Recent results of the energy spectrum and mass composition from Telescope Array Fluorescence Detector

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Abstract. The Telescope Array experiment is the largest hybrid detector to observe Ultra-High Energy Cosmic Rays in the northern hemisphere. The observation started in November 2007 for Fluorescence Detector (FD) and in March 2008 for Surface Detectors (SD). Here, we present the preliminary results of the energy spectrum and mass composition of the UHECRs measured by the FD and hybrid technique from the Telescope Array three year observations. The energy spectrum measured by the Middle Drum FD station, which is the refurbished HiRes-I detector is consistent with the results from HiRes. The energy spectrum with the two newly constructed FDs and SD is also in good agreement with the result from HiRes, especially for the energy scale. The mass composition study with the slant depth of the maximum shower development (X_{max}) is obtained by using the stereo and hybrid analysis. The result of the mass composition is consistent with the proton prediction.

1. Introduction
The Telescope Array (TA) experiment is the largest Ultra-High Energy Cosmic Ray (UHECR) observatory in the northern hemisphere, located in the west Utah desert. This is a hybrid UHECR detector using two types of detectors: three stations of Fluorescence Detectors (FDs) and 507 Surface Detectors (SDs). The main subjects of TA are to clarify the origin of UHECR as a follow-up to the AGASA [1] and HiRes [2] experiments.

Each of the SD consists of two layers of plastic scintillator. TA SD array covers a ground area of approximately 700 km² on a grid of 1.2 km spacing [3]. Three FD stations (Black Rock Mesa (BR), Long Ridge (LR) and Middle Drum (MD)) are located surrounding the SD array. The MD station consists of the 14 refurbished HiRes-I telescopes [4]. The BR and LR stations are constructed newly for the TA experiment. The hybrid operation was started from May 2008.

In particular, the FD observes the fluorescence photons proportional to the energy deposit as the longitudinal development of the air shower. By using this observation technique, the energies of the UHECRs are measured without strong dependence on the interaction models for the ultra-high energy region. Moreover, since the difference of the primary nuclear types appears in the longitudinal developments of the air showers, the mass compositions of the UHECRs are also measured. Currently, in TA observation, the energy scale and mass composition are measured by using the FDs. Here, the preliminary results from the TA three-year observations about energy spectra and mass composition are presented.
Figure 1. Energy spectra measured by TA data, MD monocular mode (filled upward triangle), MD hybrid mode (filled downward triangle), BR/LR hybrid mode (filled square) and SD (filled circle).

Figure 2. Averaged $X_{\text{max}}$ measured by TA MD hybrid-mode. Lines are expected values obtained from MC data (Red: Proton, Blue: Iron) for which applied same analysis procedure as that for the data.

2. Shower Analysis

The FDs observe photons emitted along the track of air showers passing through the atmosphere. Due to the fact that the amount of the fluorescence lights which is the main component of light emission is proportional to the energy deposit, the energy deposit profile along the shower axis can be reconstructed from FD data. The calorimetric energy of the air shower is obtained by integrating the longitudinal profile. By taking into account the missing energy which is carried away by the neutral particles, the energy of the primary particle is obtained.

The analysis procedure for the MD data is almost identical to that of HiRes experiment [5]. For the BR/LR data analysis, new analysis procedure which is called an Inverse Monte Carlo method has been developed [6]. The observed charges at each PMT are compared with that produced by the simulated showers with all of the effects such as Cherenkov lights, shadowing by structures, non-uniformity of the PMT surface and other calibration factors.

The detector Monte Carlo simulation which includes the air shower Monte Carlo [7] and all of the time-dependent calibration factors is also developed. It is used to check the resolution and bias for the reconstruction, to obtain the aperture for the energy spectrum analysis and to estimate the expectation for the observed $X_{\text{max}}$. By this study, we obtained that the resolution of the arrival direction as 1 degrees and of the energy resolution as 8% for the hybrid events above $10^{18.2}$eV. Moreover, the data and Monte Carlo events are in good agreement with the important parameters, impact parameter, zenith angle, azimuth angle and so on.

The systematic uncertainties in energy determination are dominated by the uncertainties in the fluorescence yield (11%), atmosphere attenuation (11%) [8], the absolute detector calibration (10%) [9][10][11], and the reconstruction procedure itself (10%). The total systematic errors are estimated at 21% for the energy scale, and 12% for the aperture uncertainties related to the cloud monitoring [12].
3. Energy Spectrum
The energy spectra above $10^{18}$ eV from the TA observations (MD monocular mode [5], BR/LR hybrid mode [6], and SD [13]) are shown in Figure 1. The MD energy spectrum, which were obtained from the refurbished HiRes-1 detectors and were analyzed with the identical procedures used in HiRes, is fully consistent with the HiRes-1 and HiRes-2 results. The BR/LR hybrid energy spectrum is also consistent with the results from HiRes experiment. This means that the energy scale measured by the TA new FDs are almost same with that measured by HiRes.

4. Mass Composition
The difference of the primary nuclear types appears in the longitudinal developments of the air showers. In particular, the depth of maximum of air showers, $X_{\text{max}}$, is used as an estimator. Here we used BR/LR stereo events [14], observed simultaneously with two FDs, and MD hybrid events [15] because the shower geometry can be determined more accurately than that of the monocular mode. Since field of view (FOV) of the FD is limited, the distribution of the observed $X_{\text{max}}$ should be different from the prediction by air shower MC. Therefore, we constructed the MC data set which is generated by CORSIKA with detector simulation, and applied the same analysis procedure for real data. Here the prediction from MC data set includes all of the bias of FOV and analysis procedure.

The averaged $X_{\text{max}}$ of the observed showers are shown in Figure 2 and Figure 3. The TA data is consistent with the proton-dominated composition of UHECR. The distributions of $X_{\text{max}}$ measured by BR/LR stereo mode in each energy bin are also compared with the expectation from MC and checked by KS tests. By this analysis, the TA data are also compatible with proton primary prediction. In the higher energies ($E > 10^{19.4}$ eV), TA data are compatible with the predictions both for proton and iron, but the statistics are still limited.

Figure 3. Averaged $X_{\text{max}}$ measured by TA BR&LR stereo-mode. Lines are expected values obtained from MC data (Red: Proton, Blue: Iron) for which applied same analysis procedure as that for the data.

Figure 4. The compatibilities of the $X_{\text{max}}$ distributions between observed data and MC obtained by KS test for various energy bins.
5. Conclusion
The FDs is a powerful detectors to measure the energy and longitudinal development of the air shower. Here, the preliminary results of the energy spectrum and mass composition of the UHECRs measured by the FD and hybrid technique from the Telescope Array three year observations are presented. The energy spectrum measured by the MD monocular mode is good agreement with the results from HiRes. The BR/LR hybrid spectrum is also consistent with the results from HiRes, especially for the energy scale. The systematic uncertainties for the energy determination is estimated to be 21%. The measured mass composition with the TA data is consistent with the proton prediction. By the comparison of the distribution of $X_{\text{max}}$ measured by the BR/LR stereo-mode, the TA data are also compatible with proton primary prediction. In the higher energies ($E > 10^{19.4}$ eV), TA data are compatible with the predictions both for proton and iron, but the statistics are still limited.

Acknowledgments
The Telescope Array experiment is supported by the Japan Society for the Promotion of Science through Grants-in-Aid for Scientific Research on Specially Promoted Research (21000002) “Extreme Phenomena in the Universe Explored by Highest Energy Cosmic Rays”, and the Inter-University Research Program of the Institute for Cosmic Ray Research: by the U.S. National Science Foundation awards PHY-0307098, PHY-0601915, PHY-0703893, PHY-0758342, and PHY-0848320 (Utah) and PHY-0649681 (Rutgers); by the National Research Foundation of Korea (2006-0050031, 2007-0056005, 2007-0093860, 2010-0011378, 2010-0028071, R32-10130); by the Russian Academy of Sciences, RFBR grants 10-02-01406a and 11-02-01528a (INR), IISN project No. 4.4509.10 and Belgian Science Policy under IUAP VI/11 (ULB). The foundations of Dr. Ezekiel R. and Edna 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 and the University of Utah Center for High Performance Computing (CHPC).

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