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Analysis of primary cosmic ray proton and helium components at the knee energy region with the Tibet hybrid experiment

THE TIBET ASγ COLLABORATION

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Abstract: Analysis has been made on air-shower cores in the knee energy region observed for three years with the Tibet Hybrid experiment at Yangbajing, Tibet (4300 m a.s.l., 606 g/cm^2). The observed characteristics of the air-shower core are in a good agreement with Monte Carlo calculations with heavy dominant chemical composition of primary cosmic rays around the knee.

Introduction

The bending of the cosmic-ray energy spectrum, so called knee, has been studied for long time and there are many discussions about the cause of the knee in terms of the source, the acceleration mechanism and the propagation of cosmic rays. The chemical composition is considered as a key importance to solve this problem, however, the results of composition measurement so far made are still divergent [1] and not established yet. Tibet hybrid experiment started in 1996 aims to overcome difficulties of the air-shower measurement by the advantage of the high altitude. It is expected that cosmic rays at the knee energy interact with the atmosphere and reach maximum development of the air showers at Tibet altitude leading to the high detection efficiency and energy resolution. The high-energy core of the air showers can be also measured at high altitude and such observation enables us to identify the nuclear species of the primary particles with use of detailed simulations. We have been observed air-shower core at Tibet by hybrid experiment, which is characterized by higher detection efficiency for light component like proton or helium than that for heavier elements. First phase observation was made in 1996-1999 using emulsion chamber (EC) of 80 m^2 operated with burst detector (BD) and Tibet II air-shower (AS) array. The result of the first phase experiment was already reported in [2]. From 2002, it runs without EC to confirm the first phase result with higher statistics, namely, second phase of Tibet experiment is aiming to measure proton+helium spectrum with lowered burst threshold [3]. The thickness of the lead plates above the burst detector has been changed from 14 r.l. to 7 r.l. to have lower threshold of the burst size than before, and operated with the upgraded Tibet III AS array, which has better energy resolution than Tibet II. In the following sections, the description of the burst detectors, experimental procedures, Monte Carlo (MC) simulations and comparison of the experimental data with MC are briefly summarized. The result on absolute flux of proton+helium spectrum is reported in a separate paper [4].
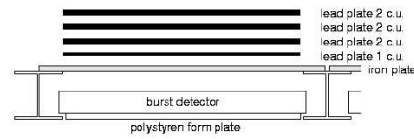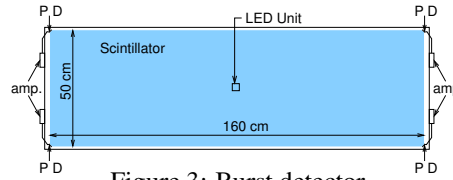

Figure 2: Side view of the chamber

Figure 3: Burst detector

Experiment

The burst detectors are located near the center of the AS array and used to measure the particle number under the lead plates (burst size; N_b). The AS array is triggered by the burst detectors.

The burst detectors are set in two rooms of the hut (Figure 1). Each room has 50 detectors (totally 100 detectors whose coverage area is 80 m^2). The DAQ system of burst detectors is set at the center of the two rooms.

Burst detector

Burst detectors are under the lead plates (7 r.l., Figure 2). Each detector is a plastic scintillation counter (BICRON BC408A) of the size 160 cm × 50 cm × 2 cm. Four photo-diodes (PD, sensitive area : 2 cm × 1 cm, Hamamatsu hotonics, S2744-08) are attached at each corner (Figure 3). The scintillator surface is processed to appreciate attenuation length of 1.2 m. The trigger signal for burst detector is made from 2 channels coincidence of PDs. The threshold voltage is changed from previous experiment, namely from -15 mV to -10 mV to have lower detection threshold. If one detector makes trigger signal, all ADC data are recorded. Also the trigger signal for air shower is sent to DAQ system for Tibet III array. Each PD are calibrated by blue LED mounted at the center position by each 10 minutes. ADC modules are calibrated by each 4 hours. ADC pedestal values are measured by each 10 minutes. The signal from PD is amplified 110 times by high speed amplifier.

The burst detector was calibrated with accelerator (Electron Synchrotron at INS, University of
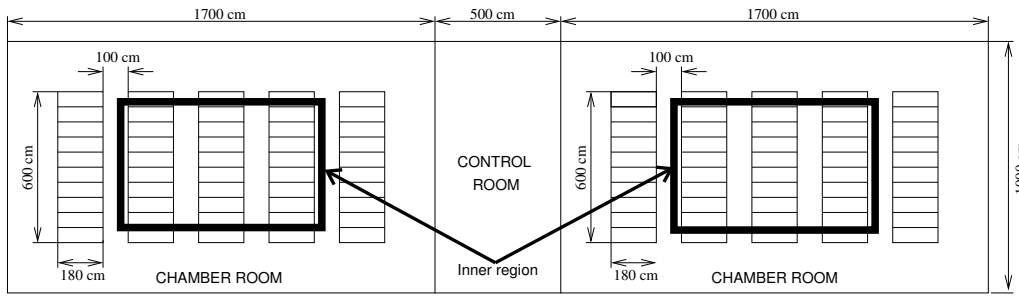
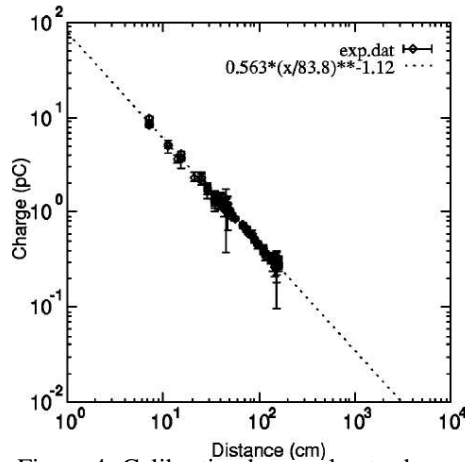Figure 1: Arrangement of burst detectors

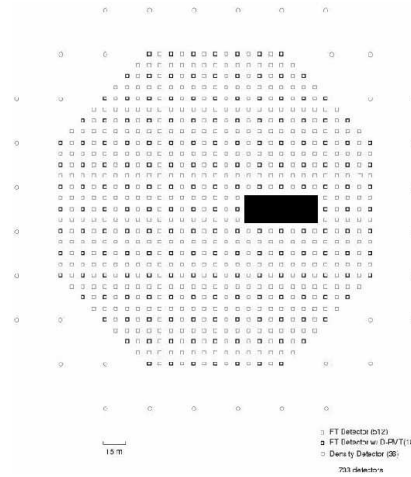Figure 4: Calibration by accelerator beam

Figure 5: Tibet III array

Tokyo). We measured the attenuation in scintillator and the absolute response (Figure 4).

Tibet III array
Tibet III array has 733 scintillation detectors (0.5 m^2). Fast-timing detectors are placed with 7.5 m spacing and Density detectors are placed with 15 m spacing (Figure 5).

The location of the burst detectors is shown by black square in Figure 5. The trigger rate of Tibet III array is 1300 Hz for general air shower. The dead time is ~12 %.

Data analysis
The recorded data by hardware triggers are analyzed with following software selection.

(1) any 3 PD channels coincidence over 3 pC in a burst detector, (2) the position of the largest burst size (N_b^{top}) is at an inner region of the burst detectors excluding the outer edges (24 detectors in each room), (3) $N_b^{top} > 5 \times 10^4$ particles, (4)

$N_b^{top} > 1.3 \times N_b^{2nd}$ (5) air-shower size $N_e > 3 \times 10^5$ particles, (6) arrival zenith angle $\theta < 25°$.

Each DAQ system has GPS clock module independently. The matching between burst data and AS data is made using coincidence of GPS clocks and trigger tag to Tibet III array. The coincidence condition of GPS is less than 1 ms. The average time difference is 8.1 μs $\pm 0.4\mu$s.

Observation period is from 2002 October 31 to 2005 November 11. The live time is 434.3 days.

Simulation

The simulation code CORSIKA 6.200 is used. Interaction models are QGSJET01c and SIBYLL2.1. Since the first phase experiment strongly suggested the dominance of the heavy primaries, we assumed heavy dominant primary composition (HD4). Primary energies are sampled above 100 TeV with
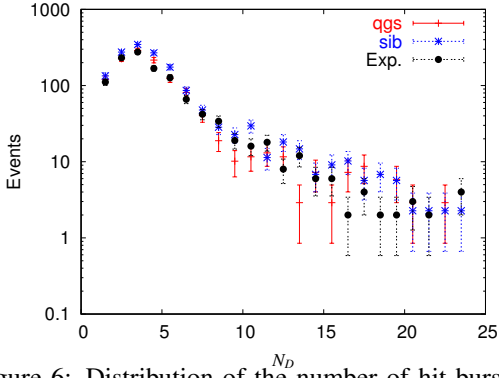
Figure 6: Distribution of the number of hit burst detectors

Figure 7: Nbtop spectrum

given spectrum by HD4 model. Minimum energies to simulate with and without thinning are set as 1 MeV and 0.3 GeV, respectively. For the burst size calculation, we use approximation formula based on the Epics code simulation. The simulation data sets are normalized by the flux of direct observations at 100 TeV when we compare the experimental data with MC.

Results and Discussion

The characteristics of the air-shower core are shown as distributions of number of hit detectors N_D (Fig. 6), top burst size N_b^{top} (Fig.7), and air-shower size N_e (8), where MC results using two interaction models are also plotted. All of these characteristics agree well with MC calculations within statistical errors except the difference of the absolute flux approximately by 30 % between QGSJET and SIBYLL model. Present assumption of QGSJET+HD model can nicely fit to the experimental data, while SIBYLL+HD model requires stronger dominance of the heavy elements at the knee. Although further analysis is needed to argue the superiority of the interaction models, it is clear that primary chemical composition at the knee is dominated by heavy primaries.

Acknowledgments

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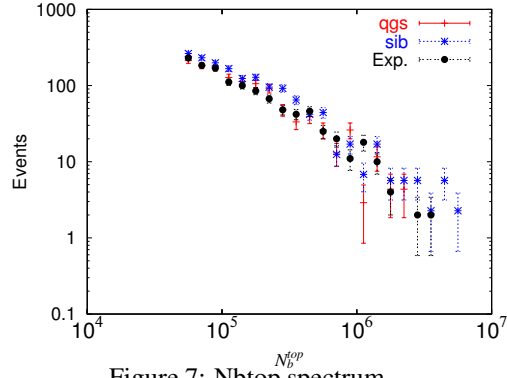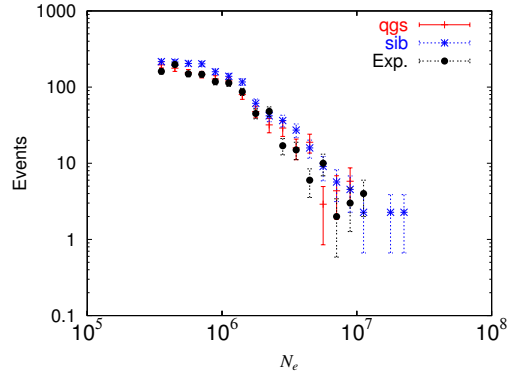

Figure 8: Burst triggered air-shower size spectrum

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