The Energy Spectrum and the Chemical Composition of Primary Cosmic Rays with Energies from 10^{14} to 10^{16} eV

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Abstract

We have measured extensive air showers(EASs) with primary energies above 6 TeV at Mt. Chacaltaya in Bolivia since March 2000 with an air shower array called the Minimum Air Shower(MAS) array. With an equi-intensity method analysis, we obtained longitudinal development curves of EAS around and deeper than their maximum developments to be compared with simulations, in which the primary chemical composition is assumed to be a mixture of protons and irons. We determined the mixing ratio of protons as a function of the primary energy, and we derived the primary energy spectrum from 10^{14} to 5×10^{16} eV. We found that the average mass number of primary cosmic rays increase with energy above $10^{14.5}$ eV and the dominant component around the knee is not protons.

pp. 131–134

1. Introduction

The origin of primary cosmic rays with energies above 10^{14} eV is still unknown. To solve this problem, we must obtain at least three kinds of accurate information on primary cosmic rays, which are the energy spectrum, the anisotropy in the distribution of their arrival directions, and the primary chemical composition. We determined EAS longitudinal development more directly with an equi-intensity method analysis. The EAS array at Mt. Chacaltaya is located at an atmospheric depth of 550 g/cm^2 so that we can observe EASs initiated by primary protons before their maximum developments.

2. Experiment and Data Analysis

The MAS array[18] is located at 16°20′52″S, 68°07′57″W, and 5200m above sea level. This array consists of sixty-eight unshielded scintillation detectors and a shielded one. These detectors are arranged over an almost flat field of about 10^4 m^2, and the central area of the array is of high detector density.

The data used for the present analysis were taken from March 2000 until November 2000. The total observation time is 8.9×10^6s and 7.5×10^7 events are selected with the core position located within 20m from the center of the array. Our detailed Monte–Carlo simulations show that the error in the determination of EAS size and the angular resolution are 13% and 1.4° respectively for vertically incident EASs with primary energy of 10^{14} eV, and 9% and 0.8° respectively for those of 10^{15} eV.

3. Results

We derived the longitudinal development curves from the observed integral EAS size (N^{obs}) spectra for each $\sec\theta$ bin for air showers with the integral of rate $F(> N^{obs}) = 10^{-5.2}$ m^{-2}sr^{-1}s^{-1} to $10^{-8.2}$ m^{-2}sr^{-1}s^{-1} for $10^{-0.25}$ steps, and the results are shown in Fig. 1. In this figure, we also show the longitudinal development curves of simulated events for primary protons and irons. The simulated curves of primary protons for the integral rate less than $10^{-6.2}$m^{-2}sr^{-1}s^{-1} show that the maximum development points should be deeper than our observation site. Our results, however, those maximum points are not seen, so that the major component of primary cosmic rays is considered to be heavier than proton even in $10^{14} - 10^{16}$ eV energy range.

With comparing observed longitudinal development curves with the simulated ones, we determined the mixing ratios of protons and irons with the least square method, and the mean logarithmic mass number $\langle \ln A \rangle$ (A is atomic number) is calculated, as shown in Fig. 2(left) with those of other measurements. Taking into account of that determined proton mixing ratio, we derived the pri-

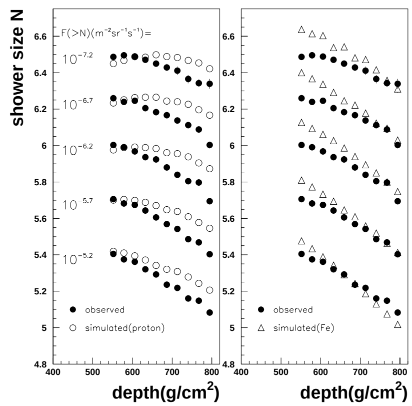

Fig. 1. The observed longitudinal development curves are compared with simulated ones for primary protons and irons. The attached number for each curve is the value of integral flux of corresponding cosmic rays. In the analysis, we derived the curves for $F(>N) = 10^{-5.2}$ $m^{-2}sr^{-1}s^{-1}$ to $10^{-8.2}$ $m^{-2}sr^{-1}s^{-1}$ with $10^{-0.25}$ step, but in this figure we show part of these curves to avoid confusions.

mary energy spectrum as shown in Fig. 2(right).

4. Discussions and Conclusions

The present result shows that $\langle \ln A \rangle$ increase with the primary energy around the knee. This result is consistent with our former result of Čerenkov radiation observations[15]. While the calculated EAS longitudinal development curves are dependent on the hadron interaction model, the simulation result with the QGSJET model which we adopted shows the most rapid developments among the major models[11]. Therefore, it is not possible to explain our observational development curves with proton dominant composition even though any available hadron interaction model is adopted.

The obtained all–particle spectrum has a gradual steepening at $10^{15.5}$ eV with the spectral index jump, from -2.66 to -3.19. Comparing our result with those by Tibet and KASCADE results, both of the absolute intensity and the energy of the knee in our spectrum are low. These differences could be due to the systematic difference of energy estimation procedures. The required energy shift is about 20%.

Finally, we conclude that the $\langle \ln A \rangle$ increases with the energy and is about 3.5 at 10^{16} eV and that the dominant component above 10^{15} eV is iron. Our result indicates that a heavier component model is more favored.

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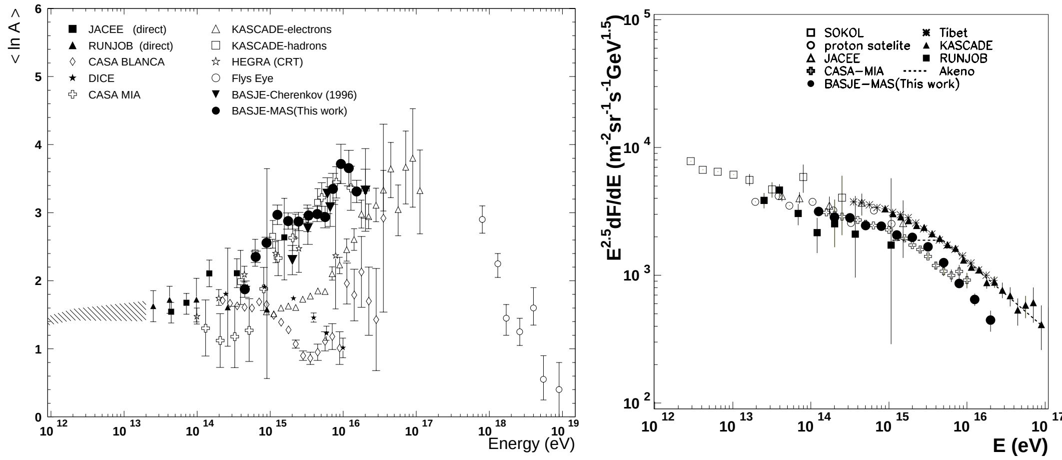

Fig. 2. *(left)* The mean logarithmic mass $\langle \ln A \rangle$ measured by BASJE–MAS array as a function of primary energy, compared with the results of other experiments with balloon–borne detectors([2,3,13]) and ground–based detectors([4,5,6,7,9,16,17]). Also the results of our former Čerenkov observations[15] are plotted. *(right)* The differential all–particle cosmic ray flux measured by BASJE–MAS array. The cosmic ray fluxes reported by other groups are also plotted ([1,2,3,8,10,12,14,17]).

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