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The energy spectrum of the light components (P+He) at the knee obtained by the Tibet air shower core detector

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The Tibet hybrid experiment carried out in 1996-1999 obtained the proton and helium spectra at the knee energy region. It was shown that the summed flux of these light components are less than 30 % of the all particle flux, strongly suggesting the dominance of the heavy component at the knee. We have been continuing to operate the apparatus as the air shower core detector (Burst Detector + Tibet III AS array) without the emulsion chamber part, which works as the selector for the air showers induced by light components (mainly protons and heliums). One can rule out the dominance of the light component at the knee from the comparison of the observed burst size spectrum with Monte Carlo calculations based on three different interaction models.

1. Introduction

The chemical composition of the cosmic rays at the knee (around 3×10^{15} eV) is considered as a key information to understand the cosmic-ray acceleration and the propagation in the galaxy [1]. Since the direct observations are inaccessible to this energy range due to the low flux of high-energy-cosmic rays, the ground based experiments are needed to investigate the primary chemical composition. Many results from air shower observations are so far reported, however, they are limited to the global behavior like the average mass number. Furthermore, there are still serious discrepancies among different experiments or the observation methods.

In order to overcome the difficulties involved in indirect observations, which are related to the primary mass separation and the primary energy determination, some new efforts have been made recently based on the detailed simulations. The Kascade experiment [2] uses the unfolding method to resolve the elementary mass groups based on the correlation between the number of electrons and muons which is a parameter sensitive to the primary mass. The Tibet experiment [3, 4] observes air shower core with calorimetric burst detectors with which the air showers induced by light elements are more efficiently triggered than those by heavy elements. The high altitude of Tibet (4300 m a.s.l.) leads to the high accuracy for the primary energy determination. The Tibet experiment carried out in 1996-1999 used hybrid detectors consisting of Emulsion Chambers (EC), Burst Detectors (BD) and Tibet II Air shower array. Analysis was made for high-energy γ-families detected by EC and accompanied air showers. Artificial neural network (ANN) [5] was used to separate the events induced by protons, heliums and others. The energy spectrum of protons is shown in Fig.1 where Tibet-B.D.(HD) and Tibet-B.D.(PD) are the results from the analysis of burst detectors based on Corsika QGSJET [12] with heavy dominant primary composition (HD) and proton dominant one (PD), respectively. Tibet-Hyb-QGSJET and Tibet-Hyb-SIBYLL are the results from the analysis of emulsion chambers based on Corsika QGSJET and Corsika SIBYLL, respectively, using the HD model. The results are independent of the primary composition models used in the analysis, while the dependence on interaction models used in Monte Carlo is seen at around 30 % level. The proton spectrum shows steeper power index than the extrapolation of the direct observations

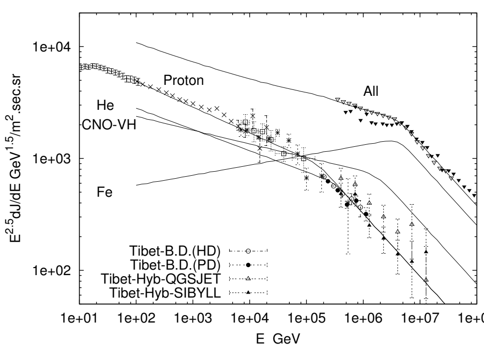

Figure 1. Proton spectrum obtained by Tibet experiment [3, 4]. Tibet-B.D.:burst detector analysis, Tibet-Hyb:emulsion chamber analysis, Other experiments are also plotted with symbols; plus:BESS [6], cross:ATIC [7](normalized to BESS), asterisk:JACEE [8], square:RUNJOB [9], open inverse triangle:Tibet III all particle [10], filled inverse triangle:AKENO all particle [11]. Solid lines:Heavy Dominant composition model (HD). See the text for the details.

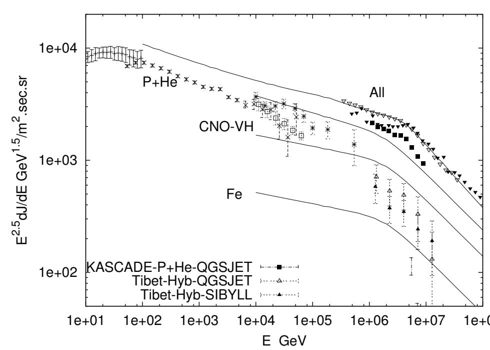

Figure 2. P+He spectrum obtained by Kascade and Tibet. Symbols for other experiments are the same as Fig.1. Solid lines:Proton dominant composition model(PD). See the text for the details.

suggesting the break point of proton spectrum at around a few hundred TeV. Solid lines in this figure are the primary composition model called 'HD', where the dominance of heavy elements is assumed at the knee.

Another results by the Kascade experiment is almost consistent with our results if one uses SIBYLL interaction model, however, a large disagreement arises when one uses QGSJET model, where the Kascade experiment shows strong dominance of the light elements, while the Tibet result remains within 30% change. The P+He spectrum is shown In Fig.2 together with the results by direct observations, where the plots are made summing up the proton spectrum and the helium spectrum from their original articles. Solid lines in this figure show an another primary composition model called 'PD', where dominance of the protons are assumed at the knee. Such model cannot describe our result but is rather close to the Kascade result.

We have been continuing to operate the apparatus as the air shower core detector (Burst Detector + Tibet III AS array) without the emulsion chamber part, which works as the selector for the air showers induced by light components (mainly protons and heliums) and provide the cross check with previous results with higher statistics. The results of the analysis on the burst size spectrum is shown in present work.

2. Experiment

The experimental setups of the burst detectors and the air shower array are described in previous papers [3, 4]. Changes made are (1) the thickness of the lead plate is changed from 7 cm to 3.5 cm to have lower threshold of burst size, (2) AS array is upgraded from Tibet II to Tibet III. The coverage area of burst detectors is 80 m^2 located near the center of the AS array. The data from alive time of 183.5 days are analyzed with following criteria; (1) The burst size $N_b > 5 \times 10^4$, whose responsible primary mode energies are around 500 TeV and 800 TeV for protons and heliums, respectively, (2) The number of hit detectors $N_D \geq 1$, (3) The largest burst size N_b^{top} among all triggered detectors should be located at inner area of BD grid excluding the most outer edges. The number of selected events is 2389 which is several times higher than the statistics used in previous analysis on γ-families.

3. Simulation

The burst events satisfying above criteria have been simulated by three Monte Carlo codes, namely, QGSJET01c, SIBYLL2.1 of Corsika v6.200 and Cosmos-DPMJET3 [13]. The minimum energy of the secondary particles contributing to the burst size is carefully examined by recalculating for various threshold values and found to be 0.5 GeV for the analysis in the knee region. The generation efficiency of the burst events is shown in Fig.3 as a function of the primary energy for P+He component and the other nuclei. The model dependence of the efficiency for P+He is within $\pm 15\%$ without any serious energy dependence as shown in Fig.4 (QGSJET$\leq$DPMJET$\leq$SIBYLL) while a remarkable deviation is seen between DPMJET3 and other two models for heavy nuclei (DPMJET3$<$QGSJET$\leq$SIBYLL), although this difference does not affect seriously to present analysis since the burst events are mostly attributed to p+He.

4. Results and Discussions

The burst size spectrum for N_b^{top} is shown in Fig.5 compared with Monte Carlo simulation of three interaction models and two primary composition models. It is obviously seen that the better agreement is obtained by primary composition model 'HD' than 'PD', irrespective of the interaction models.

The burst size spectrum observed by the Tibet experiment can be explained by heavy dominant primary composition at the knee. The interaction model dependence is within 15 % among three models, namely, QGSJET01c, SIBYLL2.1 and DPMJET3. On the contrary, the primary composition dominated by light component at the knee predicts too high flux of the burst events by a factor two or more. Since the burst events are mostly created by light components as seen in Fig.3 of the generation efficiency, the abundance of the p+He cannot be as high as that assumed in the PD model. Therefore we can conclude either the dominance of the light component at the knee is ruled out or the all particle flux should be decreased by a factor two, although the latter case contradicts to the agreement of all particle spectrum between Tibet and Kascade experiments.

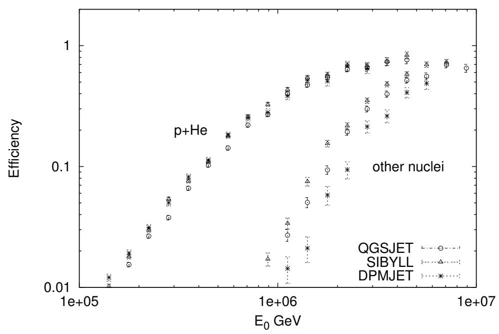

Figure 3. Generation efficiency of the burst events by P+He and other nuclei.

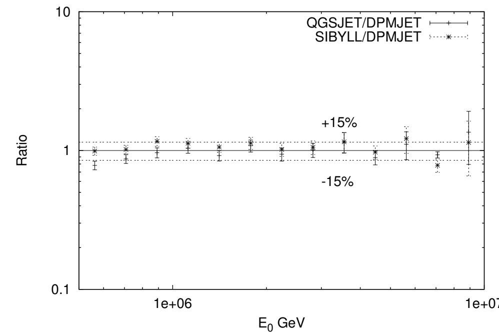

Figure 4. Relative ratio of the generation efficiency to the DPMJET by P+He.

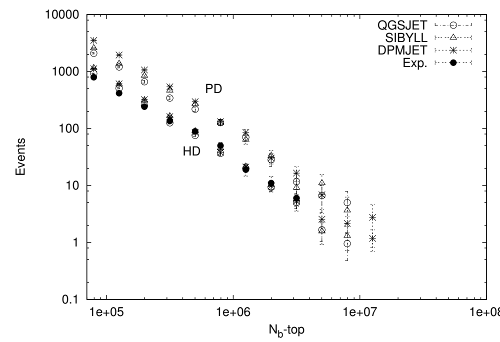

Figure 5. Top burst size spectrum. The labels HD and PD denote the Monte Carlo predictions by heavy dominant composition and proton dominant composition, respectively.

Further progress will be expected by measuring the heavy component at the knee explicitly, which is under the study as a next phase project of the Tibet AS$_\gamma$ Collaboration [14].

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