The chemical composition of the primary cosmic rays around the Knee region by measuring lateral distributions of air Cherenkov photons

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**For the full listing, see S. Ogio et al., in these proceedings.*

Abstract

For a study of the chemical composition at the Knee region, we have measured lateral distributions both of air Cherenkov photons and of charged particles simultaneously at Mt. Chacaltaya in Bolivia since August 2001. The measured lateral distributions of air Cherenkov photons were fitted with an empirical function which includes a parameter reflecting mass numbers of primary cosmic rays. The observed distributions of this parameter were compared with those simulated using the CORSIKA code with the QGSJET hadronic interaction model for three species of primary cosmic rays: proton, C, Fe. As a result, the mean logarithmic mass number of primary cosmic rays $\langle \ln A \rangle$ in the energy range from 10^{14} to 10^{16}eV was determined. The result shows that $\langle \ln A \rangle$ decreases in the range from $10^{14.1}$ to $10^{14.7}$eV and increases from $10^{14.7}$ to $10^{15.8}$eV.

1. Introduction

Around and above the Knee region it is difficult to measure the chemical composition of primary cosmic rays directly due to their low fluxes. Therefore the chemical composition of primary cosmic rays have been measured indirectly in this region. BASJE had reported the results of the mean logarithmic mass number of primary cosmic rays $\langle \ln A \rangle$ by two different analyses: an examination of time structures of air Cherenkov photons [7] and the equi-intensity method [5]. The time structures of air Cherenkov photons are good indicators of $\langle \ln A \rangle$

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for cosmic rays of energies above 10^{15}eV. The equi-intensity method can examine the longitudinal development curves of air showers around and deeper than their maximum developments above $10^{14.5}$eV. These two results show that $\langle \ln A \rangle$ increases with primary energies around the Knee region. In this experiment, we have measured lateral distributions of air Cherenkov photons for a further study of the chemical composition. Lateral distributions of air Cherenkov photons have the information of each shower development at its early stage. That information is important for the primary particle identification, because the shower developments at early stages strongly depend on the primary nuclei. To obtain that information without losing, experiments at high mountain altitude which are almost points of the shower maximum have an advantage.

2. Experiment

We have measured lateral distributions both of air Cherenkov photons and of charged particles. For this experiment, air Cherenkov photon detectors were installed within an air shower array so called the Minimum Air Shower (MAS) array [10] at Mt. Chacaltaya in Bolivia (5200m a.s.l., atmospheric depths of 550g/cm^2). The number of installed air Cherenkov photon detectors was seven in low energy mode and eight in high energy mode. The triggering condition was changed to observe air showers at different energy regions: $10^{14} - 10^{15}$eV from August to October 2001 (low energy mode) and $10^{15} - 10^{16}$eV from June to October 2002 (high energy mode). The event selection criteria are as follows; the distances of shower cores from the center of the array are less than 20m in the low energy mode and 30m in the high energy mode, the zenith angles of air showers are less than 30°, and the number of air Cherenkov photon detectors which feed outputs with pulse heights more than 9 SN ratio is more than three. During two years observation one million events were obtained, and 2657 events were selected in the low energy mode and 1815 events were selected in the high energy mode (Table 1.).

Table 1. The number of events fulfilled all criteria for each shower size $\log N_\mathrm{e}$ bin in the low energy mode (the upper table) and in the high energy mode (the lower table).

$\log N_\mathrm{e}$	4.7-4.9	4.9-5.1	5.1-5.3	5.3-5.5	5.5-5.7
Number of events	1141	738	423	226	129

$\log N_\mathrm{e}$	5.5-5.7	5.7-5.9	5.9-6.1	6.1-6.3	6.3-6.6
Number of events	1091	473	168	61	22

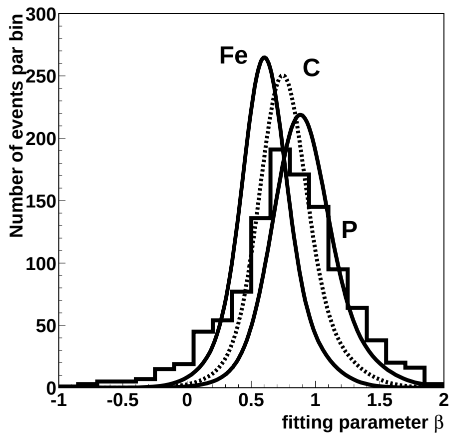

Fig. 1. The distribution of fitting parameter β for the observed events (histogram) and those simulated for each species for $4.7 < \log N_\mathrm{e} < 4.9$

3. Simulation and Analysis

In this section we outline a determination method of the chemical composition using the measured lateral distributions of air Cherenkov photons $\rho(\mathrm{r})$.

These $\rho(\mathrm{r})$ are fitted with an empirical function

$$\rho(r) = \alpha \cdot \left(\frac{\mathrm{r}}{\mathrm{R}_0}\right)^{-(\beta+\frac{\mathrm{r}}{\mathrm{R}_0})} \quad (\mathrm{R}_0 = 90m). \tag{1}$$

These fitting parameters α and β are indicators of both primary energy and the nuclear species. We select R_0 to be 90m so as to separate nuclear species significantly for this experiment. We used the CORSIKA code [4] version 5.61 with the QGSJET hadronic interaction model for simulating shower particles and air Cherenkov photons. For simulating air Cherenkov photons we took account of the effect of Mie and Rayleigh scattering, night-sky background, and the details of Cherenkov photon detectors: their positions, PMT gains, fields of views, and signal attenuations in cables. In these simulation procedures, indices of differential energy spectrum were adopt -2.7 below $10^{15.5}$eV and -3.3 above $10^{15.5}$eV. The expected distributions of the fitting parameter β classified by shower size N_e for three species (proton, C, Fe) were obtained from these simulations. We also examined the conversion factor from N_e to primary energy, estimation errors of N_e, and trigger efficiencies for each species.

The contributions of each species for the distributions of fitting parameter β for the observed events were determined by an maximum likelihood method. Fig.1. shows the distributions of the fitting parameter β for the observed events and those simulated. The contribution ratios of the species are determined using these distributions. Finally $\langle \ln A \rangle$ as a function of energy was obtained using thus determined contribution ratios, the N_e to energy conversion factors, and the trigger efficiencies for each species. The statistical error of $\langle \ln A \rangle$ were estimated by a likelihood ratio test (68% confidence level).

4. Results

As a result of the analysis, $\langle \ln A \rangle$ in the primary energy range from 10^{14} to 10^{16}eV was determined, as shown in Fig.2.. The result of the BASJE experiments [5,7] and other experimental results [1,2,3,6,8,9] are also indicated. For the point of the present result, the error bars show only statistical one in this figure. The present result shows a decreasing $\langle \ln A \rangle$ with the range from $10^{14.1}$ to $10^{14.7}$eV. Above 10^{15}eV the present result and the previous BASJE results show increasing $\langle \ln A \rangle$ with primary energies. Now we are estimating systematic uncertainties for the result obtained in this experiment.

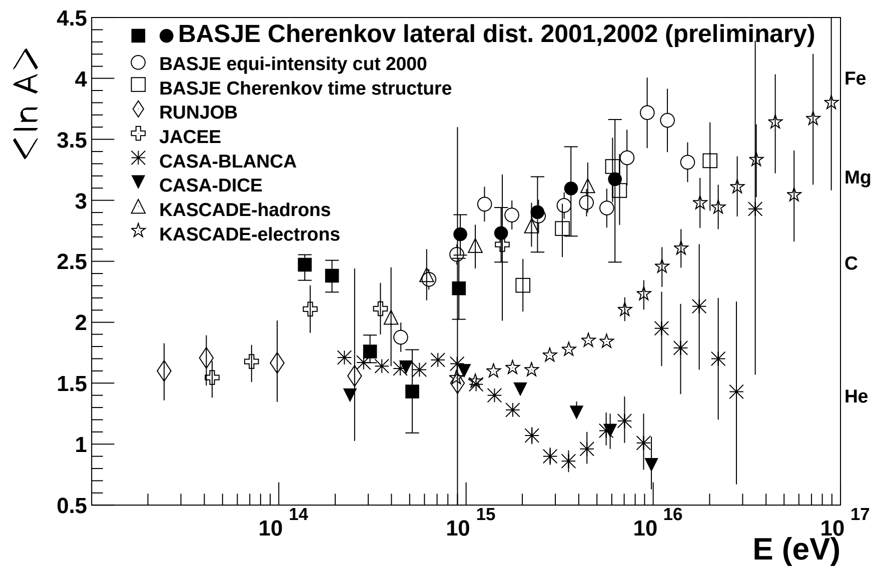

Fig. 2. The present result $\langle \ln A \rangle$ versus primary energy is shown. For comparison other results are also indicated: BASJE equi-intensity method [5], BASJE time structures of air Cherenkov photons [7], CASA-BLANCA [3], CASA-DICE [8], KASCADE hadron [2], KASCADE electron [9], and direct measurements RUNJOB [6] and JACEE [1].

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