View metadata, citation and similar papers at core.ac.uk
brought to you by CORE
provided by CERN Document Server

29th International Cosmic Ray Conference Pune (2005) **6**, 177–180

Primary cosmic-ray proton and helium spectra at the knee energy region measured by the Tibet hybrid AS experiment

The Tibet ASγ Collaboration

M. Amenomori[a], S. Ayabe[b], D. Chen[c] S.W. Cui[d], Danzengluobu[e], L.K. Ding[d], X.H. Ding[e], C.F. Feng[f], Z.Y. Feng[g], X.Y. Gao[h], Q.X. Geng[h], H.W. Guo[e], H.H. He[d], M. He[f], K. Hibino[i], N. Hotta[j], Haibing Hu[e], H.B. Hu[d], J. Huang[k], Q. Huang[g], H.Y. Jia[g], F. Kajino[l], K. Kasahara[m], Y. Katayose[c], C. Kato[n], K. Kawata[k], Labaciren[e], G.M. Le[o], J.Y. Li[f], H. Lu[d], S.L. Lu[d], X.R. Meng[e], K. Mizutani[b], J. Mu[h], K. Munakata[n], A. Nagai[p], H. Nanjo[a], M. Nishizawa[q], M. Ohnishi[k], I. Ohta[j], H. Onuma[b], T. Ouchi[i], S. Ozawa[k], J.R. Ren[d], T. Saito[r], M. Sakata[l], T. Sasaki[i], M. Shibata[c], A. Shiomi[k], T. Shirai[i], H. Sugimoto[s], M. Takita[k], Y.H. Tan[d], N. Tateyama[i], S. Torii[t], H. Tsuchiya[u], S. Udo[k], H. Wang[d], X. Wang[b], Y.G. Wang[f], H.R. Wu[d], L. Xue[f], Y. Yamamoto[l], C.T. Yan[k], X.C. Yang[h], S. Yasue[n], Z.H. Ye[o], G.C. Yu[g], A.F. Yuan[e], T. Yuda[i], H.M. Zhang[d], J.L. Zhang[d], N.J. Zhang[f], X.Y. Zhang[f], Y. Zhang[d], Yi Zhang[d], Zhaxisangzhu[e] and X.X. Zhou[g]

(a) Department of Physics, Hirosaki University, Hirosaki 036-8561, Japan
(b) Department of Physics, Saitama University, Saitama 338-8570, Japan
(c) Faculty of Engineering, Yokohama National University, Yokohama 240-8501, Japan
(d) Key Lab. of Particle Astrophys., Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China
(e) Department of Mathematics and Physics, Tibet University, Lhasa 850000, China
(f) Department of Physics, Shandong University, Jinan 250100, China
(g) Institute of Modern Physics, South West Jiaotong University, Chengdu 610031, China
(h) Department of Physics, Yunnan University, Kunming 650091, China
(i) Faculty of Engineering, Kanagawa University, Yokohama 221-8686, Japan
(j) Faculty of Education, Utsunomiya University, Utsunomiya 321-8505, Japan
(k) Institute for Cosmic Ray Research, the University of Tokyo, Kashiwa 277-8582, Japan
(l) Department of Physics, Konan University, Kobe 658-8501, Japan
(m) Faculty of Systems Engineering, Shibaura Institute of Technology, Saitama 337-8570, Japan
(n) Department of Physics, Shinshu University, Matsumoto 390-8621, Japan
(o) Center of Space Science and Application Research, Chinese Academy of Sciences, Beijing 100080, China
(p) Advanced Media Network Center, Utsunomiya University, Utsunomiya 321-8585, Japan
(q) National Institute of Informatics, Tokyo 101-8430, Japan
(r) Tokyo Metropolitan College of Aeronautical Engineering, Tokyo 116-0003, Japan
(s) Shonan Institute of Technology, Fujisawa 251-8511, Japan
(t) Advanced Research Institute for Science and Engineering, Waseda University, Tokyo 169-8555, Japan
(u) RIKEN, Wako 351-0198, Japan

Presenter: J.Huang (huang@icrr.u-tokyo.ac.jp), jap-huang-J-abs3-he12-oral

A hybrid experiment was carried out to study the cosmic-ray primary composition in the 'knee' energy region. The experimental set-up consists of the Tibet-II air shower array(AS), the emulsion chamber (EC) and the burst detector (BD) which are operated simulteneously and provides us information on the primary species. For three-year operation, we have observed 177 γ-families ($\sum E_\gamma > 20$ TeV) accompanying air showers with the shower size $N_e > 2 \times 10^5$. Using this data set and a neural network method to select proton and helium induced events, the primary proton and helium energy spectra are obtained between 10^{15} and 10^{16} eV. The proton spectrum, thus obtained, can be expressed by a single power-law function with a differential index of -3.01 ± 0.11 and -3.05 ± 0.12 based on the QGSJET+HD and SIBYLL+HD models, respectively, which are steeper than that extrapolated from the direct observations of -2.74 ± 0.01 in the energy range below 10^{14} eV.

Our experiment suggests that the main component responsible for making the knee structure of the all-particle spectrum is composed of nuclei heavier than helium.

1. Introduction

Cosmic ray energy spectrum can be well described by a power law dN/dE $\propto E^{\gamma}$ in the energy range from 10 GeV upto 100 EeV. The most prominent structure is a change of the spectral index from $\gamma_1 \simeq -2.7$ to $\gamma_2 \simeq$ -3.1 around energies of 3 PeV, it is so-called knee. There have been some calculations of the primary cosmic-ray energy spectrum based on various models on the origin of the knee [1], but all of them are still under debate due to the lack of detailed knowledge about the chemical composition around the knee. Among primary cosmic rays, protons are the key component for understanding the origin of the knee. Direct measurements of primary cosmic rays on board balloons or satellites are the best ways, however, the energy region covered by them are limited up to 100 TeV. The chemical composition of primary cosmic rays around the knee, therefore, has been studied with ground-based air-shower experiments and/or air Cherenkov telescopes. Since the sensitivity of the ground-based experiments to the mass separation among cosmic-ray nuclei is limited, only gross features such as average mass number have been discussed. It is possible, however, to improve the sensitivity of an air shower experiment to the primary cosmic-ray mass separation by adding a function to observe the energy-flow characteristics of air-shower cores at a high-mountain altitude. From the simulation study, following advantages in doing such an experiment are clarified. One is that the primary energy generating both of air showers and γ-families can be estimated with high accuracy due to small fluctuations in air shower size. Another is that the air shower events accompanied by γ-families are dominated by the protons and heliums among the primaries, thus, the Tibet hybrid experiment enables us to measure the primary proton and helium differential energy spectra by selecting proton and helium event by event, rather independent of the hadronic interaction models and the primary composition models at the knee energy region.

2. Experiment

The experimental set-ups of the emulsion chambers (ECs) and burst detectors (BDs) and the Tibet-II air shower array (AS) are described in the previous papers [2, 3]. The γ-family events for live time of 699.2 days are analyzed with the following criteria: ${E_\gamma}^{th} = 4$ TeV, $N_\gamma \geq 4$, $\sum_i {E_\gamma}^i \geq 20$ TeV and $< R > \geq 0.2$ cm, where ${E_\gamma}^{th}$ is the minimum energy for a cascade shower, N_γ the number of cascade showers in a γ-family, $\sum E_\gamma$ the sum energy of cascade showers in a γ-family and $< R >$ ($< R > = \sum_i {r_\gamma}^i / N_\gamma$) the mean lateral spread in a γ-family. In this experiment, we observed a total of 177 γ-family events, each of which is accompanied by an air shower with $N_{\mathrm{e}} > 2 \times 10^5$ corresponding approximately to 5×10^{14} eV for protons. In the following analysis, we present our results based on the ECs and AS data, as those obtained from the BDs data were published in the previous paper[2].

3. Simulation and Analysis

We have carried out a detailed Monte Carlo (MC) simulation of air showers and γ-families using the simulation code CORSIKA (version 6.030) including QGSJET01 and SIBYLL2.1 hadronic interaction models [4]. Two primary cosmic-ray composition models are examined as the input energy spectra, namely a heavy dominant (HD) and a proton dominant (PD) ones [2]. The method of the Monte Carlo simulation is almost the same as the one described in the previous papers [2, 3]. The simulated events are passed through the same analysis chains as the experimental data. The selection of the proton-induced events is made with use of a feed-forward

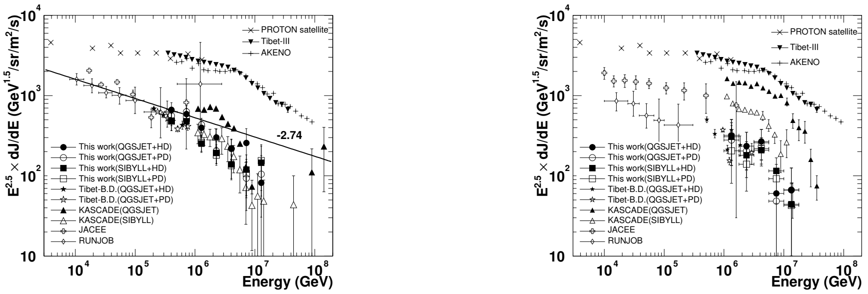

Figure 1. Energy spectra of primary cosmic-rays obtained by the present experiment. Left panel: primary protons; right panel: primary heliums. This work is compared with results from other experiments: Tibet-B.D. [2], KASCADE [6], JACEE [7] and RUNJOB [8]. The all-particle spectra are from the experiments : PROTON satellite [9], Tibet-III [10] and AKENO [11]. For the solid line with the power index -2.74, see the text.

artificial neural network (ANN [5]) whose applicability to our experiment was well confirmed by the Monte Carlo simulation [2].

4. Results and Discussions

In Fig. 1, we show the measured energy spectra of primary protons assuming the two interaction models (QGSJET and SIBYLL) and two primary composition models (HD and PD), together with the results from other experiments. As seen in Fig. 1, the present results assuming the HD and PD models in the simulation are in good agreement with each other within the statistical errors. This demonstrates that the selection of primary cosmic-ray protons is successfully made by the ANN method. The measured proton energy spectra can be expressed by a single power-law function with a differential spectral index, $J(E)(\mathrm{m}^{-2}{\cdot}\mathrm{s}^{-1}{\cdot}\mathrm{sr}^{-1}{\cdot}\mathrm{GeV}^{-1}) = A \times 10^{-13} \times (\frac{E}{10^6 GeV})^{-B}$, where (A,B) is $(4.56 \pm 0.46, 3.01 \pm 0.11)$, $(4.14 \pm 0.44, 3.08 \pm 0.11)$, $(3.21 \pm 0.34, 3.05 \pm 0.12)$ and $(3.24 \pm 0.34, 3.08 \pm 0.12)$ based on the QGSJET+HD, QGSJET+PD, SIBYLL+HD and SIBYLL+PD models, respectively, where the errors quoted are the statistical ones. The error in the spectral index is statistics dominant, while that in the absolute flux value is model-dependence dominant. For the absolute flux value, the QGSJET model gives approximately 30% higher flux than the SIBYLL model. This can be mainly attributed to the difference of Feynman x_F-distribution of charged mesons between QGSJET and SIBYLL model in the very forward region at a collision [4]. The Feynman x_F-distribution in the SIBYLL model is harder than that in the QGSJET model in the $x_F > 0.2$ region, so that the generation efficiency of γ-families by the former model becomes higher than the latter, resulting in a lower proton flux in the case of the SYBYLL model. A solid straight line with the power index -2.74 drawn in Fig. 1 is the best fitted line for the data points in the energy region below 100 TeV observed by recent direct measurements [12], which is harder than the indices of our proton spectra. This is consistent with the shock acceleration scenario at the supernova remnants and the heavy-enriched chemical composition at the knee energy region.

The ANN method is again applied to separate the observed events into the proton+helium group and the others. As shown in Fig. 1, the helium spectra are obtained by subtracting the proton spectra from the proton+helium spectra. The same model dependence is seen as in the case of proton spectra.

We can also estimate the fraction of the heavy nuclei in cosmic rays around the knee using the proton+helium spectra and the all-particle energy spectrum obtained by the Tibet air shower array [10]. Shown in Fig. 2 is the fraction of primary cosmic rays heavier than helium nuclei obtained by using the QGSJET model and the SIBYLL model which are compared with those obtained recently by the KASCADE experiment [6].

Our results which are rather model independent within statistics indicate the average mass of primary cosmic rays is going up around the knee, towards the direction of heavy dominance. The obtained proton flux is better accommodated by the HD model. On the other hand, the KASCADE results which measures both the electron shower size (N_e) and muon shower size (N_μ) to deduce the energy spectrum of separate mass groups from the all-particle energy spectrum, strongly depend on the interaction models. N_μ contained in the air shower depends on the number of charged pions produced in the central and backward region (in the center of mass system) in the collisions of primary cosmic rays on air nuclei, which has a sizeable uncertainties experimentally as well as theoretically and is largely dependent on the interaction models. From this point of view, the size of low-energy muons N_μ may not be a suitable parameter for separating the air showers into different primary mass groups.

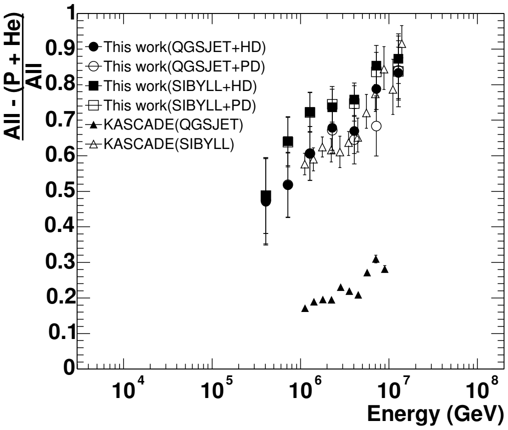

Figure 2. Fraction of the primary cosmic-rays heavier than helium nuclei obtained by assuming the QGSJET and SIBYLL interaction models. Our results are compared with those by the KASCADE experiment[6].

5. Acknowledgements

This work is supported in part by Grants-in-Aid for Scientific Research on Priority Areas (MEXT) and by Scientific Research (JSPS) in Japan, and by the Committee of the Natural Science Foundation and by Chinese Academy of Sciences in China.

References

[1] J.R. Hörandel, Astropart. Phys. 21, 241 (2004).
[2] M. Amenomori et al., Phys. Rev. D 62, 112002 (2000).
[3] M. Amenomori et al., Advances in Space Research 2004 (COSPAR) (2004).
[4] D. Heck, et al., Report **FZKA 6019**, 1998 ; http://www-ik3.fzk.de/ ~heck/corsika /physics_description/corsika_phys.html.
[5] L. Lonnblad, et al., Comp. Phys. Com. 81, 185 (1994).
[6] K.-H. Kampert et al., Acta Phys. Polon. B 35, 1799 (2004); A. Haungs et al., astroph/0312295.
[7] K. Asakimori et al., ApJ 502 278 (1998).
[8] A.V. Apanasenko et al., Astropart. Phys. 16, 13 (2001).
[9] N.L. Grigorov et al., Proc. 12th ICRC, Hobart, 5, 1746 (1971).
[10] M. Amenomori et al., Proc. 28th ICRC, Tsukuba, 1, 143 (2003).
[11] M. Nagano et al., J. Phys. G 10 1295 (1984).
[12] T.K. Gaisser, et al., Proc. 27th ICRC, Hamburg, 5 1643 (2001).