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Measurement of cosmic ray chemical composition at Mt. Chacaltaya(*)

S. Ogio(1), F. Kakimoto(1), D. Harada(1), Y. Shirasaki(2), H. Tokunou(1)
O. Burgoa(1), E. Gotoh(3), T. Kaneko(4), Y. Matsubara(5)
P. Miranda(6), Y. Mizumoto(7), A. Morizawa(8), K. Murakami(9)
H. Nakatani(3), K. Nishi(3), S. Shimoda(3), N. Tajima(3), Y. Toyoda(10)
Y. Tsunesada(1), A. Velarde(6), Y. Yamada(3) and H. Yoshii(8)

(1) *Department of Physics, Tokyo Institute of Technology - Meguro, Tokyo 152-8551, Japan*
(2) *NASDA - Tsukuba, Ibaraki 305-8505, Japan*
(3) *The Institute of Physical and Chemical Research - Wako, Saitama 351-0198, Japan*
(4) *Department of Physics, Okayama University - Okayama 700-8530, Japan*
(5) *Solar-Terrestrial Environment Laboratory, Nagoya University Nagoya, Aichi 442-8507, Japan*
(6) *Institute de Investigaciones Fisicas, Universidad Mayor de San Andres Casilla 8635, La Paz, Bolivia*
(7) *National Astronomical Observatory - Mitaka, Tokyo 181-8588, Japan*
(8) *Department of Physics, Ehime University - Matsuyama, Ehime 790-8577, Japan*
(9) *Nagoya University of Foreign Studies - Nissin, Aichi 470-0197, Japan*
(10) *Faculty of General Education, Fukui University of Technology - Fukui 910-8505, Japan*

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Summary. — BASJE group has measured the chemical composition of primary cosmic rays with energies around the "knee" with several methods. These measurements show that the averaged mass number of cosmic ray particles increases with energy up to the knee. In order to measure the chemical composition in much wider energy range, we have started a new experiment at Mt. Chacaltaya in 2000.

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1. – Introduction

The energy spectrum and the chemical composition of primary cosmic rays in the energy range around the knee are of great interest for understanding the sources, acceleration and propagation mechanisms of cosmic rays. Unfortunately, there are two

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TABLE I. – *The estimated* p/(p+Fe) *from the constant intensity method analysis.*

E(PeV)	1.3	2.4	4.4	7.2	12	19
$\frac{\mathrm{p}}{(\mathrm{p+Fe})}$	0.42 ± 0.04	0.45 ± 0.05	0.34 ± 0.05	0.28 ± 0.04	0.27 ± 0.05	0.30 ± 0.11

difficulties in determination of the mass number of cosmic ray particles. First, the flux of cosmic rays is quite low, so that we can only measure cosmic rays indirectly with ground-based air shower detectors. Second, the mass estimation methods strongly depend on nuclear high energy interaction models.

In the last decade, the BASJE group has measured the chemical composition of cosmic rays with some different methods with an air shower array at Mt. Chacaltaya (5200 m a.s.l.). The measurement at such high altitude has many advantages: we can observe air showers around their maximum development and we can detect lower energy cosmic rays, and as a result, we can compare our results with those obtained by balloon and satellite experiments.

Here we describe our results that analyzed both with a constant intensity method and with a Čerenkov light pulse shape method. The details of the equipments, the operations and the analysis are described in refs. [1-3].

2. – Constant intensity method

If it is assumed that air showers initiated by primary cosmic rays of a certain energy arrive at the Earth uniformly with constant integral rate, an air shower size spectrum as a function of the zenith angle (θ), *i.e.* the atmospheric depth, for cosmic rays with the same rate of arrival gives the corresponding longitudinal development curve. We apply this method in analysis to the data obtained with SAS array [1] from September 1987 until September 1991. For the 3.89×10^7 selected events, we obtained the longitudinal development curves at the same frequencies. Finally, we made an estimate of the chemical composition of cosmic rays by comparing the measured longitudinal development curves and those calculated. In this calculation, we assumed that the primary is a mixing of proton and Fe and that the power index of the cosmic ray energy spectrum is $\gamma = 2.66$ for the energies $E \leq 5 \times 10^{15}$ eV and $\gamma = 3.17$ for $E > 5 \times 10^{15}$ eV. We determined the best value of p/(p+Fe) as a function of energy by comparing the longitudinal development curves obtained by the constant intensity cut with Monte Carlo simulations, as in listed in table I. The errors in the table mean the allowed widths at the 68% confidence level.

This result shows the averaged mass number $\langle \ln A \rangle$ is gradually increased with the energy as shown in fig. 1.

3. – Čerenkov light pulse shape method

In order to measure the chemical composition of cosmic rays more precisely, many groups observe not only air shower particles but also air shower induced Čerenkov photons. From 1995 to 1997, BASJE group observed Čerenkov light pulse shapes for primary cosmic rays energy range from 10^{15} to $10^{16.5}$eV coinciding with SAS array by which we measured sizes and arrival directions of air showers. The observations have been made during two periods. In 1995 and 1996, we operated two photon detectors, each of which consists of 7 5-inch PMTs(HAMAMATSU R1250), and is installed at about 130 m from

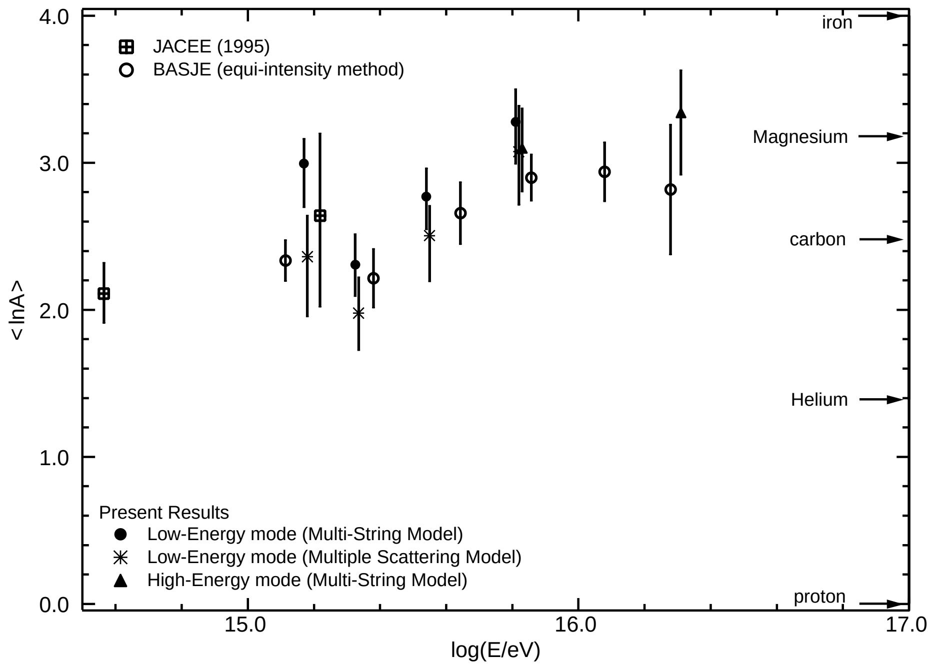

Fig. 1. – The $\langle \ln A \rangle$ obtained with constant intensity method and the Čerenkov light observation. The error bars represents 90% c.l. interval. See ref. [3] for the details of the hadron interaction models that we assumed in our simulations for this work.

the center of SAS array, which is in optimum position for the efficiency of the composition determination and number of observed Čerenkov photons. We call this the high-energy operation mode. In 1996 and 1997, we operated one detector which has 25 5-inch PMTs for the observations of the lower energy cosmic rays. Our Monte Carlo simulation study shows that the most efficient pulse shape parameter for the chemical composition determination is $T_{10\text{-}90}$, which is defined as a time interval between 10% to 90% of the integrated full pulse height.

We determined the cosmic ray composition by comparing the observed $T_{10\text{-}90}$ distribution with the simulated distributions with models in which we assumed various mixing ratio of 3 components: protons, C and Fe nuclei. The mixing ratio of the i-th component, α_i, is determined with the maximum likelihood method (fig. 2), and the averaged mass number $\langle \ln A \rangle = \sum \alpha_i \ln A_i$ is estimated.

The present result is shown in fig. 1 and compared with the results obtained by the constant intensity method and by JACEE experiment. Our result shows that the averaged mass number increases by $\delta \langle \ln A \rangle = 1.0$ in the energy range $10^{15.4}$–$10^{15.8}$ eV, *i.e.* around the knee energy, and remains almost constant around $10^{15.8}$ eV. This comparison shows good agreement with all the results. The consistency with the JACEE results ensures the validity of our method. Moreover, the agreement of the results of the independent measurements both by the constant intensity method that measures longitudinal developments beyond shower maxima and by the Čerenkov light method that measures developments before the maxima, confirms the reliability of our result beyond the knee energy.

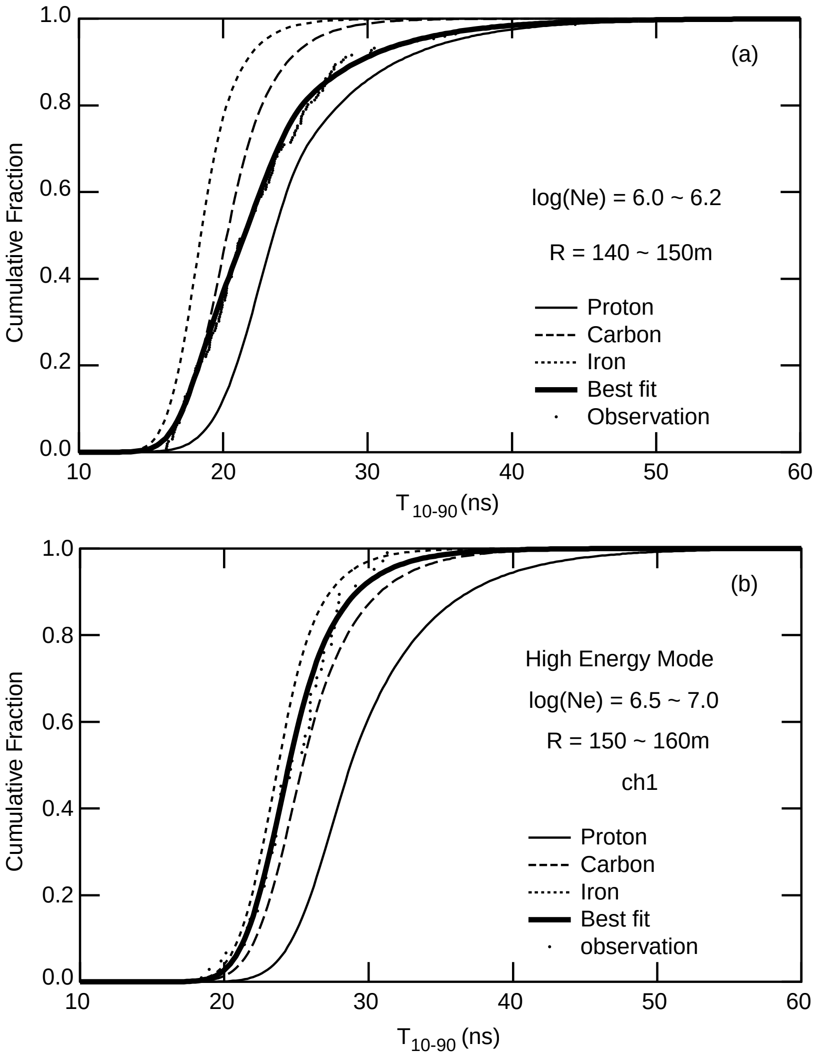

Fig. 2. – Comparison of the cumulative fraction distribution of experimentally determined $T_{10\text{-}90}$ (dots) with the distributions expected for proton, carbon and iron primaries; (a) $\log N_{\mathrm{e}} = 6.0\text{–}6.2$, $R = 140\text{–}150$ m obtained in the low energy mode observation, and (b) $\log N_{\mathrm{e}} = 6.5\text{–}7.0$, $R = 150\text{–}160$ m obtained in the high energy mode observation. The thick lines are for the most probable mixture of three nucleus groups.

In fig. 3, the present result is compared with the other indirect experimental results. Both EAS-TOP/MACRO [7] and Tien Shan [8] experiments observe the muon component of air showers. The group of University of Adelaide observed the lateral distribution of Čerenkov light from air showers and derived chemical composition by comparing it with simulation [9]. The present result at energy of $10^{15.5}$eV is consistent with that of EAS-TOP/MACRO and Tien Shan experiment. On the other hand, while EAS-TOP/MACRO and Tien Shan results show no significant change at energies above 10^{15}eV, our present results show an increase in the average mass number and is almost

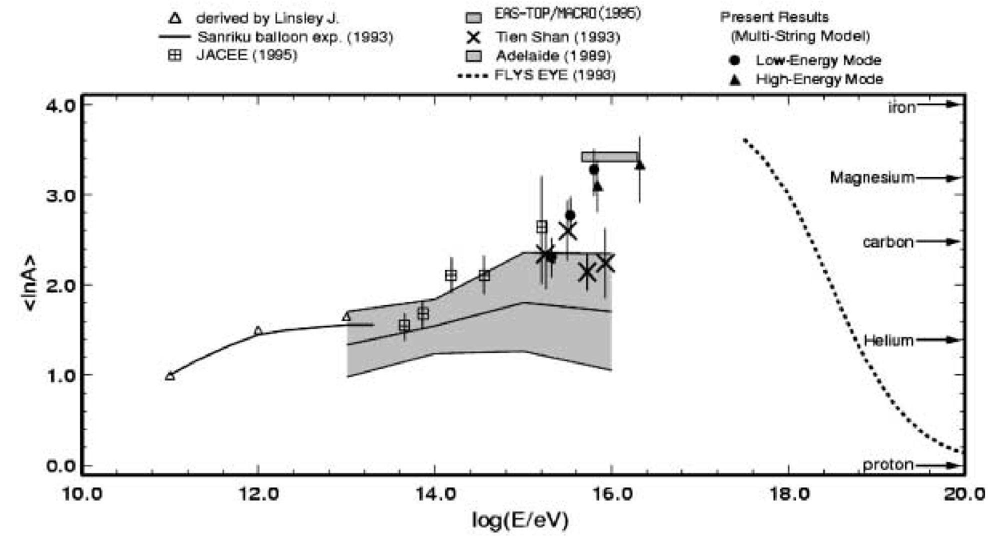

Fig. 3. – Comparison of our result of $\langle \ln A \rangle$ with the other direct and indirect experimental results [4-10]. The shaded area labeled "EAS-TOP/MACRO" is calculated by us from the result of correlated analysis of EAS-TOP and MACRO experimental data shown as table 2 in ref. [7].

consistent with the result of Adelaide group. Although the result by Fly's Eye [10] has been obtained in a much higher energy range and in the energy range from 10^{16} to 10^{18} eV no firmly established results exist about the chemical composition, our result at the highest energy and that of the Adelaide group are not inconsistent with the assumption that the extrapolations of those results connect smoothly to the Fly's Eye result.

4. – Future plan

In October 2000, we started a new experiment at Mt. Chacaltaya with MAS array to measure the chemical composition of cosmic rays in a wider energy range, 10^{14}–10^{17} eV. As for the measurement at lower energies, the validity of our measurement should be confirmed more exactly by comparing with the results of direct measurements. In the energy range from 10^{16} to 10^{18} eV no firmly established results exist about the chemical composition. Fly's Eye and MIA group show a gradual shift towards lighter primary particles above 10^{17} eV [11]. Since the energy range $10^{16} \sim 10^{17}$ eV is still a lacking measurement, we plan to fill this blank region with our future measurement.

For energies around around 10^{14}eV, according to our Monte Carlo simulation studies, the pulse shape method used for our former measurement is not useful to determine the chemical composition for energy around 10^{14}eV, because the observable core distance is limited less than about 100 m so that there are no significant differences among the pulse shapes of various primary compositions. While the lateral distributions of Čerenkov photons, as shown in the distribution of the parameter "Height" is strongly dependent on primary particles, as shown in fig. 4.

For energies more than 10^{15}eV, the lateral distribution is insensitive to the chemical composition but the observable core distance limit is larger than 100 m. So that, we can

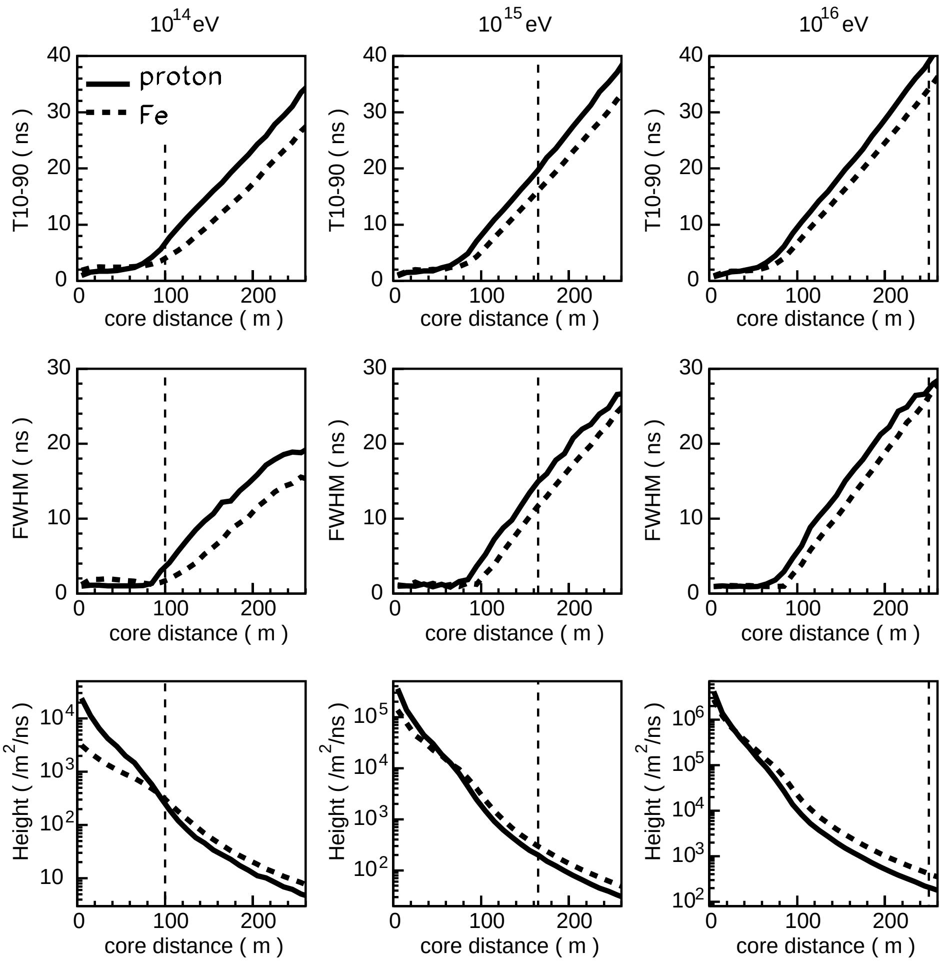

Fig. 4. – Three parameters of Čerenkov light pulses measured at Mt. Chacaltaya *vs.* core distances for three different primary energies. The vertical dashed lines indicate the core distance limits for the measurement with one 5-inch PMT due to signal-to-noise ratio of observed light pulses. We used CORSIKA [12] in our simulations with QGSJET interaction model.

determine the chemical composition with the measurement of the Čerenkov light pulse shapes, for example through the parameterizing analysis with $T_{10\text{-}90}$ and/or FWHM of pulses, for primary energies more than 10^{15}eV.

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