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

The Tibet AS\textsuperscript{\gamma} Collaboration

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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 simultaneously and provides us information on the primary species. For three-year operation, we have observed 177 $\gamma$-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 $-3.01 \pm 0.11$ and $-3.05 \pm 0.12$ based on the QGSJET+HD and SIBYLL+HD models, respectively, which are steeper than that extrapolated from the direct observations of $-2.74 \pm 0.01$ 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 up to 100 EeV. The most prominent structure is a change of the spectral index from \( \gamma_1 \approx -2.7 \) to \( \gamma_2 \approx -3.1 \) 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 \( \gamma \)-families can be estimated with high accuracy due to small fluctuations in air shower size. Another is that the air shower events accompanied by \( \gamma \)-families are dominated by the protons and heli ums 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 \( \gamma \)-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, \( N_\gamma \) the number of cascade showers in a \( \gamma \)-family, \( \sum E_\gamma \) the sum energy of cascade showers in a \( \gamma \)-family and \( < R > ( < R > = \sum_i r_i^\gamma / N_\gamma ) \) the mean lateral spread in a \( \gamma \)-family. In this experiment, we observed a total of 177 \( \gamma \)-family events, each of which is accompanied by an air shower with \( N_\gamma > 2 \times 10^6 \) corresponding approximately to \( 5 \times 10^{14} \) 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 \( \gamma \)-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
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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.

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