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# Measurement of the cosmic-ray energy spectrum with the TALE detector in hybrid mode

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The TA Low-energy Extension (TALE) experiment extends the reach of the TA experiment on the low-energy side to below $10^{16}$ eV. A primary objective of TALE is to study the transition from galactic to extragalactic cosmic rays. The TALE detector is a hybrid observatory composed of fluorescence telescopes and a surface detector array of scintillation counters. The surface detectors are arranged with inter-counter spacing optimized for hybrid energy spectrum measurements in the low-energy region. We analyzed data collected between November 2018 and May 2023, corresponding to 1,247 hours of operation, and in this presentation, we will show the results of the cosmic ray energy spectrum measurement using the TALE hybrid detector. This measurement will play an important role in understanding the transition from cosmic rays of galactic origin to those of extragalactic origin.

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## 1. Introduction

More than 100 years have passed since the discovery of cosmic rays, but the origin of ultra-high energy cosmic rays (UHECRs) has not been revealed yet. Revealing the UHECR origins is one of the most important topics of cosmic-ray physics. Galactic cosmic rays originate within the Milky Way Galaxy, while extragalactic cosmic rays originate outside the galaxy. In the energy region below $10^{18}$ eV, galactic and extragalactic cosmic rays are in competition with each other. The shape of the energy spectrum reflects various physical phenomena such as the transition from galactic to extragalactic cosmic rays, the characteristics and acceleration limits of galactic cosmic rays, and confinement by the galactic magnetic field. To unravel the intricately intertwined information, it is essential to measure the cosmic-ray energy spectrum and the composition over a wide energy range. We cover the wide energy range of five orders of magnitude from $10^{15}$ eV to $10^{20}$ eV by both the Telescope Array (TA) [1, 2] and the TA Low-energy Extension (TALE) [3, 4] experiments. We aim to measure the acceleration limit of galactic cosmic rays through the measurements of composition and energy spectrum, and the transition from galactic to extragalactic cosmic rays using the TALE detector.

## 2. TALE detector and data samples

TA is the largest cosmic-ray detector in the Northern Hemisphere, located in Millard County, Utah, USA. The TALE experiment extends the energy range observed by the TA experiment to lower energies. The TALE detector is suitable for studying the energy spectrum structure and the associated change in the composition of cosmic rays below $10^{18}$ eV. The TALE detector is a hybrid apparatus composed of scintillation surface detectors (SDs) covering an area of approximately 20 km$^2$ and fluorescence telescopes (FDs) overlooking the SDs, as shown in Fig. 1. The TALE SDs are placed at 400 m and 600 m spacing for low-energy thresholds. In this study, we analyzed data samples between November 2018 and May 2023 corresponding to 1,247 hours of operation. These data are collected using both the FDs and the SDs.

## 3. Monte Carlo simulation

Detector aperture is evaluated using a Monte Carlo (MC) simulation. The MC simulations used in this work include the generation of extensive air showers by cosmic ray primaries and the detector response to these showers. Air-shower simulations are generated with the CORSIKA program [5] using QGSJet II-04 [6] hadronic interaction model at high energies. Air showers are generated with primary energies ranging from $10^{16.3}$ eV to $10^{18.5}$ eV. Five primaries, H, He, N, Si, and Fe, are included in the air-shower generations weighted with a relative abundance based on the H4a composition model [7]. In addition to the H4a model, we fit the distributions of the depth of shower maximum, $X_{\rm max}$, measured by the TALE hybrid observation to a mixture of three primaries (H, N, and Fe) as a function of energy, and used the resulting abundances in our simulation. The primary mixture by the TALE hybrid observation is referred to as THXF [8], which is short for the TALE hybrid $X_{\rm max}$ distribution fit. These showers are thrown with an isotropic zenith angle distribution between 0° and 70° and a uniform azimuthal distribution between 0° and 360°. Particle

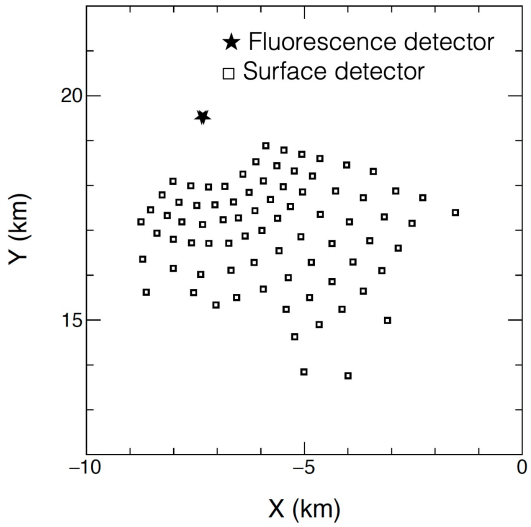


**Figure 1:** Physical location of the TALE detector. The TALE detector is a hybrid apparatus composed of surface detectors and fluorescence detectors.

information such as position and momentum at the detector level is used to obtain the energy deposit in each SD with the GEANT code [9–11]. The response of the SD electronics is also taken into account [12]. The FD simulation includes fluorescence and Cherenkov photon generations, telescope optics, detector calibration, and the response of the electronics.

## 4. Data analysis

The analysis is based on hybrid data collected by the TALE FDs and SDs. One of the advantages of hybrid observation is that the $X_{\rm max}$ which is a sensitive quantity for composition analysis is measured by FDs. In addition, the SD array is used to determine the shower axis and it improves the energy resolution compared to the FD mono observation. We used events that are triggered by the FDs and have at least one SD with a signal above one minimum ionizing particle energy loss. In this analysis, we used only the upper 10 telescopes that observe fields of view at high elevation angles.

The image of the air shower observed by FDs is referred to as the event track. The following conditions are required to select event tracks that have high-quality reconstruction: 1) $X_{\rm max}$ of the air shower is within the field of view of the FDs; and 2) the reduced $\chi^2$ in the fitting of longitudinal development of the air shower is less than 3.

As the air shower develops, both the atmospheric fluorescence and the Cherenkov light are emitted. Cherenkov light is the dominant component below $10^{17.0}$ eV, while the fluorescence component increases with increasing energy, becoming the main component above $10^{17.5}$ eV. Events with a fraction of fluorescence light above 75% are defined as fluorescence events, while the others are defined as Cherenkov events. Several filtering criteria are then applied to select shower-induced track-like events. Regarding the Cherenkov events, the following conditions are required: 1) event duration is above 0.1 $\mu$s; 2) the number of PMTs constituting the track is at least 10; 3) the average number of photo-electrons/PMT is greater than 50; and 4) the track length is greater than 6.5°.

Concerning the fluorescence events, the sum of the number of photo-electrons in all PMT's is required to be at least 2000 per event. In addition to these filtering conditions, the zenith angle acceptance was set to $\theta < 60°$, while the energy range was set between $10^{16.9}$ eV and $10^{18.3}$ eV.

The measured energy spectrum is not an exact representation of the true energy spectrum due to the efficiency and resolution of detectors. Therefore, an unfolding is performed to correct the smearing between the true spectrum and the measured spectrum. In this analysis, we used the Iterative unfolding method proposed by D'Agostini [13, 14]. This unfolding method is based on Bayes' theorem and the unsmearing can be written as

$$C'_i = \sum_{j=1}^{N_m} U_{ij} E_j^{data}, \tag{1}$$

where $C'_i$ is the number of true events in the $i$-th true energy bin, $N_m$ is the number of bins of the measured spectrum, $U_{ij}$ is an unsmearing matrix, and $E_j^{data}$ is the number of events in the $j$-th measured energy bin. Figure 2 shows a resolution map between true and measured energies. The resolution map is evaluated by the MC simulation. Unsmearing matrix can be calculated by the resolution map. The unfolded spectrum is obtained through the unsmearing process of the measured spectrum based on the unsmearing matrix. The binning was chosen so that each bin contains a comparable number of events.

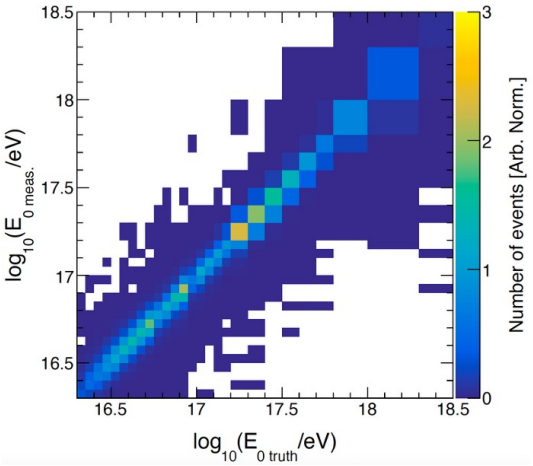


**Figure 2:** Resolution map between true and measured energies. The resolution map is evaluated by the MC simulation.

The product of the effective aperture and the observation time is called the effective exposure. Figure 3 shows the effective exposure used in this analysis. The effective exposure is evaluated by the MC simulation. The exposure in the high-energy region above $10^{18}$ eV becomes flat because the size of the ground array is fixed. The energy spectrum is expressed as

$$J(E_i) = \frac{\sum_{j=1}^{N_m} U_{ij} N_j^{sel}}{A\Omega(E_i) \cdot T \cdot \Delta E_i}, \tag{2}$$

where $J(E_i)$ is the flux in the $i$-th energy bin, $U_{ij}$ is the unsmearing matrix, $N_j^{sel}$ is the number

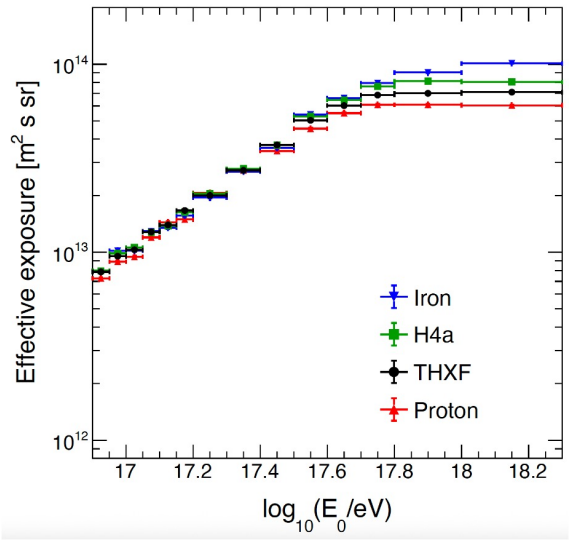


**Figure 3:** Effective exposure in this analysis. The effective exposure is expressed as a function of the true energy. This exposure is evaluated by the MC simulation.

of selected events in the $j$-th measured energy bin, $A\Omega(E_i)$ is the effective aperture, $T$ is the observation time, and $\Delta E_i$ is the width of the $i$-th bin.

## 5. Results

Figure 4 shows the distributions of the parameters related to reconstructed shower geometrical parameters which are core positions $X$ and $Y$, zenith angle, azimuth angle, $\Psi$ angle, and $R_p$. The $\Psi$ angle is the angle of the shower axis with respect to the direction of the center of the shower track and $R_p$ is the shower impact parameter to the detector.

Figure 5 shows the energy distribution of the events. The energy resolution in the range of $10^{17.4}$ eV to $10^{17.5}$ eV is +7.2%/−8.8% for protons and +6.6%/−6.4% for iron nuclei.

Figure 6 shows the result of the energy spectrum obtained in this study, as well as that reported by the TALE FD mono observation [3]. In this analysis, the TALE hybrid observation data with the THXF composition model was used. The results of a single and a broken power-law fittings are shown in Fig. 7. The $\chi^2/ndf$ of a single power-law fitting is 21.6/12, while that of a broken power-law fitting is 21.0/10. The break point is estimated as $\log_{10}(E_{\rm break}/{\rm eV}) = 17.11 \pm 0.09$, while the spectral indices are $-2.91 \pm 0.10$ and $-3.14 \pm 0.04$.

## 6. Summary

It is important to measure the acceleration limit of galactic cosmic rays through the measurements of composition and energy spectrum and to understand the transition from galactic to extragalactic cosmic rays. To study those physical topics, it is essential to measure the cosmic-ray energy spectrum and the composition over a wide energy range. In this work, we observed and analyzed the cosmic-ray events in the energy range of $10^{16}$ eV to $10^{18}$ eV using hybrid observations with the TALE FD and the TALE SD array with 400 m–600 m spacing. In this talk, we presented

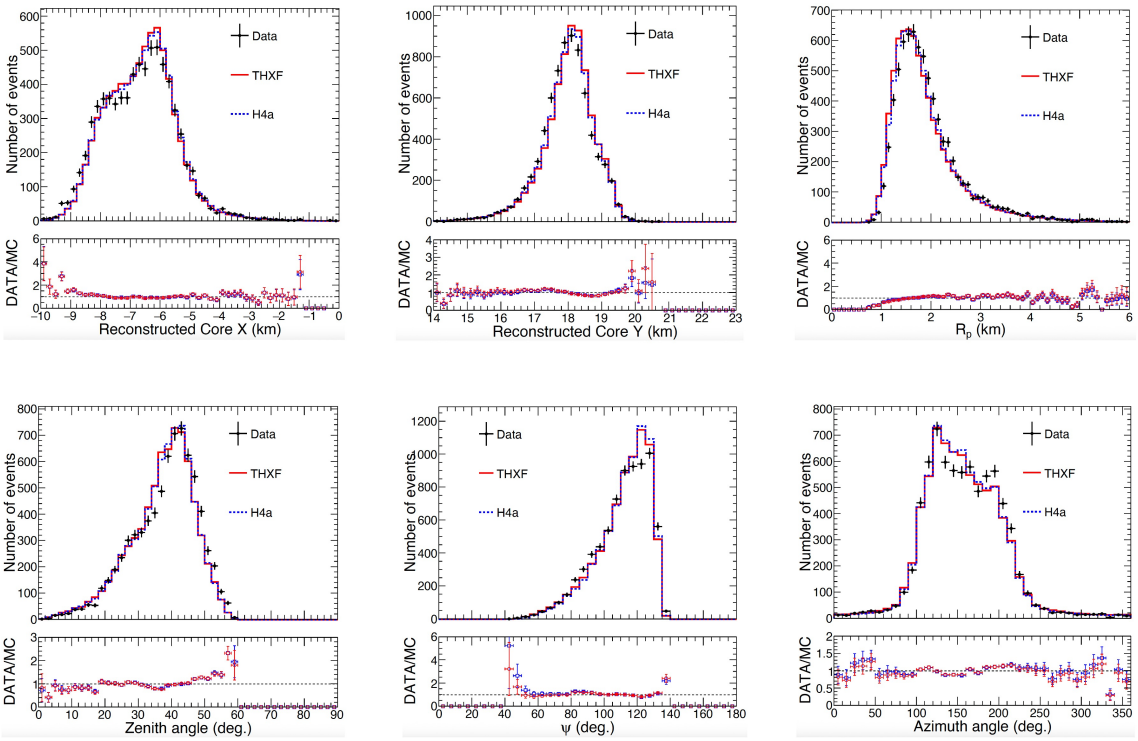


**Figure 4:** Distributions of reconstructed shower geometrical parameters. The figures show the $X$- and $Y$-projections of the shower core positions, $R_p$, $\Psi$, and zenith- and azimuth- angles of the shower axis. The data are shown by marker points, while the MC prediction are shown by the histograms for the THXF model and the H4a model, respectively. The MC predictions are normalized to the number of events in the data.

the preliminary results of the fundamental information and the energy spectrum with the TALE hybrid observation corresponding to the 1,247 hours of observation data. As a future prospect, it is expected that observations can be extended down to $10^{15}$ eV range through hybrid observations with the TALE infill SD array with 100 m spacing. Combining the TA and TAx4 as well as the TALE observation data, the energy spectrum is measured over five orders of magnitude from $10^{15}$ eV to $10^{20}$ eV. This energy spectrum measurement will play an important role in understanding the transition from cosmic rays of galactic origin to those of extragalactic origin.

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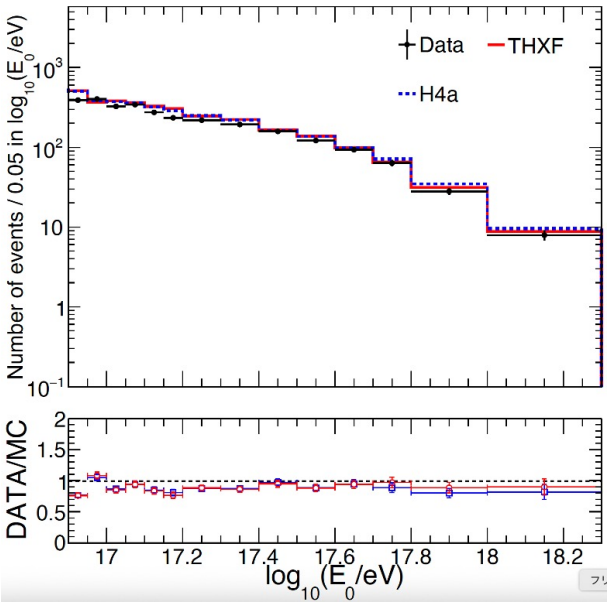


**Figure 5:** Comparisons of the measured energy distributions between the data and the MC predictions. The data are shown by marker points, while the MC prediction are shown by the histograms for the THXF model and the H4a model, respectively. The MC predictions are normalized to the number of events in the data.

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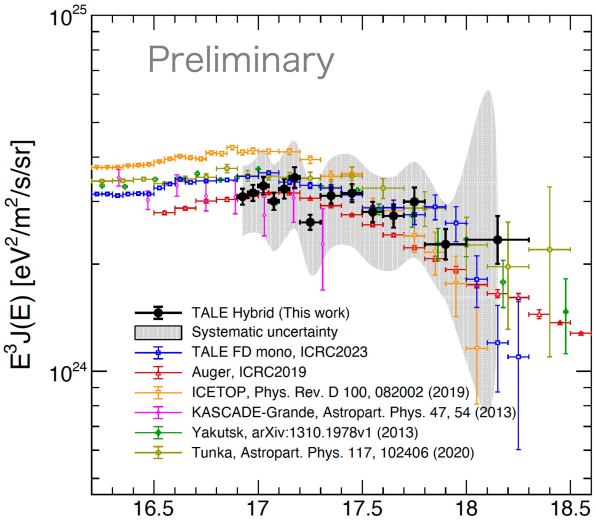


**Figure 6:** The result of energy spectrum. The spectrum obtained in this analysis is shown by the black data points. The error bars indicate the statistical uncertainties, while the gray band represents the systematic uncertainties. A mixed primary composition given by the THXF is assumed in this work.

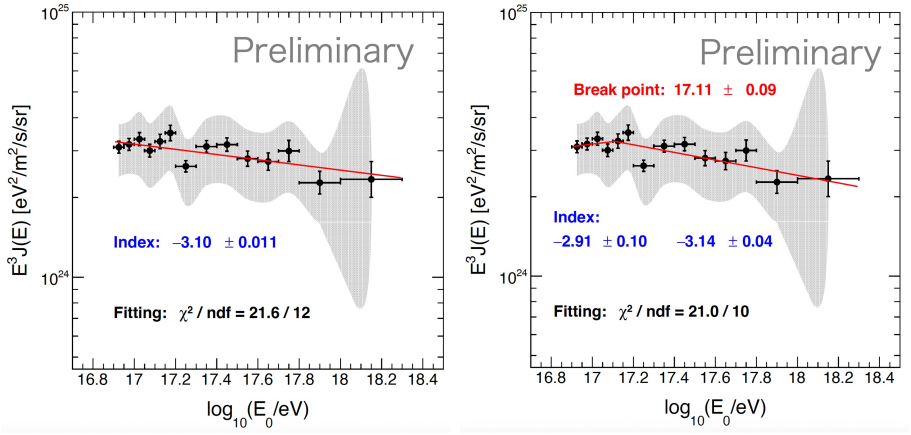


**Figure 7:** The results of energy spectrum with single and broken power-law fittings.

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