Mass Composition Study of Ultra-high Energy Cosmic Ray with the Telescope Array Fluorescence Detector Stereo Events

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***Abstract*. In order to clarify the origin of ultra high energy cosmic rays, an observational determination of the mass composition is of crucial importance. The primary particle type of cosmic rays can be distinguished by measuring the longitudinal development of an air shower event, since it strongly depends on the interaction cross sections of cosmic ray-atmospheric nuclear reactions, and cascade developments in the atmosphere. The fluorescence detection technique provides a powerful tool for the mass composition study because it is possible to observe the shower developments directly.**

In the Telescope Array (TA) experiment, we have started data taking using the fluorescence detectors (FDs) since November 2007, and accumulated air shower data for more than one year. In this paper, we present the first results of TA FD data analysis for the mass composition of ultra high energy cosmic rays. It is known that the atmospheric depth of shower maximum, $X_{\max}$, is one of the sensitive parameter of longitudinal development for primary particle. We also discuss the new method to determine the primary particle by other parameters tuned by air shower simulation.

***Keywords*: ultra high energy cosmic ray, mass composition, Monte Carlo simulation**

I. INTRODUCTION

It had been predicted that the cosmic-ray flux has a suppression above $\sim 10^{19.5}$eV due to an interaction with cosmic microwave background (CMB) [1][2]. The Akeno Giant Air Shower Array (AGASA) [3], the High Resolution Fly's Eye (HiRes) [4], the Yakutsk Experiment [5], and the Pierre Auger Observatory [6] had reported the energy spectra of ultra high energy cosmic rays (UHECRs) with energy above 10^{18}eV, but they are not consistent.

In order to clarify the source or propagation mechanism of UHECRs, it is quite important to determine the mass composition for several reasons. First, cosmic ray composition should strongly depend on that of production and acceleration sites. Second, interactions and spallation processes during propagation in inter/intra-galactic space are different for various nuclei. Third, the predicted characteristic structures of the energy spectrum of UHECRs are also affected by the mass composition. The one is the ”cut-off” above $10^{19.5}$ eV due to photo-pion productions through interactions with the CMB. The another structure is known as ”dip” due to energy losses through electron-positron pair productions [7]. Additionally, gamma primary bears out the exotic model such as topological defect [8] or super heavy dark matter[9].

The Telescope Array (TA) experiment is designed to study UHECR [10]. The TA observatory is located in Millard County, Utah, USA (39.1°N,112.9°W) with average hight 1400 m above sea level. TA is a hybrid detector consisting of the surface detector (SD) array and fluorescence detectors. The SDs are plastic scintillation counters similar to those of AGASA arranged in 1.2km grid [11]. The FDs are installed in three station around the SD array. In two of these stations in south of TA site, newly developed 12 fluorescence telescopes are mounted. Each telescope consists of spherical mirror with 3.3m diameter and 256 photo-multiplier tube cluster. The fields of view of each telescope is 15° in azimuth and 18° in elevation. The total field of view of the 12 telescopes is 108° in azimuth and 3 to 33° in elevation covering over the SD array. In the other northern station, 14 telescopes were transfered from HiRes-I. Hybrid measurement will be able resolve the difficulties in determination of cosmic ray energies in different detector types and techniques as in AGASA and HiRes Energy scale of SD can be cross-checked by calorimetric measurement by FD.

In this paper, we discuss a method to determine the mass composition of UHECRs from shower parameters, as atmospheric depth at shower maximum, $X_{\max}$, which is the one of the sensitive parameter for primary particle. We also discuss a new method to determine the primary particle by other parameters tuned by air shower simulation.

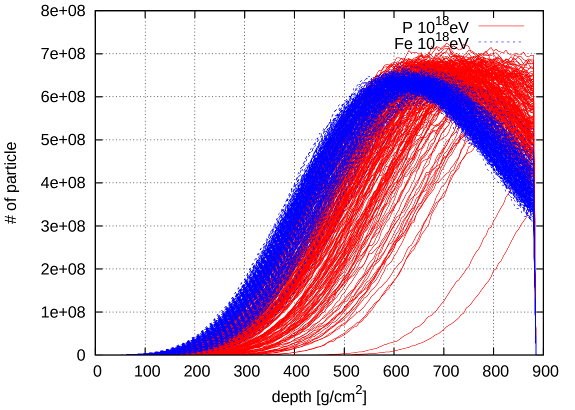

Fig. 1. Typical air shower longitudinal developments of primary proton and iron by Monte Carlo simulation

II. COMPOSITION DEPENDENCE

It is quite important to determine the mass composition of UHECR. The profile of cosmic-ray air shower shows the strongly dependence on the primary energy and particle type. The TA FDs can directly observe the longitudinal development of air shower to measure the fluorescence light induced by the energetic particles in air showers. In this section, we describe shower simulation studies to find out characteristics of air showers and parameters sensitive to primary nuclear types.

We have simulated air showers using CORSIKA 6.735 [12]. We use the QGSJET-01 models for high energy and GHEISHA for low energy hadronic interaction simulation. Simulated particles are followed down to the energy of 50MeV for hadron and muon and 50keV for electron and photon. In order to reduce the computing time, thinning option is applied.

Typical profiles of air showers induced by a proton and an iron nuclei are shown in Fig. 1. The atmospheric depth at the shower maximum, $X_{\rm max}$, is easily found as one of the parameter which depend on the primary energy and particle.

A. $X\max$ distribution

The mass composition of UHECRs has been estimated with $X_{\rm max}$ technique: comparison observed $X_{\rm max}$ distribution with simulated events. It is expected that $X_{\rm max}$ for showers initiated by heavier nuclei are smaller than those produced by protons, which is attributed to a smaller mean free path of the primary particle in the atmosphere, and smaller energy per nucleon. In order to examine composition of UHECRs as a function of energies, *elongation rate* $dX_{\rm max}/dln(E)$ is used also.

The detector configuration including atmospheric condition should be taken into account for the $X_{\rm max}$ distribution to be compared with observed one. Fluorescence lights induced by energetic shower particles are attenuated by Rayliegh or mie scattering in the atmosphere. The obscuration of detector structure, reflection by the mirrors and transmission and reflection by filter mounted on photomultiplier-tube also should be reflected.

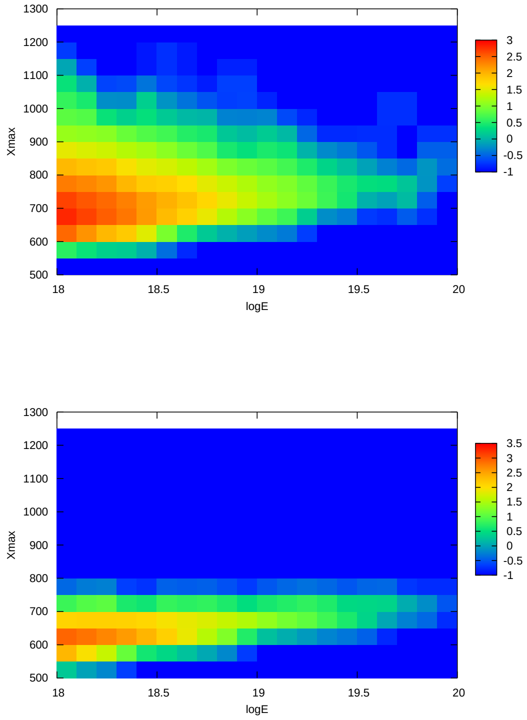

Fig. 2. Expected $X_{\rm max}$ distribution observed with TA FD. Upper and lower correspond to pure proton primary and pure iron respectively.

Figure 2 are the expected $X_{\rm max}$ distributions observed with TA FD. These distribution is applied the trigger efficiency calculated by detector simulation and the arrival frequency of UHECR is supposed proportional to $E^{-3.1}$. Figure 2 shows that difference of $X_{\rm max}$ distribution between pure proton and pure iron is distinguishable.

B. Characteristic parameters

Characteristic air shower parameters for the primary particle type are not only the $X_{\rm max}$. We can find other parameters which show the primary energy or particle type dependence. In Fig. 3, such characteristic parameters are shown acquired by air shower simulation. A multiparametric analysis improves the determination of primary particle. In this section, we discuss the possibility to use other parameters.

We simulated 13,000 air showers for each primary particle: proton, helium, oxygen and iron. From 10,000 simulated shower, we choose four parameters: $X_{\rm max}$, $N_{\rm max}$, N_{300} and N_{900}. $N_{\rm max}$, N_{300} and N_{900} are shower sizes at $X_{\rm max}$, 300 and 900 g/cm^2 respectively. The four parameters distribution are divided with into dimensional cubes and the number of showers of which parameters are within the i-th cube is $N_i(A)$ for A primary. Therefore, the probability that the primary particle of the shower is A whose parameters are within the i-th cube can be defined as

$$P_i(A) = \frac{N_i(A)}{N_i(P) + N_i(He) + N_i(O) + N_i(Fe)}. \quad (1)$$

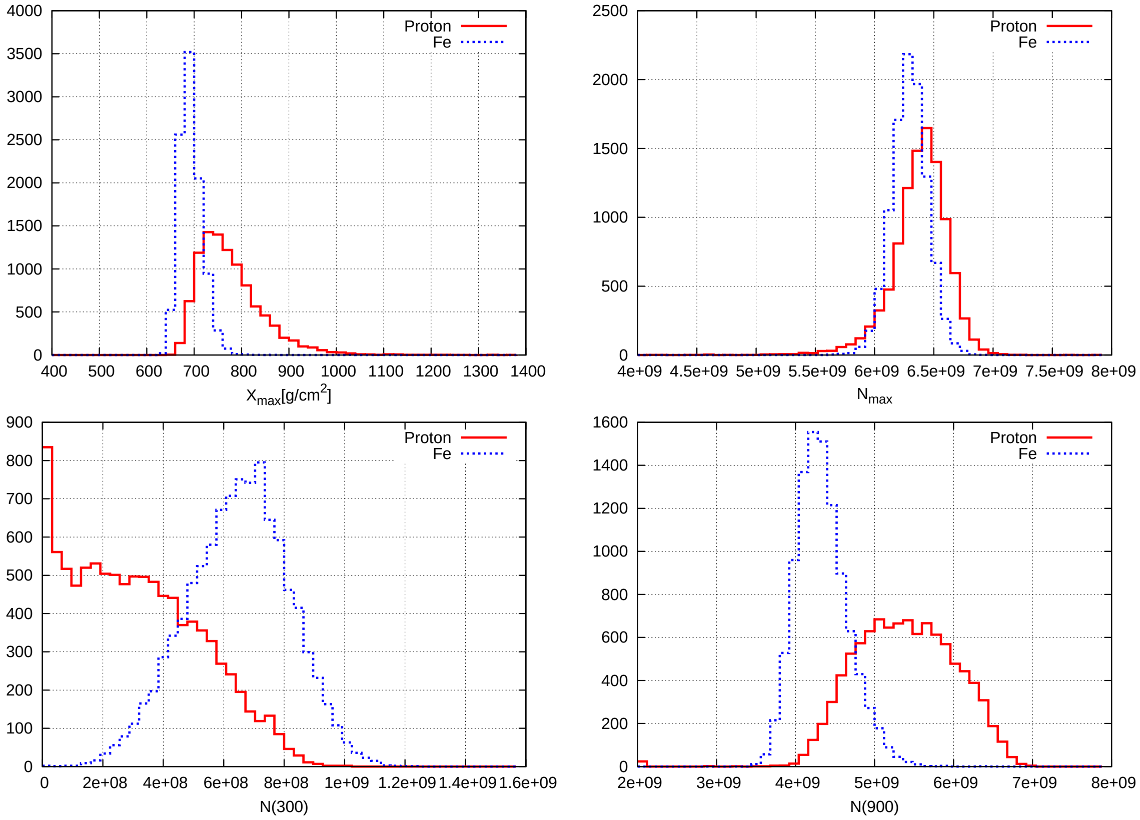

Fig. 3. Characteristic parameters of 10,000 simulated air shower profiles of proton(black) and iron(red) primary particle with energy 10^{18}eV. parameters are upper left:$X\max$, upper right:N_{max}, lower left:$N(300)$ and lower left:$N(900)$.

When the probability of A primary is maximum, the examined shower's primary type is judged as A. For another 3,000 simulated showers, we calculated the probability shown in table I. Figure 4 shows the result of judgement for proton and iron primary with energy 10^{19}eV.

TABLE I
MEAN PROBABILITY OF PRIMARY PARTICLE DETERMINATION

		proton	helium	Oxygen	iron
10^{18}eV	P	0.519	0.314	0.133	0.030
	He	0.314	0.386	0.231	0.066
	O	0.133	0.237	0.372	0.253
	Fe	0.028	0.069	0.263	0.609
10^{19}eV	P	0.458	0.302	0.167	0.069
	He	0.302	0.338	0.242	0.116
	O	0.170	0.241	0.320	0.268
	Fe	0.066	0.113	0.268	0.553
10^{20}eV	P	0.401	0.292	0.188	0.112
	He	0.294	0.309	0.244	0.152
	O	0.184	0.235	0.301	0.279
	Fe	0.112	0.153	0.279	0.456

For iron primary with energy 10^{19}eV, 70% of those are judged as iron. This is better than proton due to the fluctuation of proton primary showers larger than iron. The resolutions of judgment becomes worse as energy becomes high because the difference of those distribution of selected parameters becomes not distinct. We should choose the other parameters which efficient for any energies or change for each energy.

III. Summary

To determine the mass composition of UHECRs, the $X_{\max}$ distribution was estimated in which detector response was taken in account. Possibility of mass composition determination from some characteristic parameters was examined. For the four primaries, resolution to determine the primary type has room for improve. In this paper, we show the calculation using only QGSJET-01 but other interaction models also should be examined such as QGSJET-II, DPMJET etc. At all events, the mass composition of UHECRs will be determined by air shower simulation and detailed detector response.

Acknowledgements

The Telescope Array experiment is supported by the Ministry of Education, Culture, Sports, Science and Technology-Japan through Kakenhi grants on priority area (431) “Highest Energy Cosmic Rays”, basic researches 18204020(A), 18403004(B) and 20340057(B); by the U.S. National Science Foundation awards PHY-0601915, PHY0703893, PHY-0758342, and PHY-0848320 (Utah) and PHY-0305516 (Rutgers); by the Korean Science and Engineering Foundation (KOSEF, Grant No. R01-2007-000-21088-0); by the Russian Academy of Sciences, RFBR grants 07-02-00820a and 09-07-00388a (INR), the FNRS contract 1.5.335.08, IISN and Belgian Science Policy under IUAP VI/11 (ULB). The foundations of Dr. Ezekiel R. and Edna

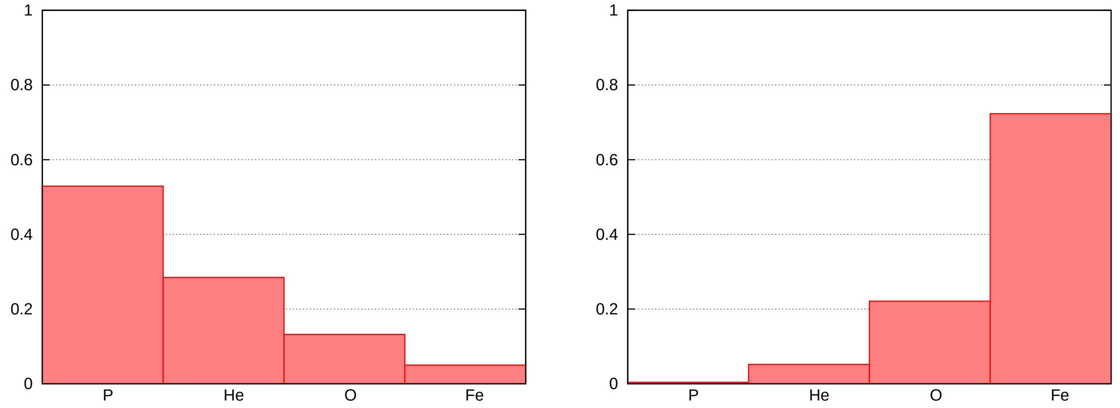

Fig. 4. Result of primary particle determination for proton(left) and iron(right).

Wattis Dumke, Willard L. Eccles and the George S. and Dolores Dore Eccles all helped with generous donations. The State of Utah supported the project through its Economic Development Board, and the University of Utah through the Office of the Vice President for Research. The experimental site became available through the cooperation of the Utah School and Institutional Trust Lands Administration (SITLA), U.S. Bureau of Land Management and the U.S. Air Force. We also wish to thank the people and the officials of Millard County, Utah, for their steadfast and warm support. We gratefully acknowledge the contributions from the technical staffs of our home institutions. This work was supported by a 21st Century COE program at Tokyo Institute of Technology “Nanometer-Scale Quantum Physics” by the Ministry of Education, Culture, Sports, Science and Technology.

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