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Average mass of primary cosmic rays in the knee energy region inferred from Tibet experiment

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Abstract: Study of the chemical composition of cosmic rays in the knee region has been made by the Tibet AS$_\gamma$ Collaboration using the Tibet-III air shower array and an air-shower-core detector. Based on the data of all-particle spectrum, proton, and helium spectra obtained by Tibet hybrid experiment, upper and lower limits of the average mass number of primary cosmic rays were estimated in the energy interval between 10^{15}eV and 10^{16}eV assuming unmeasured components (all $-$ proton $-$ helium) are any mixture of nuclei between carbon and iron. The lower limit of $\langle \ln A \rangle$ with carbon model is approximately 2 and the upper limit with iron model is approximately 3.5 with weak energy dependences. The systematic errors involved in estimating $\langle \ln A \rangle$ due to the primary energy determination or the interaction model dependence in deriving the flux of each nuclear element are discussed and found to be small enough to set the boundary for $\langle \ln A \rangle$. A comparison of our result with recent Icecube data suggests that the primary mass composition is dominated by carbon at 10^{15} eV and it tends to be dominated by iron at 10^{16} eV.

Keywords: knee, chemical composition , Tibet hybrid experiment

1 Introduction

The energy spectrum of cosmic rays decreases with a power law and the power index of the all-particle spectrum sharply varies around 4×10^{15}eV. This energy region is called the ”knee” It is considered that the main acceleration mechanism of cosmic rays up to the energy around 10^{15} eV is the diffusive shock acceleration (DSA) at the shock front of SNRs. It is commonly believed that the ”knee” is caused by the acceleration limit of such mechanism. That is, the maximum energy that can be attained by a cosmic ray depends on its rigidity, and its energy spectrum consequently decreases dramatically at around 10^{15} eV, also causing the chemical composition to change dramatically. Therefore, studying the chemical composition of the ”knee” region should play an important role in understanding the mechanism of cosmic ray acceleration. For energy regions of approximately 100 TeV and higher, long-term, indirect observations have been made using large-area air-shower detectors installed on the ground to overcome the low frequency of the cosmic rays. The indirect cosmic-ray observation using air showers involves two difficulties. One is the fact that the precision of energy determination depends on the chemical composition of the primary cosmic ray. The other is that the nuclear interaction of cosmic rays in the atmosphere at relevant energies has not been fully known yet and air shower calculation is based on the phenomenological interaction models such as QGSJET and SIBYLL. Many groups conducted cosmic ray spectrum measurements by adopting different methods, but still have not reached definite conclusions with precision high enough to argue for the intensities of individual elements. Many of these cases only compared the average mass numbers. Recently, Icecube Collaboration has reported new data on primary mass composition of cosmic rays around the knee energy in terms of averaged logarithmic mass in which strong increase of $\langle \ln A \rangle$ has been demonstrated [16] between 10^{15} eV and 10^{16} eV. In this energy region, we have already measured proton, helium and all-particle spectra by Tibet-hybrid-experiment consisting of AS array and core detectors, and we are preparing the next phase experiment to measure heavier components than helium. Therefore, we have not reported $\langle \ln A \rangle$ value until now, however, it is interesting to compare data of Icecube and data of other groups with our upper and lower limit of $\langle \ln A \rangle$. In present work, possible range of $\langle \ln A \rangle$ is calculated using Tibet data assuming that the heavier components than helium are any mixture of nuclei between carbon and iron.

2 Tibet-hybrid-Experiment

The Tibet-hybrid-detector consists of air-shower-core detectors and the Tibet-III air-shower array. The Tibet-III has 761 fast timing counters(FT) and 28 density counters(D) surrounding them. In the inner 36,900 m^2, FT counters are deployed at 7.5 m lattice intervals, among 761 FT counters, 249 sets of detectors are also equipped with D-PMT in addition to FT-PMTs to measure particle density with high dynamic range [13] [14] [15].
In the hybrid experiment, the AS array is used to determine the primary energy and the arrival direction of each event. The core-detector consisted of emulsion chambers (ECs) and burst detectors (BDs). Four hundred blocks of ECs and 100 BDs in total (a large BD under the 4 EC blocks, total coverage area of 80 m^2) are constructed near the center of the air-shower array, and are used to detect high-energy γ-rays or electrons in an air-shower cores [10] [11] [12]. The EC is a multi-layered sandwich of lead plates and X-ray films used to detect high-energy γ-rays of energies greater than a few TeV through the detection of the electromagnetic cascade showers developed in lead. A bundle of γ-rays can be detected with a lateral spread of a few cm at most.

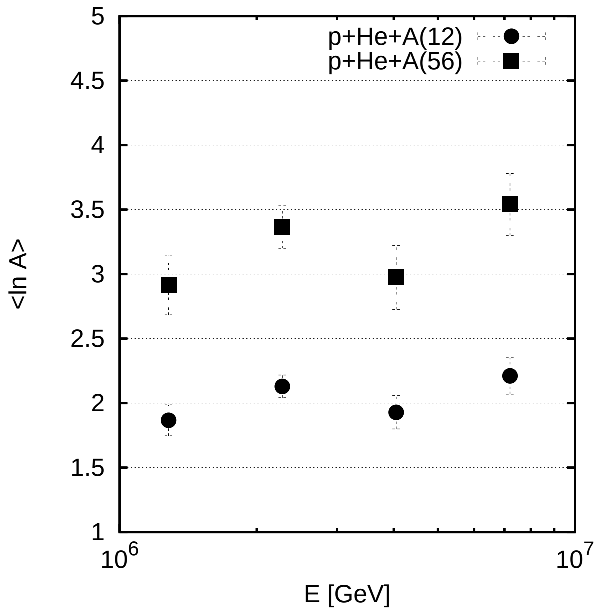

Figure 1: Average mass of primary cosmic rays based on the QGSJET+PD model. Closed squares are calculated under an assumption that all nuclei heavier than helium are iron, and closed circles are assuming carbon.

3 Proton and Helium Spectrum

The first phase of the Tibet-hybrid-experiment was performed from 1996 through 1999. In the analysis, two interaction models of QGSJET01 and SIBYLL2.1 were used in CORSIKA simulation. For the primary particles, we examined the HD and the PD models [11]. The obtained proton spectrum can be expressed by a single power law with power index of about 3. The details are described in previous papers [10] [11] [12]. The helium component can also trigger our detector although the efficiency at 10^{15} eV is about 4 times lower than the case of protons. It is possible to set the selection criteria for proton + helium events (light component) in the analysis. Helium spectrum was obtained by subtracting the proton flux from the flux of the light component.

4 All particle spectrum

The all-particle spectrum of primary cosmic rays was measured with the Tibet-air-shower array in a wide range over 3 decades between 10^{14} eV and 10^{17} eV [15]. The estimation of the primary energy was made under two primary chemical composition models of HD and PD. The interaction model dependence was also examined by two models of QGSJET01c and SIBYLL2.1. The knee of the primary cosmic-ray energy spectrum is clearly observed and its position is located at the energy around 4 PeV. The spectral power index is -2.67±0.01below 1 PeV, while it is -3.10±0.01 above 4 PeV in the case of QGSJET+HD

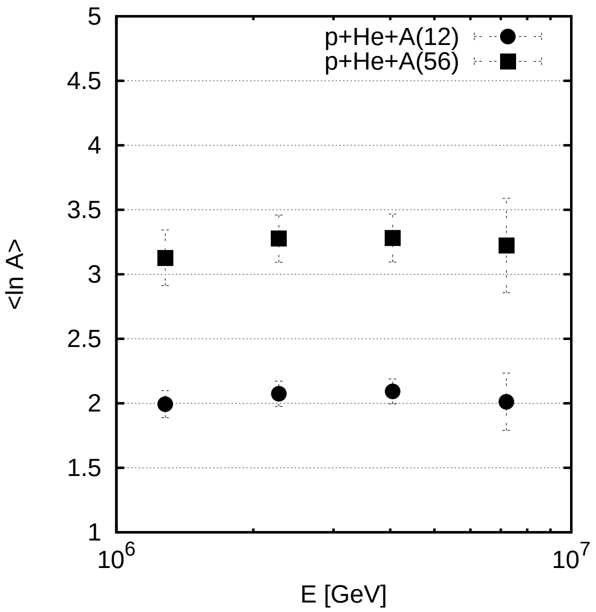

Figure 2: Average mass of primary cosmic rays based on the QGSJET+HD model. See the caption of Fig. 1 for the symbols.

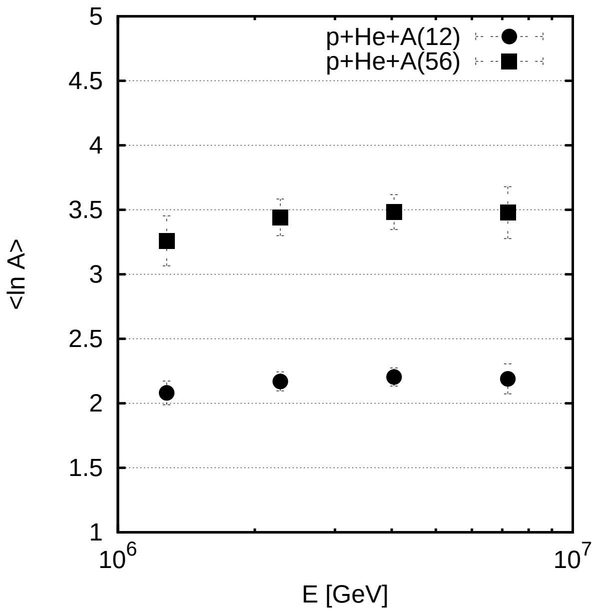

Figure 3: Average mass of primary cosmic rays based on the SIBYLL+HD model. See the caption of Fig. 1 for the symbols.

model, -2.67±0.01 below 1 PeV, -3.12±0.01 above 4 PeV in the case of SIBYLL+HD model, and -2.65 ±0.01below 1 PeV, -3.08±0.01 above 4 PeV in the case of QGSJET+PD model.

5 Average mass of primary cosmic rays

The average mass number of cosmic rays was estimated based on the all-particle spectrum data [15], and data on proton and helium [11] obtained in the phase I hybrid experiment. Since the Tibet experiments has not explicitly measured heavier elements than helium yet, we can estimate the lower and upper limit of the average mass number as follows assuming that the heavier component consists of purely carbon or iron, respectively, although the realistic case is the any mixture of nuclei between them.

$$< \ln A >= \frac{f_p \times \ln(1) + f_{He} \times \ln(4) + f_{other} \times \ln(A_{other})}{f_{all}}$$

Here, f_p, f_{He} and f_{all} are the intensities of the proton, helium, and all-particles, respectively, which were obtained in the phase I experiments and Tibet-III as described in section 3 and 4, while $f_{other} = f_{all} - f_p - f_{He}$ corresponds to the intensity of the nuclei heavier than helium. The results of the analysis are shown in figures 1, 2, and 3. The black squares were obtained by assuming the heavy nuclei are iron, and they are distributed around 3 to 3.5. The black circles were obtained by assuming they are carbon, and they are distributed around 2. Only weak energy dependence is seen in these figures. Figure 2 shows the results when QGSJET+HD model was used and figure 3 shows the results when SIBYLL+HD model was used. The model dependence is at most 10%. Present result is shown by hatched area in figure 4(A) and (B) together with other data. A comparison of our result with recent Icecube data suggests that the primary mass composition is dominated by carbon at 10^{15} eV and it tends to be dominated by iron at 10^{16} eV.

6 Summary

The upper and lower limit of average mass number in the energy range from 10^{15} eV to 10^{16} eV was estimated by using the all-particle, proton, and helium data measured in the Tibet hybrid experiment. They showed weak energy dependence, and the lower and upper limit was approximately 2 and 3.5, respectively. To identify the heavy nuclei components, we are planning a new experiment(YAC3) with high sensitivity for iron nuclei [6] [21]. In the YAC3 experiment, 400 units of YAC detectors placed at 3.75 m-interval will be used to measure the air shower core particle density. The area of each detector comprises of a 0.2 m^2 scintillator detector and a lead piece of thickness 3.5 cm placed over it, and it is used to measure the energy flow over a region of about 10 m radius from the shower axis. It has been planned to observe the heavy atomic nuclei components of 500 TeV and higher in YAC3.

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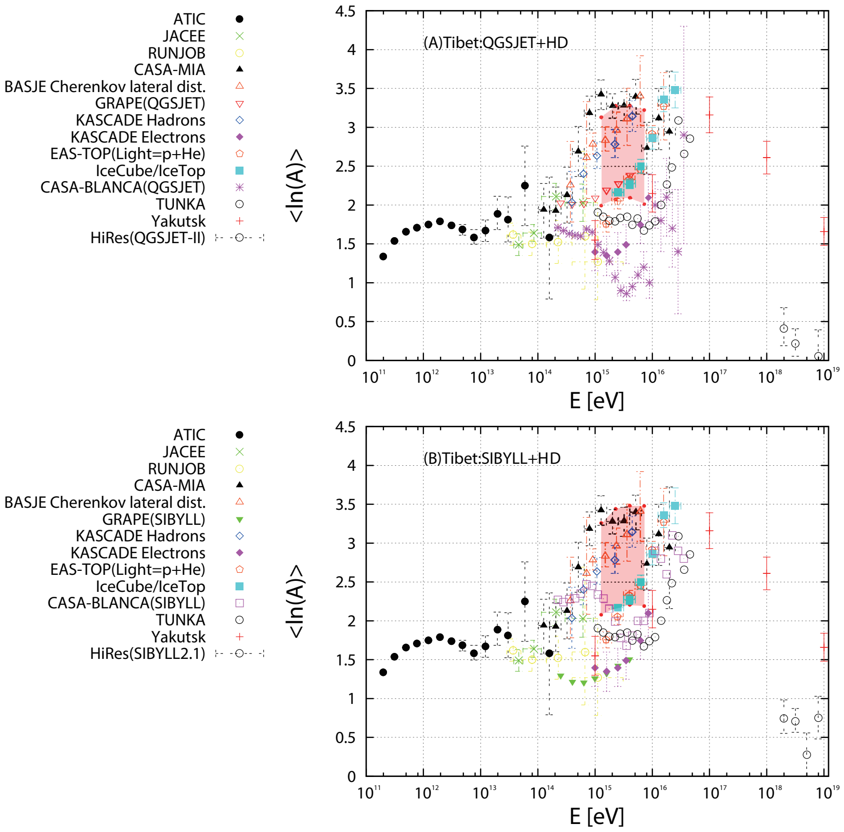

Figure 4: Energy dependence of primary cosmic-ray composition in terms of ⟨ln A⟩. The hatched area shows the allowed range inferred from Tibet experiment. (A) The analysis is based on QGSJET+HD model. (B) The analysis is based on SIBYLL+HD model. Other experimental data: ATIC [1], JACEE [19], RUNJOB [20], CASA-MIA [9], BASJE [4], GRAPES [3], KASCADE [5], EAS-TOP [8], IceCube/IceTop [16], CASA-BLANCA [7], TUNKA [2], Yakutsk [17], HiRes [18]

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