

Primary cosmic-ray energy spectrum around the knee energy region measured by the Tibet hybrid experiment

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Abstract.

The Tibet hybrid experiment composed of emulsion chambers, burst detectors and the Tibet-II air-shower array was done at Yangbajing (4,300m above sea level, 606 g/cm²) in Tibet. For 3-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 deduced 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 result suggests that the main component responsible for making the knee structure of the all-particle spectrum should be composed of nuclei heavier than helium.

1. Introduction

The energy spectrum of cosmic rays is represented by a power-law function in a wide energy range from about 10^{10} eV to 10^{20} eV, however, it shows slight changes of the power-law index at several points. These break points of the power-law spectrum are assumedly related to the origin, acceleration mechanism and propagation mechanism of cosmic rays in the Galaxy. One of them, in which the present paper is concerned, is traditionally referred to as the “knee” located around 3×10^{15} eV. Many experiments have reported that the power-law indices below and above the knee approximately take the values -2.7 and -3.1 , respectively. Although existence of the knee has been well established experimentally, there still remain controversial arguments on its origin. One of them is a possibility that acceleration mechanism could be less effective above the knee. Along with this line, there is a general consensus that stochastic shock acceleration at supernova blast waves could explain the cosmic-ray spectrum up to about $Z \times 10^{14}$ eV [?], or perhaps even higher to $Z \times 10^{15}$ eV [?], where Z denotes the atomic number, despite lack of direct evidence. Another argument attributes the knee structure to the leakage of the cosmic rays from the galaxy [?]. It is noted that both scenarios mentioned above give a rigidity-dependent cutoff for each chemical component leading to a heavy-enriched composition of primary cosmic rays at the knee. On the other hand, there is another approach in which cosmic rays around and beyond the knee are assumed to be of extra-galactic origin such as the active galactic nuclei [?] or gamma-ray bursts [?]. In this case, the primary chemical composition is expected to become proton-enriched. There have been some calculations of the primary cosmic-ray energy spectrum based on various models on the origin of the knee [?], but all of them are still under debate due to 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 10^{14} eV. 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 to the mass separation among cosmic-ray nuclei with ground-based experiments is limited, only gross features such as average mass number have been discussed. A lot of reports have so far been made on the energy spectrum as well as the chemical composition of primary cosmic rays, however, there are still serious disagreements among them especially on the chemical composition [?].

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. The Tibet hybrid experiment [?] was designed to detect γ -families in an air shower core by large-area emulsion chambers in coincidence with an accompanied air shower, where a bundle of energetic γ -rays and electrons in the emulsion chambers are called a γ -family caused by a young air shower. Among primary cosmic rays, protons can penetrate deep into

the atmosphere and produce a young air shower accompanied by a γ -family event most efficiently due to their longest interaction mean free path in the air. Therefore, tagging an air shower with a γ -family event favors to the proton component naturally. Another merit in doing a hybrid experiment in Tibet is that the atmospheric depth of the experimental site (4300 m a.s.l., 606 g/cm²) is close to the maximum development of the air showers with energies around the knee irrespective of the masses of primary cosmic rays. We can determine the primary cosmic-ray energy much less dependently upon the chemical composition [?] than those experiments at sea level.

In this paper, we briefly report on the study of the energy spectra of the proton and helium components in cosmic rays around the knee energy region obtained with the Tibet hybrid experiment.

2. Experiment

The Tibet hybrid experiment, consisting of emulsion chambers (ECs), burst detectors (BDs) and the Tibet-II air-shower (AS) array, composed of 298 scintillation counters each placed on a 15 m square grid with an enclosed area of 36,900 m² was operated at Yangbajing in Tibet during the period from August 1996 through August 1999[?], and a total live time of 699.2 days.

The Tibet-II AS array is used to measure the shower size and the arrival direction of each air shower. Any fourfold coincidence in the detectors is used as the trigger condition for air-shower events. The air shower direction can be estimated with an error smaller than 1°. The primary energy of each event is determined by the shower size N_e . The energy resolution is estimated to be about 17 % at energies around 10¹⁵ eV by our simulation, almost independent of the interaction models used.

The ECs and the BDs are constructed near the center of the AS array [?], and are used to detect high-energy air shower cores accompanied by air showers induced by primary cosmic rays with energies above $\sim 10^{14}$ eV. The total area of ECs is 80 m². The basic structure of each EC is a multilayered sandwich of lead plates and photosensitive films of 40 cm \times 50 cm in area, where photosensitive films are put every 2 cascade units (here, one cascade unit is taken to be 0.5 cm) of lead in the chamber. The photosensitive films in ECs are replaced by new ones every year to reduce the background. The ECs are used to measure the energy and the position and the arrival direction of each γ -family shower with energies above 1 TeV. The BDs with the same area are placed just below ECs, namely, 4 ECs are set above one unit of the BD. Thus, 400 blocks of ECs and 100 BDs in total are used in this experiment. A burst event is triggered when any twofold coincidence of signals from four photodiodes of a BD appears. When the BDs trigger an event, its accompanying air shower is simultaneously recorded. The BDs are used to measure the burst size N_b and the position of each air shower core with energies above 1 TeV. The arrival direction of the γ -family event is determined by the spatial reconstruction of the cascade showers in ECs, whose details are described in [?]. The matching between an AS and a BD events is made by their arrival time stamps, and

Table 1. Fractions of the proton and helium components in the assumed primary cosmic-ray spectrum for the HD and PD models(upper table), together with those of the same components responsible for making air showers accompanied by γ -families (lower table) after the γ -family selection (see the Section 4).

Primary		HD		PD	
	Energy (eV)	P	He	P	He
Generated	$10^{14} - 10^{15}$	22.6	19.2	39.0	20.4
(%)	$10^{15} - 10^{16}$	11.0	11.4	38.1	19.4

Primary			HD		PD	
	Energy (eV)	Int.model	P	He	P	He
After γ -family selection (%)	$10^{14} - 10^{15}$	QGSJET	87.3 ± 1.2	12.6 ± 1.2	91.8 ± 0.8	8.1 ± 0.8
	$10^{15} - 10^{16}$		58.9 ± 0.9	27.2 ± 0.8	80.0 ± 0.6	16.0 ± 0.6
After γ -family selection (%)	$10^{14} - 10^{15}$	SIBYLL	87.2 ± 0.8	12.6 ± 0.8	94.2 ± 0.6	5.7 ± 0.6
	$10^{15} - 10^{16}$		57.3 ± 0.7	24.2 ± 0.7	78.7 ± 0.6	17.9 ± 0.6

the matching between a γ -family event in EC and the BD candidate events is made by their positional correlation, and finally the matching between the γ -family event in EC and the corresponding AS event is made by their directional correlations.

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[?].

3. Simulation

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 [?]. Two primary cosmic-ray composition models are examined as the input energy spectra, namely a heavy dominant (HD) and a proton dominant (PD) ones [?]. The method of the Monte Carlo simulation is almost the same as the one described in the previous paper [?]. The simulated events are passed through the same analysis chains as the experimental data. The fraction of the proton and helium components in the assumed primary cosmic-ray flux models are summarized in Table ??, and that of the same components responsible for making air showers accompanied by γ -families after the γ -family selectiondescribed in the next section. It is worthwhile to note that more than 80 % of the selected γ -family events are induced by protons and helium nuclei even if we assume the HD model in the energy range below 10^{16} eV. This is the reason why we can obtain the primary cosmic-ray proton and helium fluxes from the Tibet hybrid experiment reliably.

4. Analysis

Shower spots registered by high-energy γ -rays or electrons in the photosensitive films were analyzed by using an automatic image scanner [?]. The γ -family events are selected by imposing the conditions of $E_{th} = 4$ TeV, $N_\gamma \geq 4$ and $\Sigma E_\gamma \geq 20$ TeV, where E_{th} is the minimum energy deposit for a cascade shower, N_γ the number of cascade showers in a γ -family and ΣE_γ the sum energy of cascade showers in a γ -family. In this experiment, we have observed a total of 177 γ -family events, each of which is accompanied by an air shower with $N_e > 2 \times 10^5$ corresponding approximately to 5×10^{14} eV for a proton.

The selection of the proton-induced events is made with use of a feed-forward artificial neural network (ANN) whose applicability to our experiment was well confirmed by the Monte Carlo simulation [?, ?]. Similar procedures are applied to obtain the helium energy spectrum.

The following six parameters are input to the ANN[?] with thirty hidden nodes and one output unit : (1) The sum energy of the γ -family ΣE_i in ECs, (2) the number of cascade showers in the family N_γ in ECs, (3) the mean lateral spread $\langle R \rangle = \Sigma r_i / N_\gamma$ in ECs, (4) the mean energy-flow spread $\langle ER \rangle = \Sigma E_i r_i / N_\gamma$ in ECs, where E_i and r_i are the energy of each cascade shower in the γ -family and its distance from the energy-weighted family-center, respectively, (5) the air shower size N_e in AS, and (6) $\sec \theta$, where θ is the zenith angle of the arrival direction of the air shower in AS. The target values for protons and others are set to 0 and 1, respectively. Then, we can obtain 111, 111, 112, 112 candidate events induced by protons out of 177 observed events based on the QGSJET+HD, QGSJET+PD, SIBYLL+HD and SIBYLL+PD models by setting the ANN output threshold to 0.4. The purity of protons is estimated to be 96.7 %, 97.4 %, 96.2 %, and 97.3 % between 10^{14} and 10^{15} eV and 83.1 %, 86.7 %, 82.8 %, and 86.1 % between 10^{15} and 10^{16} eV, based on the QGSJET+HD, QGSJET+PD, SIBYLL+HD, and SIBYLL+PD, respectively. The numbers of proton events thus selected agree within 4 %, irrespective of the assumptions of the input primary cosmic-ray chemical composition models and the interaction models used in the simulation.

5. Results and Discussions

In Fig. ?? and Fig. ??, we show the measured primary cosmic-ray proton energy spectra assuming the two interaction models QGSJET and SIBYLL, respectively, with two primary composition models (HD and PD), together with the results from other experiments.

As seen in Fig. ?? and Fig. ??, the present results assuming the HD and PD models in the simulation are in a good agreement with each other within the statistical errors. This demonstrates that the selection of primary cosmic-ray protons is successfully made by ANN method. The measured proton energy spectra can be expressed by a single power-law function with the differential power indices estimated to be -3.01 ± 0.11 ,

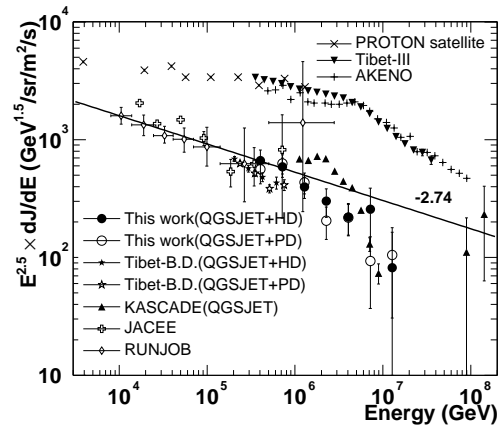


Figure 1. Energy spectra of primary cosmic-ray protons obtained by the present experiment assuming the QGSJET model in comparison with other experiments : Tibet-B.D. [?], KASCADE [?], JACEE [?], and RUNJOB [?]. The all-particle spectra are from the experiments : PROTON satellite [?], Tibet-III [?] and AKENO [?]. For the solid line with the power index -2.74, see the text.

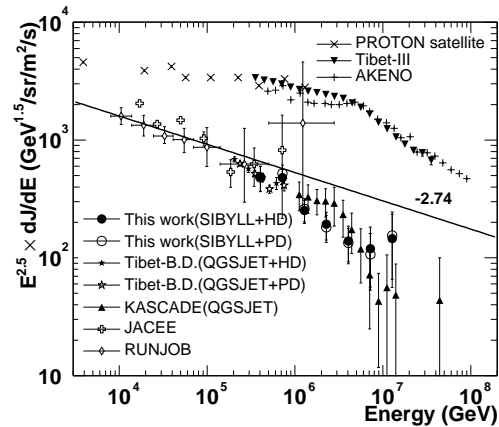


Figure 2. Energy spectra of primary cosmic-ray protons obtained by the present experiment assuming the SIBYLL model in comparison with other experiments : Tibet-B.D. [?], KASCADE [?], JACEE [?], and RUNJOB [?]. The all-particle spectra are from the experiments : PROTON satellite [?], Tibet-III [?] and AKENO [?]. For the solid line with the power index -2.74, see the text.

-3.08 ± 0.11 , -3.05 ± 0.12 and -3.08 ± 0.12 for the spectra based on the QGSJET+HD, QGSJET+PD, SIBYLL+HD and SIBYLL+PD models, respectively, where the errors quoted are the statistical ones. 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 between Feynman x_F -distribution of charged mesons in the very forward region at a collision [?]. The Feynman x_F -spectrum in the SYBYLL 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

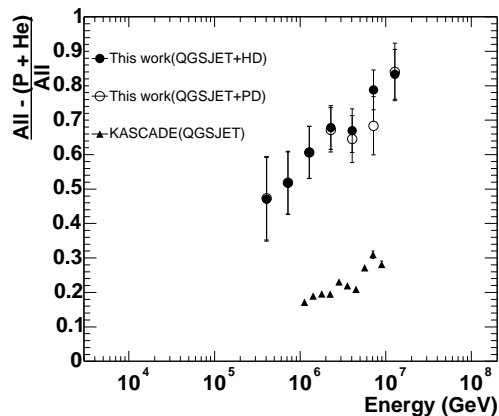


Figure 3. Fraction of the primary cosmic-rays heavier than helium nuclei obtained by assuming the QGSJET interaction models. Our results are compared with those by the KASCADE experiment[?].

proton flux in the case of the SYBYLL model. It should be noted that while the absolute flux obtained by our experiment depends slightly on the interaction models ($\sim 30\%$), the power index is much less model-dependent ($\sim 2\%$) than the absolute flux. As compared in Fig.1, the present results are consistent with those obtained by the burst detectors in this experiment within 25% [?], this implies that the systematic energy-scale uncertainty in our experiment is estimated to be 10% level. 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 10^{14} eV observed by recent direct measurements [?]. Our proton spectra are consistent with the shock acceleration scenario at the supernova remnants and the heavy-enriched chemical composition at the knee.

Thanks to its light mass, the helium component can also trigger our hybrid experiment although the efficiency is lower than in the case of protons. The ANN method is again applied to separate the observed events into the proton+helium group and the others. 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 nuclei heavier than helium in cosmic rays around the knee using the proton+helium spectra and the all-particle energy spectrum obtained by the Tibet air shower array [?]. Shown in Fig. ?? and Fig. ?? is the fraction of primary cosmic rays heavier than helium nuclei assuming the QGSJET model and the SIBYLL model, respectively, which are compared with those obtained recently by the KASCADE experiment. 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, while the KASCADE results which measures both air shower size (N_e) and muon size (N_μ) to deduce the energy spectrum of separate mass groups from the all-particle energy spectrum, strongly depend on the

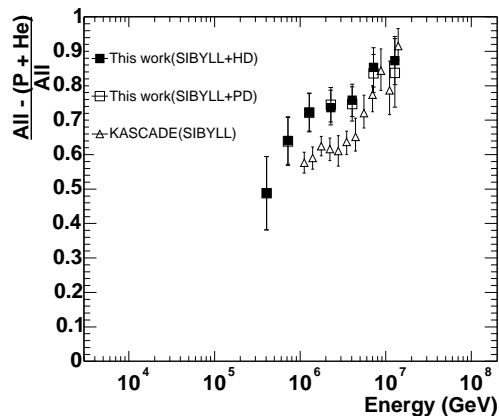


Figure 4. Fraction of the primary cosmic-rays heavier than helium nuclei obtained by assuming the SIBYLL interaction models. Our results are compared with those by the KASCADE experiment[?].

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 be not a suitable parameter for separating the air showers into different primary mass groups.

Our results indicate that the main component responsible for making the knee structure in the all-particle energy spectrum is the nuclei heavier than the helium component and that a rigidity-dependent acceleration scenario holds for the primary cosmic-ray chemical composition. Thus, the obtained proton flux is better accommodated by HD model than PD model, the power index can be estimated as -3.01 ± 0.11 and -3.05 ± 0.12 based on the QGSJET+HD and SIBYLL+HD models, respectively. We plan a new high-statistics hybrid experiment in Tibet which will measure the air shower cores induced by the heavy component in primary cosmic rays around and beyond the knee in the very near future to confirm the present results [?].

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