the result on simulation codes, interaction models, primary models, other possible systematic biases should be carefully checked. And the analysis of the data taken in 2001-2002 is still going on.

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