

Energy Spectrum and Mass Composition of Ultra-High Energy Cosmic Rays Measured with the Telescope Array Fluorescence Detector Using a Monocular Analysis

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The Telescope Array (TA) experiment is the largest cosmic ray detector to observe ultra-high energy cosmic rays (UHECRs) in the northern hemisphere. We report on results of the energy spectrum of UHECRs covering a wide energy range, and the mass composition using the maximum shower depth, from analyzing data collected in monocular mode by the fluorescence detectors of TA during the first seven years.

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1. Introduction

In the research field of cosmic ray physics, one of the most intriguing topics is the origin of ultra-high energy cosmic rays (UHECRs) which are the most energetic particles in the universe. Because of an extremely low flux of UHECRs, a huge effective coverage is required to observe UHECRs. Measurements of the energy spectrum and the mass composition of UHECRs are essential for understanding origins and propagations of cosmic rays and for testing several theoretical models to produce UHECRs.

When UHECRs enter the Earth's atmosphere, a huge number of secondary particles are generated via hadronic and electromagnetic interactions with atmospheric nuclei, called an extensive air shower (EAS). The slant depth at which the longitudinal development of EAS reaches its maximum, X_{\max} , is an important parameter because it depends on the mass composition of UHECRs. A fluorescence detector (FD) observes atmospheric fluorescence photons emitted by molecules excited by an EAS, providing a determination of the primary energy and the longitudinal development of EAS including X_{\max} . This measurement has less dependence on simulations than other techniques such as the muon content of the EAS, because the production and energy-loss mechanisms of the EAS electromagnetic components (which make the dominant contribution to fluorescence photon emissions) are less dependent on hadronic interaction models.

The Telescope Array (TA) experiment is the largest cosmic ray detector in the northern hemisphere [1]. TA consists of 507 surface detectors (SDs) deployed on a square grid with 1.2 km spacing, covering an effective area of about 700 km² [2], overlooked by 38 fluorescence detectors at three locations [3]. One FD station located northwest of the SD array, consists each of 14 FDs previously used in the High Resolution Fly's Eye (HiRes) experiment [4]. Two other stations at the array's southeast and southwest consist of 12 newly designed and constructed FDs [3], with with new calibrations [5, 6, 7] and atmospheric monitors [8, 9, 10].

2. Monocular Analysis and Monte Carlo Simulation

In this paper, we report on an analysis of data collected at the newly constructed FD stations using a monocular analysis, which is an analysis mode to reconstruct an EAS to obtain properties of the primary particles using the measured shower image by one FD station. To reconstruct a geometry of an observed EAS, an arrival time t_i of the signal in each photo-multiplier tube (PMT) i is fitted by

$$t_i = t_{\text{core}} + \frac{1}{c} \frac{\sin \Psi - \sin \alpha_i}{\sin(\Psi + \alpha_i)} r_0 \quad (2.1)$$

where α_i is an angle formed by the i -th PMT viewing direction and a direction vector from the FD station to the shower core (impact point of shower axis on the ground), Ψ is the angle on the shower detector plane (SDP) formed by the shower axis and the direction to the shower core, t_{core} is the time when the shower impacts the ground, and r_0 is the distance from the FD station to the shower core. When the EAS geometry has been determined, the longitudinal development of EAS is calculated by the inverse Monte Carlo method [11]. This inverse Monte Carlo technique iteratively explores the longitudinal-development parameter space, searching for the optimum solution to reproduce the observed shower image.

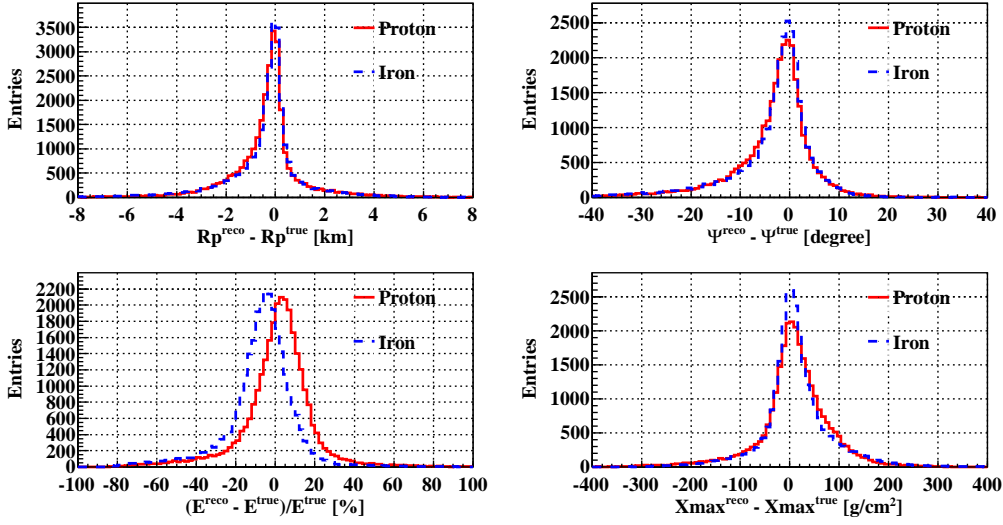


Figure 1: Resolutions of R_p , Ψ , primary energy and X_{max} estimated by the reconstruction of artificial data using proton (red), and iron (blue dashed line) with the QGSJetII-03 interaction model in the monocular analysis.

The geometries of too faint or too short showers are difficult to reconstruct accurately. Thus, we apply quality cuts to select only well-reconstructed events in our analysis; the number of hit PMTs is larger than 10, the track length is larger than 10° , the time extent is larger than $2 \mu\text{s}$, and the depth of EAS maximum, X_{max} , is within a field of view of FD, falling between the first and the last depths (X_{start} and X_{end} , respectively). To avoid the Cherenkov light contamination, we require the angle on the SDP is less than 120° and the minimum viewing angle is greater than 20° .

The performance of the monocular analysis is estimated by the Monte Carlo (MC) detector simulation and reconstruction, comparing between the generated true parameters and reconstructed ones. Figure 1 shows the obtained resolution of the impact parameter R_p , angle on SDP Ψ , primary energy and X_{max} for proton and iron of the QGSJetII-03 interaction model in the CORSIKA software [12]. As seen in Figure 1, there is no large difference between proton and iron except for the reconstructed energy because the invisible energy for FD is corrected assuming a proton fraction reported by the HiRes/MIA experiment [13] with the QGSJetII-03 model. The reconstructed energy of iron primary showers are underestimated about 6% because of the difference of the invisible energy. The resolutions of typical parameters in the monocular analysis are: 1.4 km on R_p , 7.7 degree on Ψ angle, 17% on energy and 72 g/cm^2 on X_{max} .

3. Energy Spectrum Measurement

To evaluate the energy spectrum of UHECRs, it is essential to calculate an aperture and an exposure of FD stations. The aperture cannot calculate a simple geometrical factor because it depends on not only the energies, but also the performance of FD, atmospheric models, PMT gains and primary shower species. Thus, we estimate the aperture of FD using MC simulations including these dependences. For the energy spectrum measurement, we use the QGSJetII-03 model to evaluate the aperture of the monocular analysis. The aperture of FD, $A\Omega$, is calculated

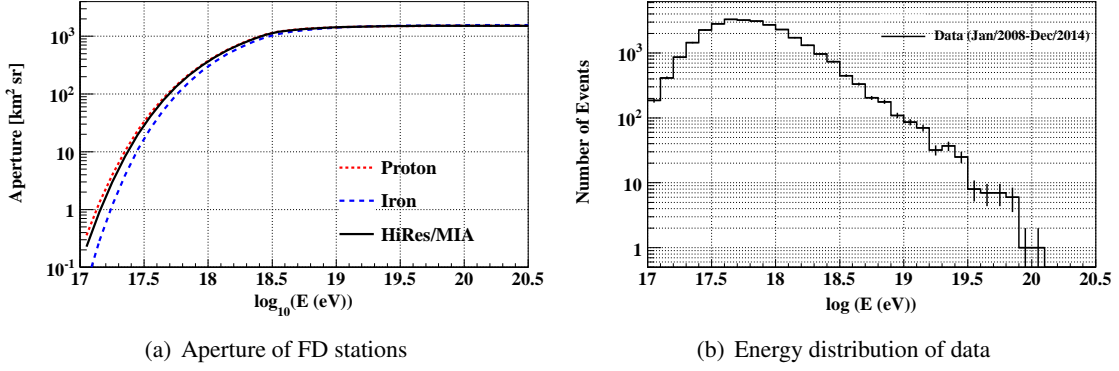


Figure 2: (a) The combined aperture of newly constructed FD stations evaluated by MC simulations for proton (red dotted line), iron (blue dashed line) and HiRes/MIA composition (black solid-line) in the monocular analysis. (b) Obtained energy distribution analyzing data observed by the newly constructed FD stations from January 2008 to December 2014.

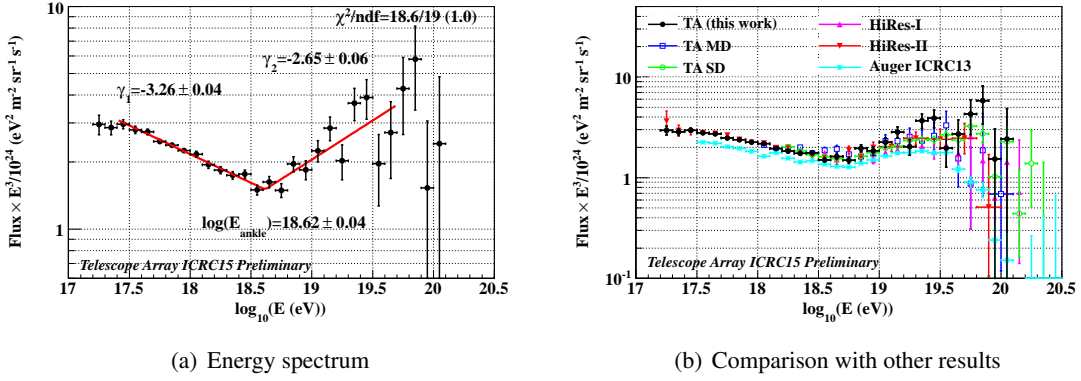


Figure 3: (a) Energy spectrum observed by the newly constructed FD stations. (b) Energy spectrum compared with results reported by HiRes [4] and Auger [14] and other analyses of TA [15, 16].

from a ratio between the number of reconstructed events with the quality cuts and the number of thrown ones, $A\Omega(E) = A\Omega_{\text{gen}} \cdot N_{\text{reco}}(E)/N_{\text{thrown}}(E)$ where E is the primary energy of cosmic ray, $A\Omega_{\text{gen}}$ is the thrown aperture region of MC simulation, N_{reco} is the number of reconstructed events and N_{thrown} is the number of thrown events.

Since TA was designed for stereoscopic observations of air showers above $10^{19.0}$ eV, we define the combined aperture of the newly constructed FD stations in each monocular mode. When an energetic shower is reconstructed by the both stations, we select one result with a large number of photo-electrons to avoid the double counting of high energy showers. Using these reconstructed events by both stations, we estimate the combined aperture of newly constructed FD stations with proton, iron and HiRes/MIA reported composition [13] as shown in Fig. 2(a). In the low energy region, the aperture is dependent on the primary species. In contrast, in the high energy region, it is independent of them.

Analyzing data collected from January 2008 to December 2014 using the monocular analy-

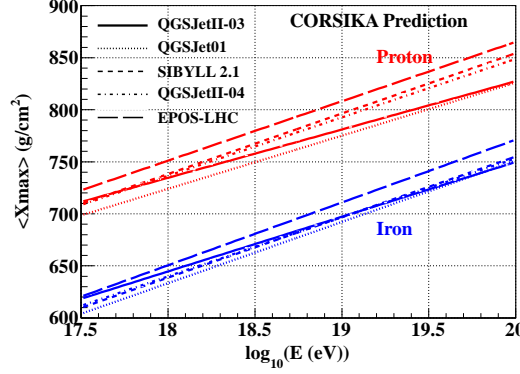


Figure 4: The average X_{\max} of proton- and iron-induced (red and blue, respectively) showers generated by CORSIKA before detector simulation using QGSJet01 (dotted line), QGSJetII-03 (solid line), QGSJetII-04 (dash-dotted line), Sibyll 2.1 (short dashed line) and Epos-LHC (long dashed line).

sis, 28869 shower candidates above 10^{17} eV are obtained as shown in Figure 2(b). The energy spectrum is evaluated by the aperture assuming the HiRes/MIA composition, the number of events and the live time of FD. The obtained spectrum is shown with a single-broken power-law fitting in Figure 3(a). There is an obvious broken energy at $\log(E_{\text{ankle}}) = 18.62 \pm 0.04$ corresponding to the ankle structure. The total uncertainty on the energy scale is evaluated as 21% [17]. The obtained spectrum is compared with the other results reported by HiRes [4], Auger [14] and other analyses of TA [15, 16]. The obtained spectrum is in good agreement with the HiRes-II spectrum in a broad energy region.

4. Mass Composition Measurement

For the mass composition measurement, we simulate shower developments of UHECRs using proton and iron, each according to five types of hadronic interaction models: QGSJet01, QGSJetII-03, QGSJetII-04, Sibyll 2.1 and Epos-LHC in the CORSIKA software. Figure 4 shows the average values of the generated X_{\max} as a function of the primary energy. As seen in Figure 4, the average X_{\max} difference between proton and iron is ~ 100 g/cm², with the choice of interaction model making at most difference of ~ 25 g/cm² at $10^{17.5}$ eV and ~ 38 g/cm² at $10^{19.5}$ eV for proton and ~ 20 g/cm² for iron in the same energy range.

Since the FD has a limited field of view (FoV) and the X_{\max} must be observed between X_{start} and X_{end} , the observed X_{\max} may be biased as a function of X_{start} and X_{end} . In order to reduce the bias on X_{\max} , we define the biased X_{start} and X_{end} regions using the observed data and the MC simulations. We estimated that the fiducial FoV cuts on X_{start} and X_{end} are parameterized as $X_{\text{start}}(E) \leq 45.8 \times \log(E) - 215.8$, $X_{\text{end}}(E) \geq 20.8 \times \log(E) + 501.4$ where E (eV) is the reconstructed energy of UHECRs.

The fiducial FoV cuts and energy threshold are applied in the Monte Carlo detector simulation to evaluate expected average X_{\max} and its distribution for proton or iron. Figure 5 shows the distribution of observed X_{\max} and expected ones in several energy bins. The expected distributions for three different mass compositions are shown for comparison: pure proton, pure iron, or an equal

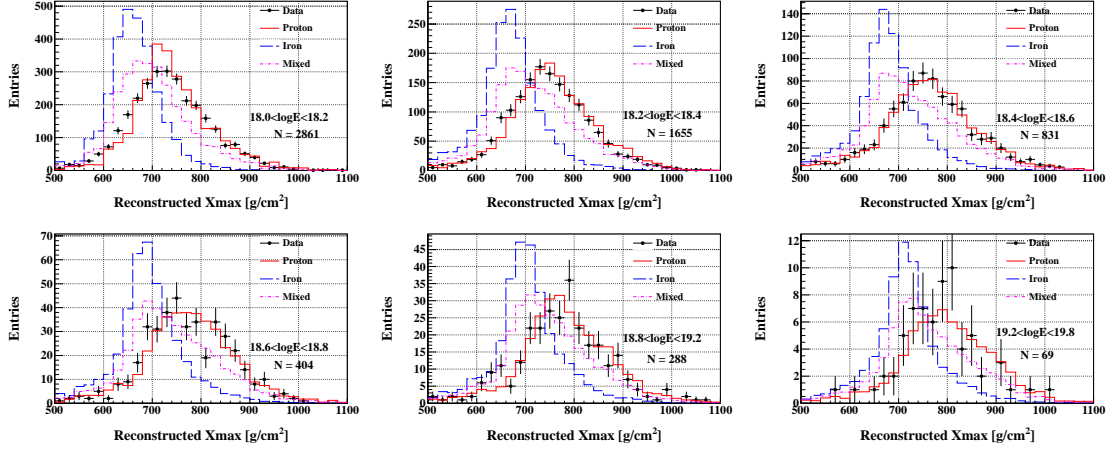
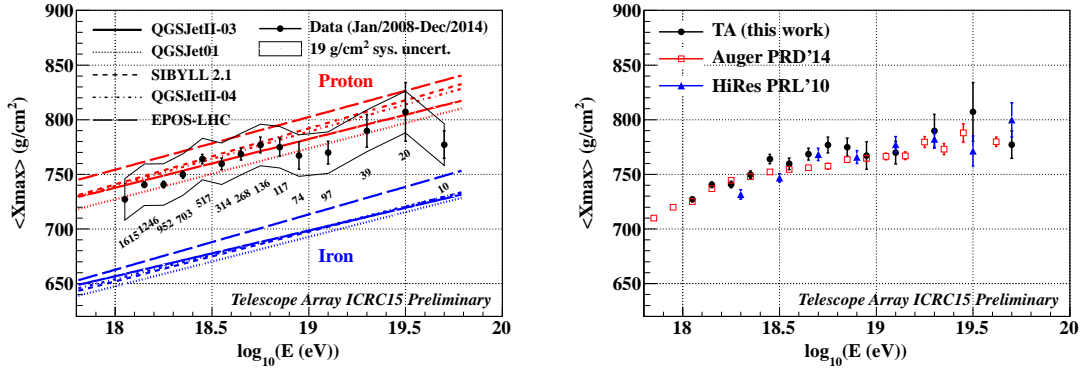


Figure 5: X_{\max} distributions in each energy range using the fiducial FoV cuts, compared with the expected distributions estimated from MC simulations using QGSJetII-03 with three different compositions: pure proton (red solid line), pure iron (blue dashed line), and a equal mixture of both (pink dash-dotted line).



(a) Obtained $\langle X_{\max} \rangle$ compared with MC predictions

(b) $\langle X_{\max} \rangle$ compared with other results

Figure 6: (a) Evolution of the average X_{\max} with energy from data (black points), plotted with the MC simulation results (lines) for two particle species (proton, iron) and five hadronic interaction models. The box region shows the systematic uncertainty on X_{\max} , 19 g/cm^2 , for the monocular analysis. (b) Average X_{\max} compared with results reported by HiRes [18] and Auger [19].

mixture of both using the best matched model of QGSJetII-03 model. Figure 6(a) shows the comparison between observed X_{\max} and expected X_{\max} estimated by the Monte Carlo simulations. The systematic uncertainty on $\langle X_{\max} \rangle$ is 19 g/cm^2 for the monocular analysis indicating the box region in this figure. The uncertainty includes the fluorescence yield (5 g/cm^2), the atmospheric condition (12 g/cm^2), the FD calibration (5 g/cm^2), the FD geometry (9 g/cm^2) and the shower reconstruction (10 g/cm^2). The obtained average X_{\max} and its distributions indicate proton-dominated composition at this energy range which is consistent with results already reported by TA stereo or hybrid analyses [20, 21]. The obtained X_{\max} is compared with results reported by HiRes [18] and Auger [19] as shown in Figure 6(b). Those results show in good agreement within the systematic uncertainty.

5. Conclusions

We report on a measurement of the cosmic ray spectrum covering a broad range of energies above $10^{17.2}$ eV analyzed by the newly constructed fluorescence detectors of the Telescope Array experiment using the monocular analysis during the first seven years. The obtained spectrum has an obvious broken structure at energy of $\log(E_{\text{ankle}}) = 18.62 \pm 0.04$. The structure is in good agreement with the spectra reported using the TA surface detector, and by the HiRes-II. We report the mass composition using the fiducial FoV cuts to reduce observation bias on X_{max} . The obtained average X_{max} and its distribution shows proton-dominated composition at this energy range which is consistent with already reported results within the systematic uncertainty.

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