29th International Cosmic Ray Conference Pune (2005) **8**, 229–232

Measurement of Chemical Composition Using Telescope Array

S. Ogio[a], F. Kakimoto[b], S. Machida[b] and T. Iguchi[b]
for Telescope Array Collaboration

(a) Graduate School of Science, Osaka City University, Osaka 558-8585, Japan
(b) Graduate School of Science and Engineering, Tokyo Institute of Technology, Tokyo 152-8550, Japan
Presenter: H. Tokuno (htokuno@icrr.u-tokyo.ac.jp), jap-tokuno-H-abs3-he15-poster

With observations of air showers by Telescope Array fluorescence detector, we can distinguish primary species of cosmic rays with energies greater than 10^{18} eV event by event. This is mainly because of the good determination accuracies of the longitudinal development of air showers. Assuming cosmic rays consist of three species, *i.e.*, protons, carbon nuclei, and iron nuclei, we simulated observed events with TA fluorescence detector and analyzed the data. As a result, we found that we can determine the primary species event by event with the accuracy of 60 % using a multivariate analysis technique with the parameters expressing longitudinal development of air showers, for example, Xmax. When we perform these analysis for actual events, we can determine the component spectra of cosmic rays, and obtain the correlation between arrival directions and the composition. These results are keys to solve the mystery of origins and propagations of cosmic rays.

1. Introduction

Ultra high energy cosmic rays(UHECRs) are believed to be concerned with the most energetic phenomena in the Universe. Cosmic rays above the ankle are thought to be extragalactic, but the origin of them are not identified. In order to solve this mystery, we must experimentally obtain many pieces of information, such as the energy spectrum and the chemical composition. For example, if we find heavier nuclei than protons in UHECRs, this result indicates that UHECRs are accelerated by astronomical objects. Since the characteristics of source objects and acceleration mechanisms appears on the chemical composition, it is possible to identify sources with chemical composition studies. On the other hand, Yamamoto et al. pointed out that the major component of UHECRs transits from light to heavy nuclei with increasing energy owing to the attenuations and the fragmentations of nuclei during propagations in the inter–galactic space[1]. For this scenario, we need to detailed measurement of the chemical composition to determine whether it is correct or not.

AGASA group reported the detections of doublet and triplet events with high statistical significance[2][3]. This result indicates the existence of point sources of UHECRs. In order to identify the objects and the acceleration mechanism, we want to measure the chemical composition of cosmic rays from the point sources. For these measurement we need to distinguish particle species event by event.

With atmospheric fluorescence telescopes used for the Telescope Array(TA) experiment[4] we can observe longitudinal development profiles of air showers. These are useful information enabling for us to distinguish primary species. Practically some fluorescence telescope experiment, such as Fly's Eye[5] and HiRes[6], have ever studied the chemical composition with X_{max} distributions of observed air showers, but they have never individually determined particle species. However, since the fluorescence detectors for TA have a high angular resolution, this experiment possesses capability of discriminations of species event by event. In this report, we propose a method to identify primary species using the multivariate analysis technique. Here, we studied the capability of the method through Monte Carlo simulations of air shower observations with TA fluorescence detectors and through the subsequent reconstructions of shower profiles and the multivariate analysis.

2. Telescope Array Fluorescence Detectors

The site of the TA experiment is located at Milard county in Utah, and the altitude is about 1500 m. The TA fluorescence detector array consists of three telescope stations, each of which contains twelve telescopes of 3.3 m diameter. The stations are placed on the edges of the surface detector array, and the separations between the stations is about 40 km. The field of view of each station has an azimuthal angle of $108°$ and a elevation angles of $3° - 34°$. An imaging camera of a telescope has 256 hexagonal PMTs, and the pixel size is nearly corresponding to $1°$ on the celestial sphere. The light falling on a photocathode are converted into an electric signal, and the signals are recorded as digitized waveforms which are sampled with a frequency of 100 MHz by FADC electronics. The detailed descriptions of our instruments and techniques will be appeared on other contribution papers and presentations for this Conference[7].

3. Simulations

In the simulations we computed longitudinal development profiles of air showers with the Gaisser–Hillas(GH) formula, but we calculated the parameters of this formula and their energy dependences with Monte Carlo simulations of CORSIKA, individually for primary species. Please see the reference[8] for a detailed descriptions of Monte Carlo simulations and event reconstructions for the TA fluorescence experiment.

Figure 1 and 2 are two dimensional plots of GH formula's parameters which were obtained with reconstructions for these events. The plots in Figure 1 are relations between $\mathrm{X_{max}}$ and the first interaction depth, $\mathrm{X_{int}}$, and the plots in Figure 2 are relations between $\mathrm{X_{max}}$ and the shower size at $300\mathrm{g/cm^2}$, $\mathrm{N_{300}}$. In the simulations we assumed as follows: a) the primary energies are $\log E = 20.00 \pm 0.03$, where the energy fluctuation, $\Delta \log E = 0.03$ is equivalent to the energy determination error with the reconstruction procedure, b) the arrival directions of primary particles are uniformly distributed within zenith angles of less than $60°$, c) the core positions are randomly distributed within $R_p \leq 30$ km, where R_p is an impact parameter of an shower axis from the center of gravity of the station distributions. We selected events with conditions of, for example, a track length on imaging cameras, total numbers of detected photo–electrons, a magnitude of χ^2 of images fitting to GH formula, and so on. We simulated 15000 events for each primary species, and the remaining events after the reconstructions and the event selections are 5717 for primary protons, 6126 for carbon nuclei, and 6466 for iron nuclei. From these figures we can conclude that every parameter considered here depends on primary species, and then we use these parameters for discriminations of species, as described in the next section.

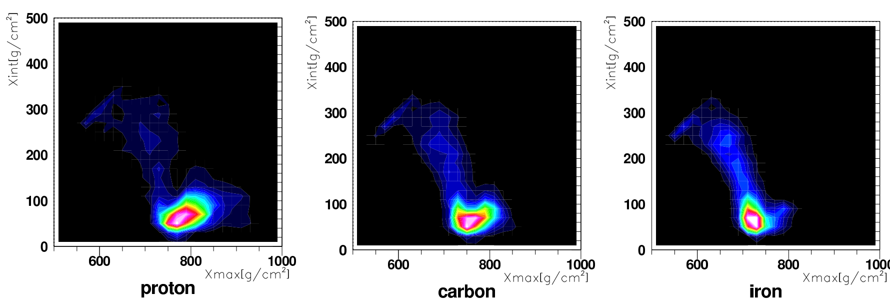

Figure 1. Two dimensional distributions of $\mathrm{X_{int}}$ and $\mathrm{X_{max}}$ for reconstructed events which are simulated of primary protons(*left*), carbon nuclei(*center*), and iron nuclei(*right*).

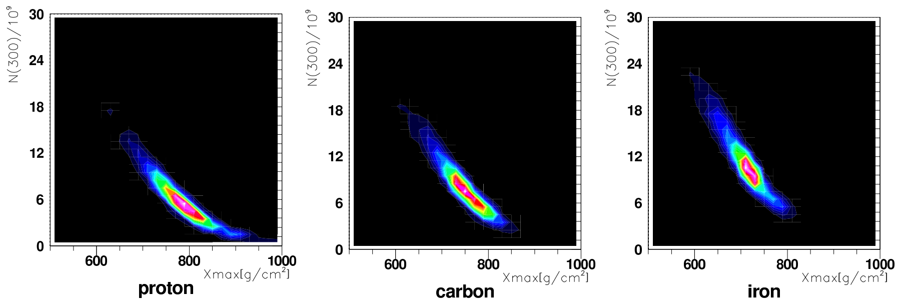

Figure 2. Two dimensional distributions of N_{300} and X_{max} for reconstructed events which are simulated of primary protons(*left*), carbon nuclei(*center*), and iron nuclei(*right*).

Table 1. Discriminant Rates and Error Discriminant Rates for Two Component Simulations

	protons(%)	irons(%)	others(%)
primary protons	81.9	16.0	2.1
primary irons	17.0	81.5	1.5

4. Multiple Classification Analysis

In order to discriminate primary species event by event we use the nearest neighbour method for GH formula parameter distributions for reconstructed events. In this analysis, we used the data which are plotted in Figure 1 and 2 as group data. Moreover, we simulated 7500 events for each species. After we applied the reconstruction procedures for these data, the number of the remained sample data is 2927 for protons, 3072 for carbon nuclei, and 3215 for iron nuclei. In the nearest neighbour method, the position of a sample in the explanatory variable space is the indicator for the discriminations. Thus, in our case, as explanatory variables we use normalized X_{max}, X_{int}, and N_{300} with determination accuracies of each parameters.

The results of the discriminations are shown in Figure 3, and 4. The histograms in Figure 3 are the probability distributions when we assumed cosmic rays consist of two components; protons and iron nuclei. The histograms in Figure 4 are the distributions under an assumption that cosmic rays consist of three components; protons, carbon and iron nuclei. When we define the threshold of a discriminant rule is 50%, the discriminant rates and the error discriminant rates are obtained as listed in Table 1 and 2.

Table 2. Discriminant Rates and Error Discriminant Rates for Three Component Simulations

	protons(%)	carbons(%)	irons(%)	others(%)
primary protons	53.3	40.1	4.8	1.8
primary carbons	19.9	62.5	16.6	1.0
primary irons	3.8	30.8	64.0	1.4

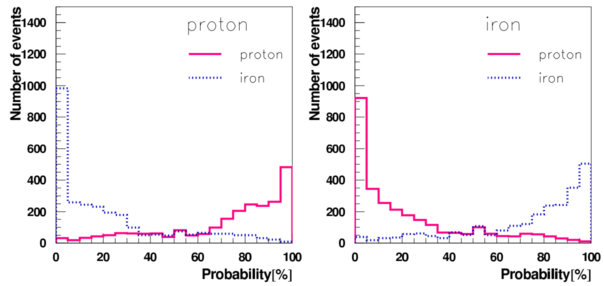

Figure 3. The histograms of probabilities for the nearest neighbour method; $P_i = r_i / \sum_k r_k$, where, $r_i = n_i / N_i i$. n_i is the number of events for the type i particle within the unit length radius from a sample event in explanatory variable space. N_i is the total number of events or the type i particle. The left panel is for primary proton samples and right panel is for primary iron nuclei samples.

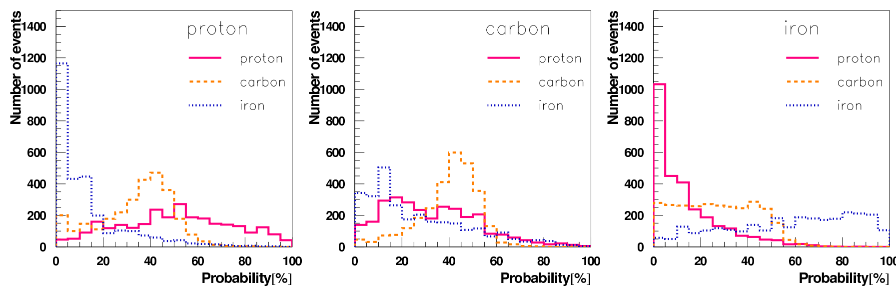

Figure 4. The histograms of probabilities as same as Figure 3, for three components: protons, carbon nuclei and iron nuclei.

5. Discussion

As a result, we found that we can discriminate species with a discriminant rate of about 80% if cosmic rays consist of protons and iron nuclei. When cosmic rays consist of three components, discriminant rates are about 60% for every species. For farther development of analysis procedures and improvement of accuracies , we will try to use other method of discriminant analysis, and to optimize explanatory variables and normalization factors. Moreover we plan to add observable values with the surface array as members of explanatory variables.

References

[1] T. Yamamoto, et al., Astropart. Phys., 20, 405(2004).
[2] M. Takeda, et al., Astrophys. J. 522, 225 (1999).
[3] N. Hayashida, et al., astro-ph/0008102(2000).
[4] M. Fukushima, et al., 29th ICRC, Pune (2005).
[5] J. D. Bird, et al., Phys. Rev. Lett., 71, 3401(1993).
[6] R. U. Abbasi, et al., astro-ph/0407622(2004).
[7] S. Ogio, et al., 29th ICRC, Pune (2005).
[8] The Telescope Array Project, Design Report(2000).