Proceedings of the 30th International Cosmic Ray Conference
Rogelio Caballero, Juan Carlos D'Olivo, Gustavo Medina-Tanco,
Lukas Nellen, Federico A. Sánchez, José F. Valdés-Galicia (eds.)
Universidad Nacional Autónoma de México,
Mexico City, Mexico, 2008
Vol. 2 (OG part 1), pages 121–124

30TH INTERNATIONAL COSMIC RAY CONFERENCE

Chemical composition of cosmic rays at the knee measured by the Tibet air-shower-core detector

THE TIBET ASγ COLLABORATION

shibata@phys.ynu.ac.jp

Abstract: Further analysis is made on the second phase of the Tibet hybrid experiment to measure the energy spectrum of light component (proton and helium) of the cosmic rays at the knee. The dominance of the heavy elements at the knee which was reported by the first phase experiment has been confirmed with higher statistics by one order.

Introduction

One of main subjects in the Tibet AS$_\gamma$ Collaboration is to study the origin of the cosmic rays by measuring the chemical composition at the 'Knee' energy region. At the Tibet altitude (4300 m a.s.l., 606 g/cm^2), one can observe near maximum development of air showers in the knee energy region leading to the high accuracy of the energy determination irrespective of the species of primary nuclei. The first phase of the Tibet hybrid experiment [1] (1996 - 1999) consisted of Tibet II air-shower array (AS), Emulsion Chamber (EC) and burst detector(BD). The EC was used to detect high energy γ-families of the energy greater than 20 TeV at the core of ASs of which more than 80% are induced by light nuclei like protons or helium (pHe). Due to the high spatial resolution of the EC, Artificial Neural Network (ANN) was used to separate proton and helium events from others and we could obtain the energy spectrum of each of them using 177 γ-family events. These results strongly indicated that the fraction of the light component to the all particle spectrum is decreasing around the knee suggesting the dominance of the heavy nuclei. The observation of the AS core has been continued with upgraded Tibet III array and burst detectors without using X-ray films, which still works as the selector for the air showers induced by light component (pHe). In this second phase experiment, it is aimed to confirm the first phase result with higher statistics using BD by triggering the AS core whose energy is above a few TeV. Detailed Monte Carlo calculation (MC) was made using Monte Carlo code Corsika 6.200 with QGSJET01c and SIBYLL2.1 interaction models for the analysis of the experimental data. The details of the MC calculation is reported in a separate paper in this conference [2]. In this paper, experimental result is compared mainly with QGSJET model only, because it can better reproduce features of air-shower core and partly because of the limited space.

Energy determination

The primary energy of the air showers is determined by fitting the lateral density of the shower particles to the modified NKG function [3] by which we obtain the shower size N_e and shower age s. The relation between the shower size and primary energy for ASs associated with the high energy core (burst) is shown in Fig.1 using the age parameter s as a parameter. The estimated primary energy (E_0^{est}) shows good correlation with the input energy (E_0^{true}) as shown in Fig.2 with the energy resolution of 13% in average (Fig.3) for $E_0 > 5 \times 10^{14}$ eV.

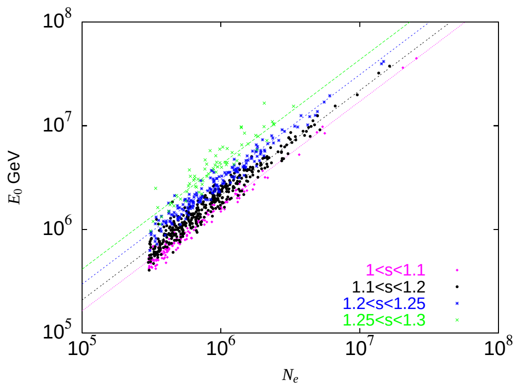

Figure 1: The conversion of the shower size into primary energy using the age parameter s for the burst trigger events (QGSJET model).

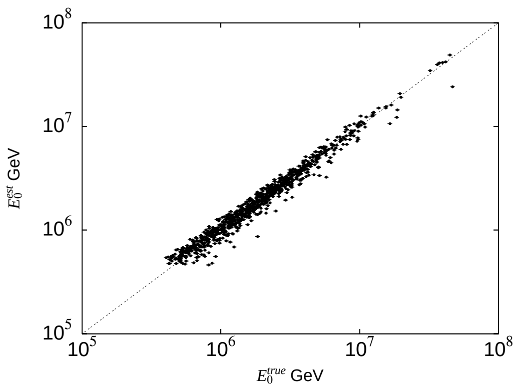

Figure 2: The correlation between the estimated primary energy (E_0^{est}) and the input energy (E_0^{true}).

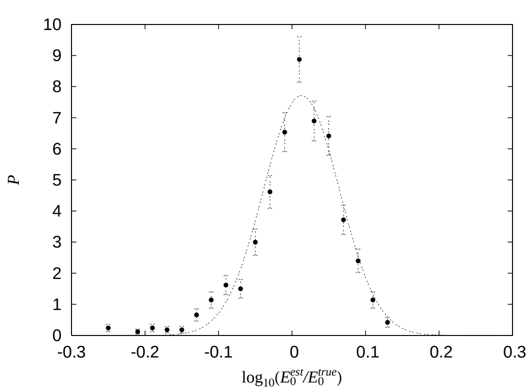

Figure 3: The resolution of the primary-energy determination is 13% in average for $E_0 > 5 \times 10^{14}$ eV.

The separation of the light component

The separation of the light component (pHe) is made with use of ANN where five parameters are input to train the network as listed below. (1) the shower size N_e, (2) the shower age s, (3) the number of fired burst detectors N_D, (4) the top burst size among fired detectors N_b^{top}, (5) the arrival zenith angle θ of the AS. These parameters represent the characteristics of the AS core, for example, N_D corresponds to the lateral spread, N_b^{top} does the energy concentration of AS of given size N_e, age s and arrival zenith angle θ. The role of ANN is to examine the five dimensional correlation and to separate the light component from others as shown in Fig.4. We treat those events as pHe-like ones when ANN output value T is less than 0.5. The purity P and the selection efficiency Q of the light component by this selection is over 80 % which weakly depends on the energy but the ratio P/Q, which is included as a correction factor in deriving the flux, remains almost constant independent of the primary energy, as it should be to avoid distortion of the energy spectrum of the light component by contamination of the other nuclei.

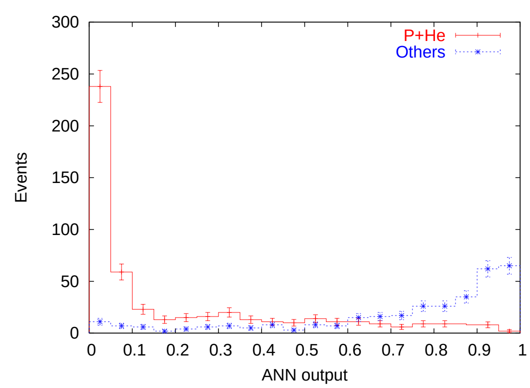

Figure 4: The distribution of the ANN output T for the MC data. Red histogram shows pHe events and blue one by other nuclei.

Analyses of experimental data

The details of the installation and the experimental procedure are described in a separate paper [2]. The analysis is made for the 1176 selected burst events by following criteria.

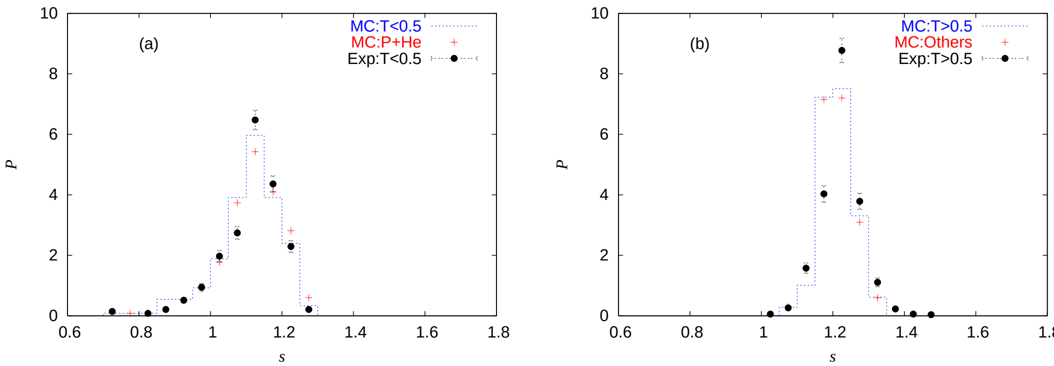

Figure 5: Age distribution of the events classified as (a) pHe-like and (b) others. Closed circles show experimental data and histogram shows MC data. The red plus symbol shows events induced by (a) proton or helium and (b) by nuclei heavier than helium.

$N_b^{top} > 5 \times 10^4,\ N_e > 3 \times 10^5,\ \theta < 25°$
The experimental data are compared extensively with MC events and good agreement with MC is found (see ref.[2]). The separation of the light component is made by ANN and 632 events are classified as pHe-like events. The features of each components separated by ANN are also consistent with MC as shown in Fig.5, in which the shower age distributions are shown for pHe-like events and for others (compared with QGSJET model calculation). The consistency of the separation can be seen by red plus symbol which corresponds to the MC events induced by pHe and other nuclei in (a) and (b), respectively. The same comparison using SIBYLL model results in worse fit to the experimental data (not shown).

Results and discussions

The energy spectrum of the light component is derived by following formula.

$$\frac{dJ}{dE} = (\frac{\Delta N}{\Delta E})_{pHe-like} \cdot \frac{P}{Q} \cdot \frac{1}{(S\Omega T)_{eff}}$$

where $(\frac{\Delta N}{\Delta E})_{pHe-like}$ is the event density in a given energy bin for those classified as pHe-like events, P the purity, Q the selection efficiency and $(S\Omega T)_{eff}$ denotes the effective exposure including the detection efficiency as a function of the energy E and an alive time of the detector system, in which both of the AS array and BD are alive. The energy spectrum of light component (proton+helium) is shown in Fig.6 and Fig.7 which are derived from the analysis using QGSJET model and SIBYLL model, respectively. Present results are quite consistent with the first phase results (cited as Tibet-EC) but with higher statistics.

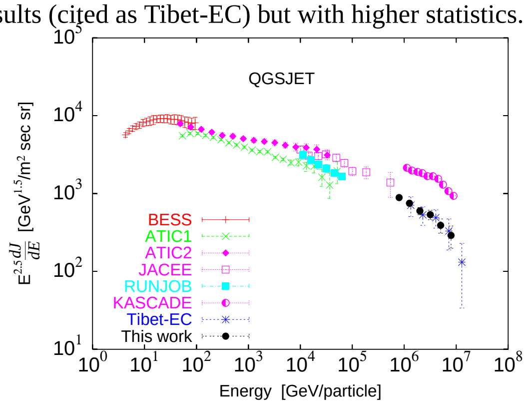

Figure 6: The energy spectrum of the light component (P+He) derived from the analysis using QGSJET model. Present result is shown by black closed circles. Cited other works are ploted by summing up their proton and helium data points from original papers [4] as a function of the energy per particle.

Acknowledgments

The collaborative experiment of the Tibet Air Shower Arrays has been performed under the auspices of the Ministry of Science and Technology of China and the Ministry of Foreign Affairs of Japan. This work was supported in part by Grants-in-Aid for Scientific Research on Priority Areas

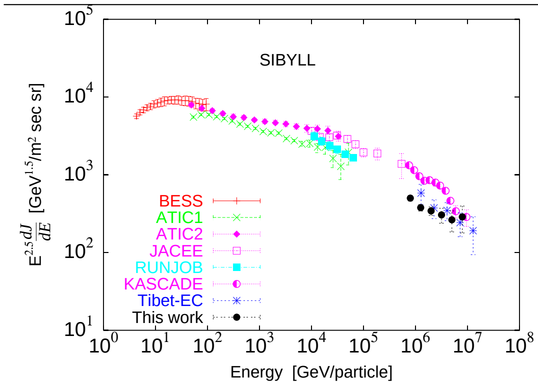

Figure 7: The same as Fig.6 using SIBYLL model.

(712) (MEXT), by the Japan Society for the Promotion of Science, by the National Natural Science Foundation of China, and by the Chinese Academy of Sciences.

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