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Cosmic ray mass composition measurement with the TALE hybrid detector

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We report on the cosmic ray mass composition measured by the Telescope Array Low-energy Extension (TALE) hybrid detector. The TALE detector consists of a Fluorescence Detector (FD) station with 10 FD telescopes located at the TA Middle Drum FD Station (itself made up of 14 FD telescopes), and a Surface Detector (SD) array of scintillation counters. The SD array consists of 40 counters with 400 m spacing and 40 counters with 600 m spacing. The FD station, with a total of 24 telescopes, overlooks the SD array and provides sky coverage with an elevation angle range of 3° to 59°. In this contribution, we will present the latest result of the cosmic ray mass composition measurement in the energy range from $10^{16.5}$ eV to $10^{18.5}$ eV using almost 5 years of TALE hybrid data.

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1. Introduction

The Telescope Array located around 39° S, 113° W has the largest cosmic ray observatory in the northern hemisphere, designed to detect ultra high energy cosmic rays. The main part of the experiment consists of a SD array and three FD stations that overlook the SD area. The TA SD deployed 507 scintillation counters in a square grid with 1200 m spacing, covering a total of $\sim$ 700 km^2 area on the ground. Each surface counter has two layers of a plastic scintillators each with an area of 3 m^2 and a thickness of 1.2 cm. The scintillation light produced by the charged particles energy deposition are guided to the photomultipliers that connected from each layer through wavelength shifting fibers [1]. The three TA FD stations are located at Black Rock Mesa (BRM), Long Ridge (LR), and Middle Drum (MD). The stations have a viewing range of 3° to 31° in elevation A fluorescence telescope of TA is composed of a segmented spherical mirror and a camera of 256 hexagonal photomultipliers, with a field of view is 1° × 1° [2].

In addition to the main TA experiment, the Telescope Array Low-energy Extension(TALE), located at the north part of the site, is aimed at measuring the very high energy cosmic rays above 10^{16} eV to reveal the nature of the transition from galactic to extra-galactic cosmic rays. The TALE detector consists of one FD station with ten fluorescence telescopes and an array of 80 scintillation surface detectors, which were deployed to cover a total area of approximately 20 km^2. The TALE FD began operation in 2013 at the MD station. The ten fluorescence telescopes used in TALE were refurbished from components previously employed by the HiRes experiment [3]. These telescopes have a field of view ranging from 31° to 59° in elevation, directly above the field of view of the MD telescopes. The TALE SD consists of 40 scintillation counters with 400 m and 40 counters with 600 m spacing, and started observation from 2017. In addition, an external trigger from the TALE FD to the TALE SD to detect low energy cosmic ray showers, so-called hybrid trigger system, was installed in 2018. The TALE detector configuration is shown in Fig. 1. The full details of the detectors are found in [4–6]. We will present the latest result of the cosmic ray mass composition measurement using almost 5 years of the TALE hybrid observation data including the MD telescope data, for which the deeper $X_{\max}$ showers can be detected by the lower field of view. The combination of sky coverage by MD and TALE FD provides more uniform $X_{\max}$ acceptance for interest energy range.

2. Event Reconstruction

In the energy range of just below 10^{17} eV, we use the TALE FD as an Imaging Air Cerenkov Telescope (IACT) to extend the energy threshold of the detector down to $\sim 10^{15}$ eV. The Cherenkov light produced by a shower has the same characteristic as fluorescence light, being directly proportional to the number of shower particles for any given point in the shower development. This property means that the observed Cherenkov signal can be used to infer the shower properties (energy and $X_{\max}$) in a similar way to how the fluorescence light is used. A significant difference between Cherenkov light and fluorescence light is that the Cherenkov light emitted by the shower particles is strongly peaked forward along the shower direction, and falls off rapidly as the shower viewing angle changes while the fluorescence light is emitted isotropically. As a result, Cherenkov events are seen only if the shower geometry with respect to the detector is such that the shower

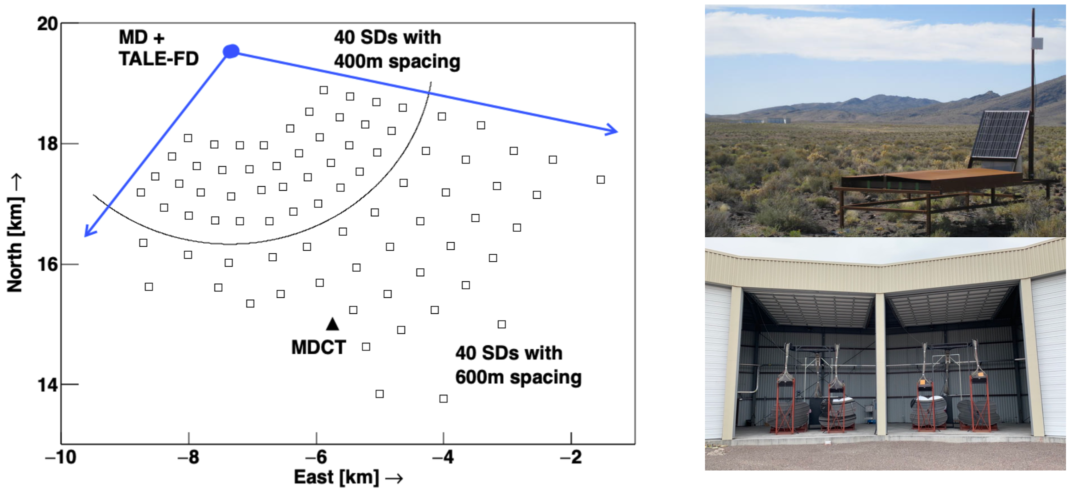

Figure 1: Left: The layout of the TALE detector. Open square boxes represent the locations of the TALE SD counters and a small filled circle corresponds to the MD / TALE FD station. The arrows represent azimuthal viewing ranges of both FDs. Top-Right: A deployed SD in the field. Bottom-Right: The photograph of TALE telescopes in the FD station.

is moving towards the detector (viewing angle $\sim 10°$ or smaller), and are observed much faster (total event duration and shower image are much shorter) than fluorescence dominated events seen by main TA hybrid detector where energies above 10^{18} eV. Due to the above reasons, the lower energy events seen by Cherenkov light are processed for reconstruction by the Profile-Constrained Geometry Fit (PCGF) that simultaneously reconstructs the shower geometry and the shower profile, originally developed by the HiRes collaboration [7]. This method scans over all possible shower geometries compatible with the arrival times of photons at individual pixels of the FD camera and for each such geometry calculates a trial shower profile in the atmosphere. In this work, the possible shower geometries are provided by a process of the hybrid geometry calculation that combines the timing information from the FD and SD to constrain the arrival time and impact point of the shower at the ground. The shower profile fitting in given shower geometry uses the Gaisser-Hillas parameterization formula [8]

$$N(x) = N_{\max} \left(\frac{x - X_0}{X_{\max} - X_0} \right)^{\frac{X_{\max} - X_0}{\lambda}} \exp\left(\frac{X_{\max} - x}{\lambda} \right), \tag{1}$$

where $N(x)$ is the number of charged particles at a given slant depth, x, $X_{\max}$ is the depth of shower maximum, $N_{\max}$ is the maximum number of particles at $X_{\max}$, X_0 is the depth of the first interaction, and λ is the interaction length of shower particles. The best expectation of the shower geometry and longitudinal profile is chosen.

3. Monte Carlo Simulation and Data / MC Comparison

We run the Monte Carlo simulations to evaluate our detector performance and reconstruction resolution. In this work we generated three primary cosmic rays particles; proton, nitrogen, and iron based on the QGSJetII-04 [9] hadronic interaction model. Equal numbers of events were generated for each primary type. The generated MC follows a broken power law spectrum in which the spectrum index is -2.9 below $10^{17.1}$ eV and is -3.2 above $10^{17.1}$ eV, where each parameter comes from observable values by the TALE FD monocular spectrum measurement [5]. All of the calibration factors with time dependence are considered in the SD and FD detector simulations. All reconstructed events are subjected to the quality cuts summarized in Table. 1. The criteria were divided into two parts by the contribution of the flux of fluorescence and Cherenkov light from the air shower due to different characteristics of the fluorescence/Cherenkov dominated events. The obtained shower parameter resolutions energies above $10^{16.5}$ eV are 30 g/cm^2 in X_{max} and 10 % in energy (Fig. 2). In addition, Data/MC comparisons were performed to verify that the observed events are well reproduced by our MC simulations, as shown in Fig. 3. The same quality cuts were applied to the data and the MC events.

Variable	CL	FL
No saturated PMTs in FD	applied	
X_{max} bracketing cut	applied	
Angular track-length [deg]	$> 6.5°$	-
Event duration [ns]	> 100 ns	-
# of PMTs	> 10	-
# of Photo-electrons	> 1000	> 2000

Table 1: we define events of which fractional contribution of Fluorescence Light (FL) to the total signal exceeds 0.75 as fluorescence events, and events of which fractional contribution of FL to the total signal less than or equal to 0.75 as Cherenkov Light (CL) events.

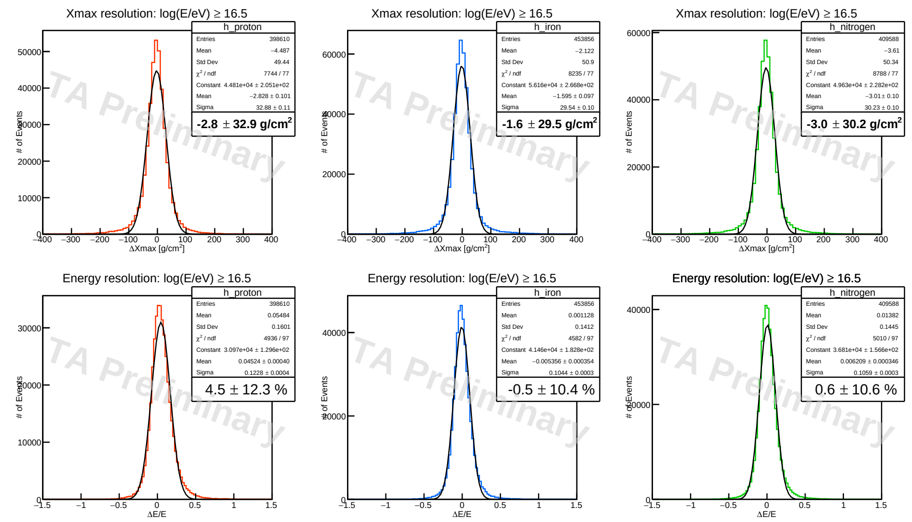

Figure 2: Reconstruction resolutions of the shower maximum X_{max}, and the shower energy E, respectively. The X_{max} resolutions for each primary are shown in the top panels, and the energy resolutions are in the bottom panels.

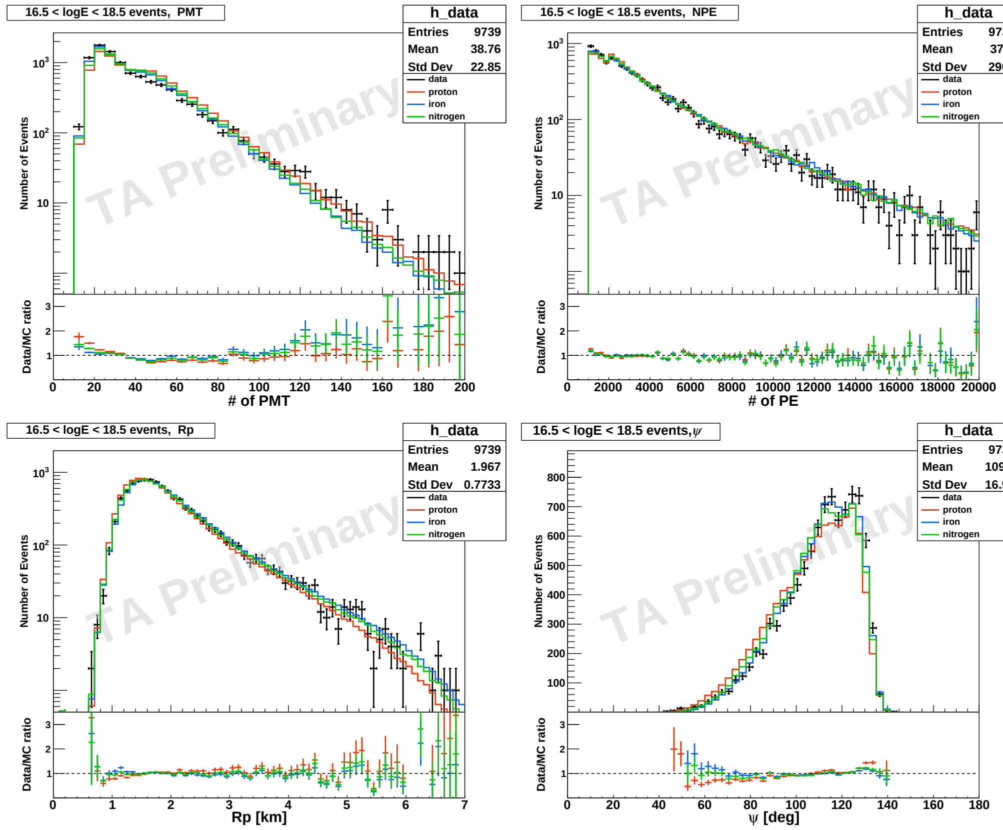

Figure 3: Data / MC comparisons. From top left to right bottom, the number of PMTs, the number of photo-electrons, the impact parameter R_p, the shower inclination angle in the shower detector plane, ψ are shown, respectively. The black points with error bars show the data, while the proton/nitrogen/iron MC are shown by the red/green/blue histograms. The MC distributions have been normalized to the same number of entries as the data.

4. Data Analysis

We present the preliminary results of the cosmic rays mass composition in the energy range from $10^{16.5}$ eV to $10^{18.5}$ eV measured with the TALE hybrid data. The result for the mean of the shower maximum, $\langle X_{\max} \rangle$, and the width of the observed $X_{\max}$ distributions, $\sigma(X_{\max})$, as a function of the shower energy are presented in Fig. 4. For the comparison, the pure proton, pure nitrogen, and pure iron predictions calculated by our Monte-Carlo simulation are also shown beside the observed ones. In the left panel of Fig. 4, the observed elongation rate shows clearly a break, where the energy is just above 10^{17} eV. The elongation rate before the break energy is 23 ± 5 g/cm^2/decade and after the break energy is 98 ± 5 g/cm^2/decade, while the pure composition assumptions are around 60 g/cm^2/decade, respectively. On the other hand, the $\sigma(X_{\max})$ is compatible with or wider than pure proton assumption in whole energies.

We also estimate the primary fraction of cosmic rays using TFractionFitter [10, 11]. Data $X_{\max}$ distributions were divided into each energy bin with a width of 0.1 in $\log_{10}(E/\mathrm{eV})$ below $10^{17.9}$

eV, for 0.2 in $\log_{10}(E/\text{eV})$ up to $10^{18.5}$ eV. These distributions were fitted using those of MC ones containing three primaries. Fit results are shown in Fig. 5. The nitrogen fraction becomes dominant at $10^{16.7}$ eV, then iron fraction follows at higher energies as expected by the Peters cycle [12] while the low contribution of proton primary at around 10^{17} eV.

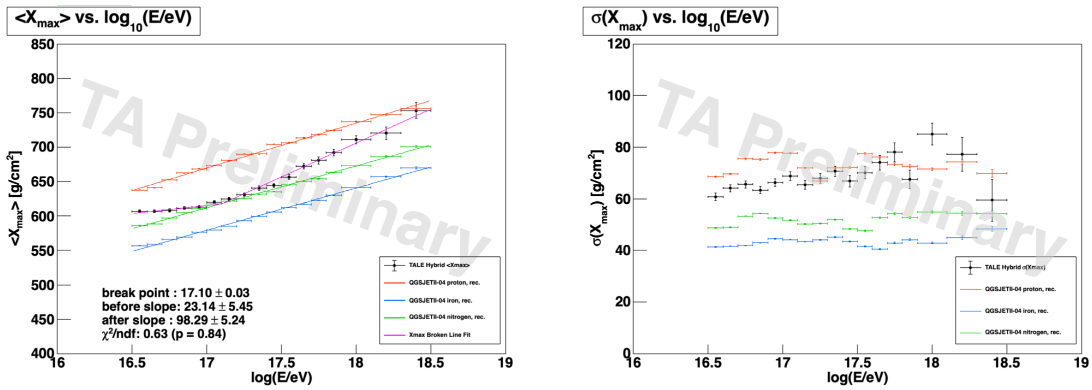

Figure 4: Top: $\langle X_{\max} \rangle$ as a function of shower energy, measured by using 5 years of the TALE hybrid data. Bottom: $\sigma(X_{\max})$ as a function of shower energy. For both panel, the proton, nitrogen, and iron MC rails are also shown for comparison.

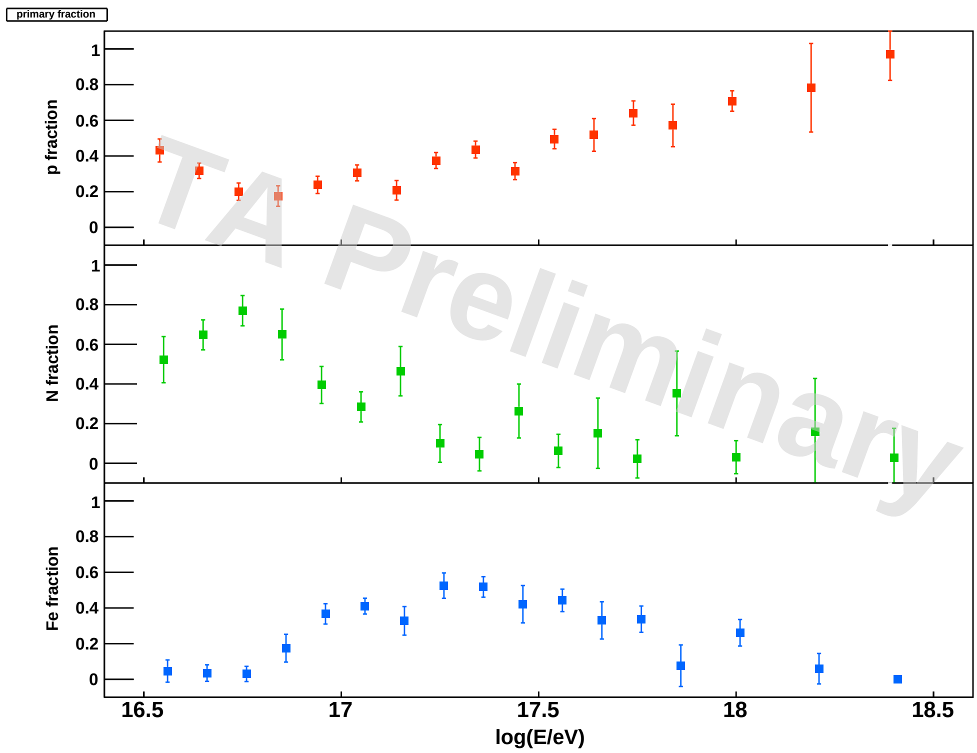

Figure 5: Primary cosmic ray fraction estimated by fitting of MC distributions with the hadronic interaction model of QGSJetII-04. From top to bottom, estimated proton fraction, nitrogen, and iron one are displayed.

5. Conclusion

We reported on the preliminary result of the mass composition measurement obtained by using 5 years of TALE hybrid data. In this contribution, we presented the measured $\langle X_{\rm max}\rangle$ and $\sigma(X_{\rm max})$ as a function of primary energy. The $\langle X_{\rm max}\rangle$ elongation rate shows a change in the slope at the energy just above 10^{17} eV. This break in the elongation rate is likely correlated with the observed break in the cosmic ray energy spectrum by the TALE FD monocular measurement [5]. Furthermore, we estimate the primary cosmic rays fraction by fitting the data $X_{\rm max}$ distributions to the MC ones. These results are consistent with a picture that the transition of the origin of the galactic cosmic rays to the extra-galactic cosmic rays is around "2^{nd} knee", at around 10^{17} eV, with which the changing of the elongation rate in the mean $X_{\rm max}$ while a wider $X_{\rm max}$ distribution at these energies due to the mixed composition of heavier galactic cosmic rays and lighter component of extra-galactic one.

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