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The mass composition of ultra-high energy cosmic rays measured by new fluorescence detectors in the Telescope Array experiment

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Abstract

The longitudinal development of an extensive air shower reaches its maximum at a depth, X_{max}, that depends on the species of the primary cosmic ray. Using a technique based on X_{max}, we measure the cosmic-ray mass composition from analyses of 3.7 years of monocular mode operations with the newly constructed fluorescence detectors of the Telescope Array experiment. The X_{max} analysis shows our data to be consistent with a proton dominant composition at energies above $10^{18.0}$ eV.

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Keywords: Mass composition; Ultra-high energy cosmic rays; Fluorescence detector; Telescope Array experiment

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1. Introduction

Measurements of the mass composition and its energy dependence are essentially important for understanding sources and propagations of cosmic rays and for constricting several theoretical models. Because of a low flux of ultra-high-energy cosmic rays (UHECRs), the mass composition can not be measured directly. However, we can make an indirect measurement via a technique using X_{max}, which is the depth at which the longitudinal development of an extensive air shower (EAS) reaches its maximum. The longitudinal shower development of a typical iron nucleus with 56 nucleons, arriving with total energy E, is essentially the superposition of the longitudinal developments of 56 protons, each with energy $E/56$; the X_{max} value for this shower will be smaller than that of a single proton with energy E. The observed distribution of X_{max} for cosmic rays at a given energy therefore depends on their mass composition.

Fluorescence detectors (FDs) observe atmospheric fluorescence photons emitted by molecules excited by an EAS, providing a determination of the primary energy and the longitudinal shower development including X_{max}. This measurement has less dependence on simulations than other techniques, because the production and energy-loss mechanisms of the EAS's electromagnetic component (which make the dominant contribution to fluorescence photon emissions) are less dependent on hadronic interaction models. The Telescope Array (TA) experiment is the largest hybrid detector in the northern hemisphere continuing the effort on understanding the origins of UHECRs [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 km^2, and three FD stations outlook over the SD array. The full operation of TA began in March 2008.

One FD station, called "Middle Drum" (MD) and located northwest of the SD array, consists of 14 FD telescopes previously used in the High Resolution Fly's Eye (HiRes) experiment [2]. Two other stations at the array's south-east and southwest, respectively called "Black Rock Mesa" (BRM) and "Long Ridge" (LR), each consist of 12 FD

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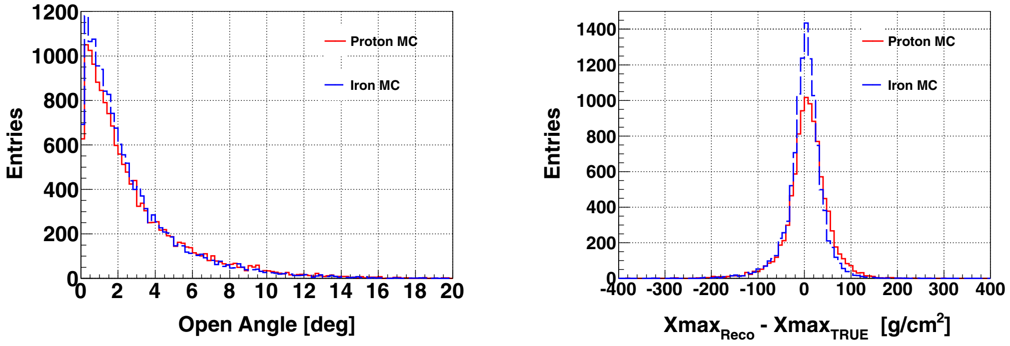


(a) Arrival direction

(b) $X_{\rm max}$

Figure 1. The resolutions of the arrival direction and the $X_{\rm max}$ for EAS in the monocular mode analysis estimated by artificial data using primary protons and irons with QGSJet-II-03 as the hadronic interaction model.

telescopes. The BRM and LR stations are newly designed and constructed for the TA experiment [3][4], with new calibration [5][6] and atmospheric monitoring [7] systems.

2. Data analysis

We analyze data collected at the BRM and LR FD stations in a monocular mode, which is an analysis mode to reconstruct an EAS to obtain primary particle's properties using the measured shower image by one FD stations. Our observation period is 3.7 years from January 2008 to September 2011. Using the $X_{\rm max}$ distribution from our monocular analysis, we obtain the mass composition of cosmic rays at energies above $10^{18.0}$ eV.

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

$$t_i = t_{\rm core} + \frac{1}{c}\frac{\sin\Psi - \sin\alpha_i}{\sin(\Psi + \alpha_i)} r_0 \tag{1}$$

where α_i is an angle formed by the i th PMT's viewing direction and a direction vector from the FD station to the shower core (shower axis's impact point on the ground), Ψ is the angle on the shower detector plane formed by the shower axis and the direction to the shower core, $t_{\rm core}$ 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 shower's longitudinal development is calculated by the inverse Monte Carlo method [10]. This inverse Monte Carlo technique iteratively explores the longitudinal-development parameter space, searching for the optimum solution to reproduce the observed shower image. 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 μs and the depth of EAS maximum, $X_{\rm max}$, is within the station's field of view, falling between the first and the last depths ($X_{\rm start}$ and $X_{\rm end}$, respectively).

Since the EAS geometry is reconstructed using the arrival times at one FD station, the geometrical resolution is not as precise as other analysis mode (such as stereo [8] or hybrid analysis [9]), and the reconstructed results may be biased. Therefore, in the mass composition analysis, we apply additional strict cuts for a bias-free measurement of $X_{\rm max}$ in the monocular mode analysis. These cuts, which remove showers with biased geometry reconstruction or a large contamination of the signal by Čherenkov photons, are similar to the "fiducial volume cuts" developed by the Pierre Auger Observatory [11].

In order to cut the showers having geometries incoming to FD stations, we applied the following selection rules; the minimum angle formed by a shower axis and a viewing direction from FD station must be larger than 20°, the

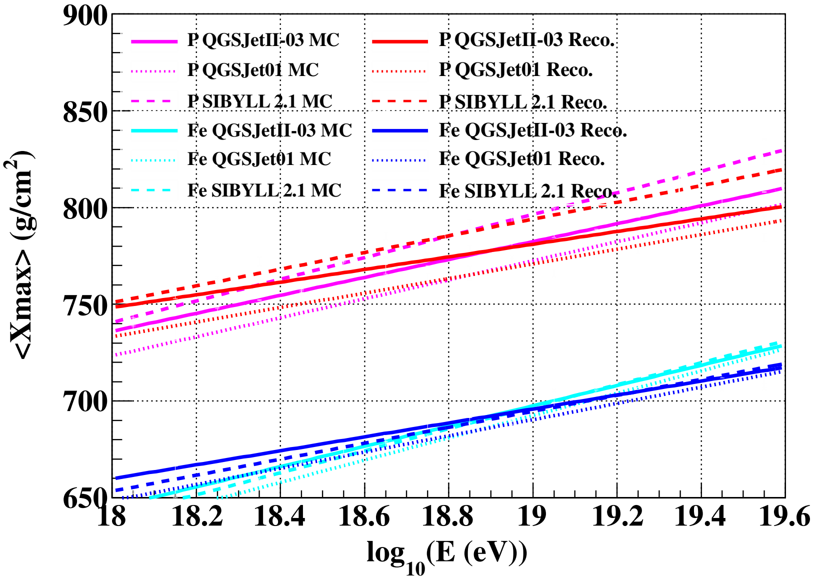


Figure 2. The averaged $X_{\max}$ with primary protons (red) and irons (blue) without detector simulations and including them based on simulated artificial events (pink and sky blue, respectively) with QGSJet01 (dotted line), QGSJet-II-03 (solid line) and SIBYLL 2.1 (dashed line).

angle of a shower axis within the shower-detector plane must be smaller than 90° and the X_{start} must be larger than 150 g/cm^2. In order to remove biased measurement on $X_{\max}$, the X_{start} should be smaller than 700 g/cm^2 , X_{end} should be larger than 900 g/cm^2 and the minimum distance from FDs to the shower axis defined as the impact parameter is larger than 5 km. In this analysis, the selection criteria that we applied are independent of the primary cosmic-ray energy, species and hadronic interaction model.

Before analyzing the observed data, we use Monte Carlo (MC) simulations to evaluate accuracies of the monocular mode analysis and calculate expected distributions of $X_{\max}$ in every energy bin under consideration. We use CORSIKA [12] to simulate EAS developments for cosmic ray primary protons and irons, and for each species we used three hadronic interaction models: QGSJet01, QGSJet-II-03 and SIBYLL 2.1. We generate artificial data based on the CORSIKA showers applying the detector responses that were obtained in advance. These artificial data are also processed with the identical method applied to the monocular mode analysis described above to obtain the distribution of reconstructed $X_{\max}$ values. The estimated resolutions for the arrival direction and $X_{\max}$ for EAS with QGSJet-II-03 are shown in Figure 1. The resolutions of the arrival direction are 3.0 and 2.8 degree, and those of $X_{\max}$ are 54.5 an 46.5 g/cm^2 for primary protons and irons, respectively.

Figure 2 shows the averaged $X_{\max}$ values calculated by CORSIKA as a function of primary energies for proton and iron species with the three types of hadronic interaction models. The averaged $X_{\max}$ difference between primary protons and irons is 100 g/cm^2, while the choice of interaction models makes the averaged $X_{\max}$ a difference of up to 30 g/cm^2 at 10^{20} eV. The predicted $X_{\max}$ for artificial events with the detector simulations and with established reconstruction procedures is also shown in the same figure. There is only less than 10 g/cm^2 difference between MC rails and reconstructed ones for all species.

3. Results and discussion

Applying the reconstruction procedure and quality cuts to observed data with both BRM and LR stations during 3.7 years, we collect 1381 showers above $10^{18.0}$ eV. Before comparing the $X_{\max}$ values from data to those of the

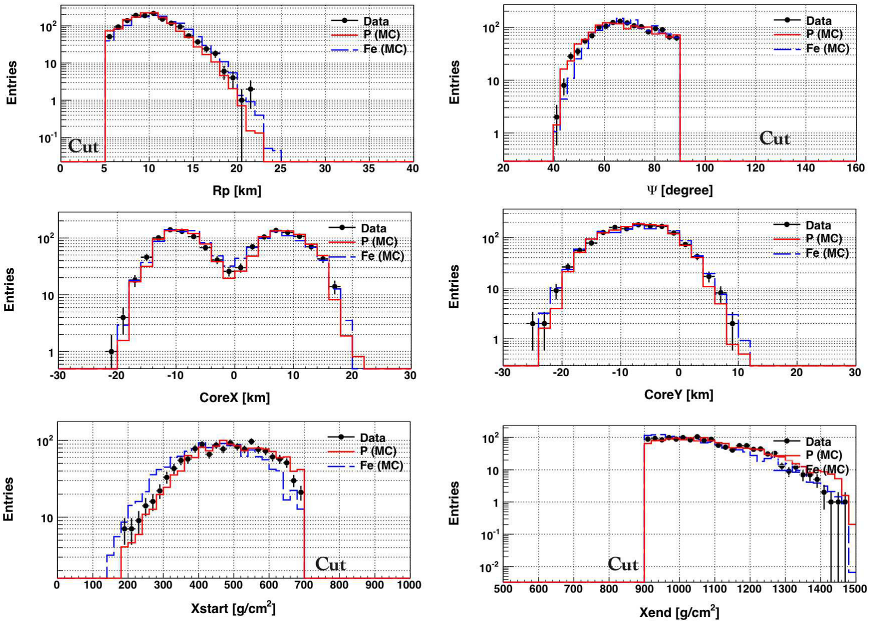


Figure 3. Distributions of the impact parameter (Rp), angle on the shower detector plane (Ψ), core location from the x-(south to north) and y-(west to east) coordinates of the core location (Core X, Core Y), X_{start} and X_{end} between observed data (black plot) and simulated expectations based on primary protons (red histogram), and irons (blue histogram) with QGSJet-II-03.

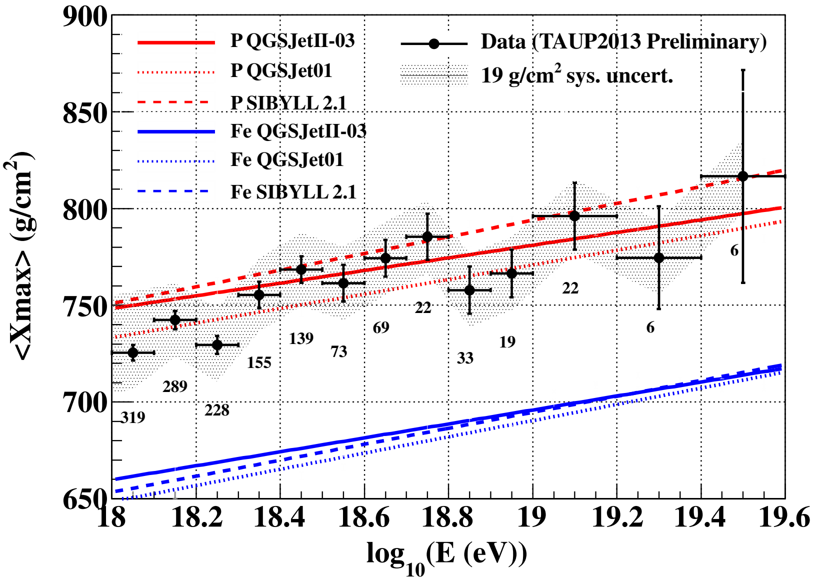
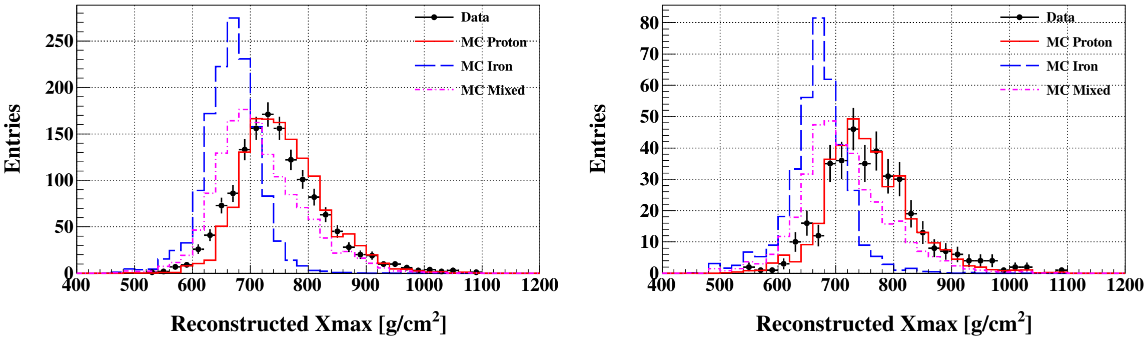
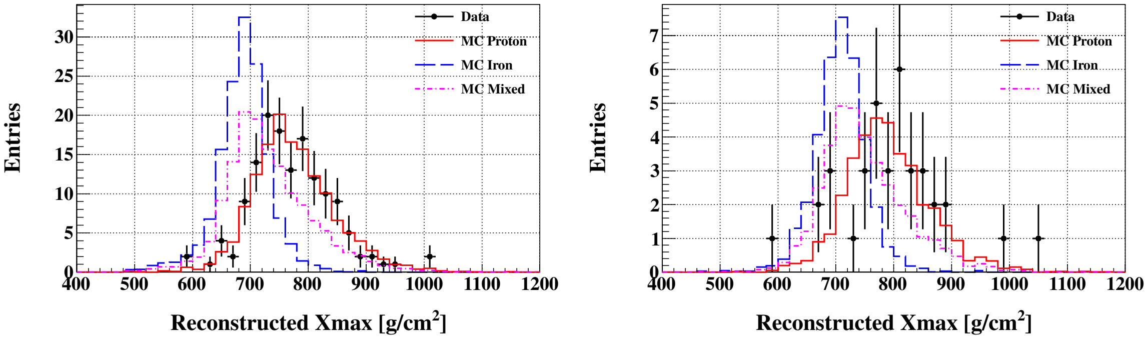


Figure 4. The obtained averaged X_{max} from data (black points), plotted with expectations estimated by the artificial simulations using primary protons and irons with three hadronic interaction models (QGSJet01, QGSJet-II-03, SIBYLL 2.1). The color and style of each line has the same as shown in Figure 2. The number of accepted showers in each energy bin is printed above that bin's data point. The shaded area shows the systematic uncertainty on X_{max}, 19 g/cm^2, for our monocular analysis.



(a) $18.0 \leq \log(E) < 18.3$

(b) $18.3 \leq \log(E) < 18.6$



(c) $18.6 \leq \log(E) < 19.0$

(d) $19.0 \leq \log(E)$

Figure 5. Reconstructed $X_{\max}$ distributions in four energy range compared with simulated expectations based on artificial data using three energy-independent compositions: purely proton (red), iron (blue) and the equal mixture of both (pink) with QGSJet-II-03.

item	Energy	$X_{\max}$
Fluorescence Yield	11%	5 g/cm^2
Atmosphere	11%	12 g/cm^2
Calibration	10%	5 g/cm^2
Detector Geometry	4%	9 g/cm^2
Reconstruction	10%	10 g/cm^2
Total	**21%**	**19 g/cm^2**

Table 1. The total systematic uncertainty of the energy scale and the $X_{\max}$ in the monocular mode analysis.

artificial simulation data, we must confirm the reliability for our analysis by detailed comparisons between observed data and simulated expectations. As shown in Figure 3, distributions of the impact parameter (Rp), angle on the shower detector plane (Ψ), core location from the x-(south to north) and y-(west to east) coordinates of the core location (Core X, Core Y), X_{start} and X_{end} are in good agreement between observed data and simulated expectations.

Finally, we compare the observed averaged $X_{\max}$ values with expected rails estimated from the artificial data using primary protons or irons as shown in Figure 4. $X_{\max}$ distributions for four energy regions are also shown in Figure 5. The expected distributions for three different mass compositions are shown for comparison: purely simulation proton, iron and the equal mixture of both. Both Figure 4 and Figure 5 demonstrate that the observed $X_{\max}$ values indicate a proton dominant composition above $10^{18.0}$ eV. The systematic uncertainty of our energy scale of FD reconstruction is 21%, and that of $X_{\max}$ is 19 g/cm^2 for our monocular analysis. In the systematic errors we take into account fluorescence yields, atmospheric conditions, detector calibrations and geometries and reconstructions as shown in table 1.

4. Conclusions

The newly constructed FDs for the TA experiment have been taking steady measurements of UHECRs since early 2008. From the monocular mode analysis for 3.7 year data observed at the BRM and LR stations, we have measured the mass composition of cosmic rays with energies above $10^{18.0}$ eV using the $X_{\max}$ technique described above. The obtained averaged $X_{\max}$ and its distributions indicate a proton dominant composition at energies above $10^{18.0}$ eV.

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References

[1] *The Telescope Array Project Design Report* (2000).
[2] R.U. Abbasi et al., *Phys. Rev. Lett.*, **100(10)**, 101101 (2008). R.U. Abbasi et al., *Phys. Rev. Lett.*, **104**, 161101 (2010).
[3] H. Tokuno et al., *Nucl. Instr. and Meth. A*, **676**, 54 (2012).
[4] Y. Tameda et al., *Nucl. Instr. and Meth. A*, **609**, 227 (2009).
[5] H. Tokuno et al., *Nucl. Instr. and Meth. A*, **601**, 364 (2009).
[6] S. Kawana et al., *Nucl. Instr. and Meth. A*, **681**, 68 (2012).
[7] T. Tomida et al., *Nucl. Instr. and Meth. A*, **654**, 653 (2011).
[8] Y. Tameda et al., *32th Proc. of International Cosmic Ray Conference*, **HE1.3**, 1268 (2011).
[9] D. Ikeda et al., *32th Proc. of International Cosmic Ray Conference*, **HE1.3**, 1264 (2011).
[10] T. Fujii et al., *International Symposium on the Recent Progress of Ultra-High Energy Cosmic Ray Observation*, AIP Conf. Proc. **1367**, 149 (2011).
[11] J. Bellido, for the Pierre Auger Collaboration, ArXiv:0901.3389v1 (2009).
[12] D. Heck et al., *Forschungszentrum Karlsruhe Report FZKA*, **6019** (1998).
[13] Y. Tsunesada et al., *32th Proc. of International Cosmic Ray Conference*, **HE1.3**, 1270 (2011).
[14] W. H. Press, B. P. Flannery, S. A. Teukolsky, W. T. Vetterling, *Numerical Recipes in C*, Cambridge University Press (1993).