PROCEEDINGS OF SCIENCE

# Measurement of the cosmic ray energy spectrum in the 2nd knee region with the TALE-SD array

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The Telescope Array Low-energy Extension (TALE) experiment observes cosmic rays with 10 atmospheric fluorescence telescopes and an array of 80 surface detectors (SDs) distributed over an area of 21 km$^2$. The SD array consists of 40 SDs spaced at 400 m and 40 SDs spaced at 600 m. One of the goals of TALE-SD is to observe cosmic rays with energies down to $10^{16.5}$ eV to resolve the origin of the second knee and the energy of a galactic-extragalactic transition. The TALE-SD was completed in February 2018 and has been in continuous operation since then. In this work, we present the cosmic ray energy spectrum from the data recorded by the TALE-SD array from October 2nd, 2019 to September 28th, 2022.

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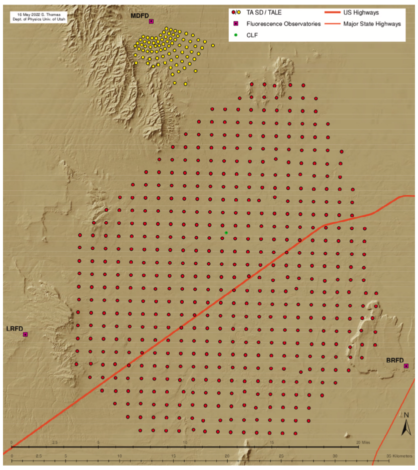
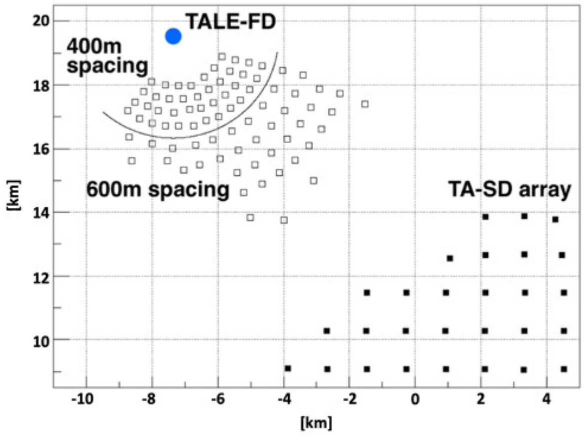
## 1. Introduction

The Telescope Array (TA) experiment measures extremely high energy cosmic rays [1]. TA is located in the western desert of Utah, USA and has been collecting data since March 2007. It includes a surface detector (SD) array and three fluorescence detector (FD) stations which measure properties of extensive air showers induced by high energy cosmic rays. The TA-SD array consists of 507 plastic scintillation detectors deployed at 1.2 km intervals, covering an area of approximately 700 km$^2$ [2]. The Black Rock Mesa (BRFD) and Long Ridge (LRFD) stations are composed of 12 telescopes which view 3° to 33° in elevation and 108° in azimuth [3]. The Middle Drum (MDFD) station consists of 14 telescopes, covering 3° to 31° in elevation and an azimuth range of 112° [4]. A map of the TA and TALE site is shown in Figure 1a.




**(a)** Map of the TA and TALE site.




**(b)** Map of the TALE site.

**Figure 1:** Maps of the TA and TALE detectors. (a) : Locations of the TA-SDs are shown as red points and the locations of the three TA-FD stations are indicated by the magenta squares. Locations of the TALE-SDs are shown as yellow points. (b) : A map of the TALE site. Locations of the TALE-SDs are shown as open squares and the location of the TALE-FD station is shown as a blue circle. Locations of the TA-SDs are shown as black squares. The area closest to the TALE-FD station has 40 SDs with a spacing of 400 m, and the outer area has 40 SDs with a spacing of 600 m. The TALE-SD array is arranged in a fan shape instead of a grid shape to optimize the hybrid observation with TALE-FD. The TALE-FD consists of 10 telescopes viewing the sky above the MDFD from 31° to 59° in elevation.

The Telescope Array Low-energy Extension (TALE) experiment observes cosmic rays with 10 FDs and an array of 80 SDs distributed over an area of 21 km$^2$. The SD array consists of 40 SDs spaced at 400 m and 40 SDs spaced at 600 m. The 10 FDs were installed at the Middle Drum site, observing elevation angles from 31° to 59° [5] above the original TA telescopes. The layout of the TALE surface detectors is shown in Figure 1b.

One of the goals of TALE-SD is to observe cosmic rays with energies down to $10^{16.5}$ eV to resolve the origin of the second knee and the energy of a galactic-extragalactic transition. TALE-SD was completed in February 2018 and has been in continuous operation since then. In this work, we present the cosmic ray energy spectrum from the data recorded by the TALE-SD array from October 2nd, 2019 to September 28th, 2022.

## 2. Event reconstruction and selection

Approximately three years of data recorded between October 2nd, 2019 and September 28th, 2022 were analyzed for measuring the cosmic ray spectrum with the TALE-SD array. In this analysis, cosmic ray events were reconstructed as follows [6].

The geometric parameters of the event were reconstructed using the following function:

$$\tau = \left(8\times 10^{-10}\right) a\left(\theta\right)\left(1.0+\frac{r}{30}\right)^{1.5}\left(\frac{\rho}{\mathrm{m}^{-2}}\right)^{-0.5} \ [\mathrm{s}]. \tag{1}$$

As shown in Figure 2, $\tau$ is the delay in particle arrival time from the shower plane, $r$ is the distance from the shower axis to the SD and $\rho$ is the particle number density.

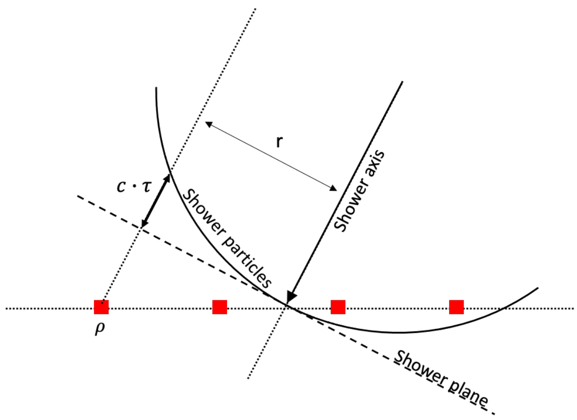



**Figure 2:** Schematic diagram of an air shower and TALE-SDs. The red squares are TALE-SDs, the dashed line is the shower plane and the black curve shows the positions of the shower particles. $\tau$ is the delay in particle arrival time from the shower plane, $c$ is the light speed, $r$ is the distance from the shower axis to the SD and $\rho$ is the particle number density recorded by the SD.

$a\left(\theta\right)$ is the curvature of the air shower plane and is given by

$$a\left(\theta\right) = \begin{cases} 3.3836-0.018848\theta & (\theta<25^\circ) \\ c_0+c_1\theta+c_2\theta^2+c_3\theta^3 & (25^\circ\le\theta\le 35^\circ) \\ \exp\left(-3.2\times10^{-2}\theta+2.0\right) & (35^\circ<\theta) \end{cases}, \tag{2}$$

$$c_0 = -7.76168\times10^{-2},\quad c_1 = 2.99113\times10^{-1},$$

$$c_2 = -8.79358\times10^{-3},\quad c_3 = 6.51127\times10^{-5}.$$

These equations were obtained by Linsley and parameterized by zenith angle $\theta$ for the TA experiment [7][8].

Next, the particle density obtained from each detector is fitted with the following lateral distribution function $f_{\mathrm{LDF}}\left(r\right)$ from the Akeno Giant Air Shower Array (AGASA) experiment [9],

$$f_{\mathrm{LDF}}\left(r\right) = A\left(\frac{r}{91.6\,\mathrm{m}}\right)^{-1.2}\left(1.0+\frac{r}{91.6\,\mathrm{m}}\right)^{-\eta(\theta)+1.2}\left(1+\left(\frac{r}{1000\mathrm{m}}\right)^2\right)^{-0.6} \ [\mathrm{m}^{-2}] \tag{3}$$

$$\eta\left(\theta\right) = 3.97-1.79\left(\sec\theta-1\right)$$

where $r$ is the distance from the shower axis to the SD, $\theta$ is the zenith angle and $A$ is the scale factor.

TALE-SD determines the energy of observed air showers using the reconstructed zenith angle $\theta$, the particle number density at 600 m from the shower axis $S_{600}$ and an energy estimation table obtained from Monte Carlo simulations. A preliminary version of the TALE-SD energy estimation table is shown in Figure 3. This result assumes a pure proton composition, and is made using

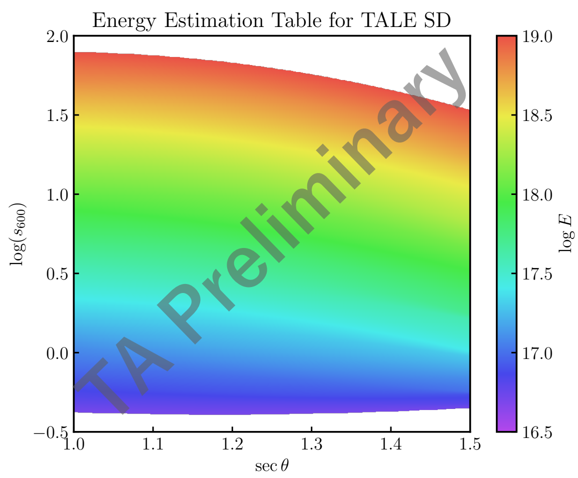



**Figure 3:** Energy Estimation Table for TALE-SD array. This energy estimation table assumes a pure proton. The energy range that can be estimated using this is from $10^{16.7}$ eV to $10^{19.0}$ eV.

the quality cuts shown below in Table 1. When calculating the spectrum a more stringent zenith angle cut, also shown in Table 1, was applied to ensure good resolution and data/Monte Carlo comparisons. As shown in Figure 4, the primary energies obtained from this analysis and the TALE-Hybrid analysis are consistent [10][11].

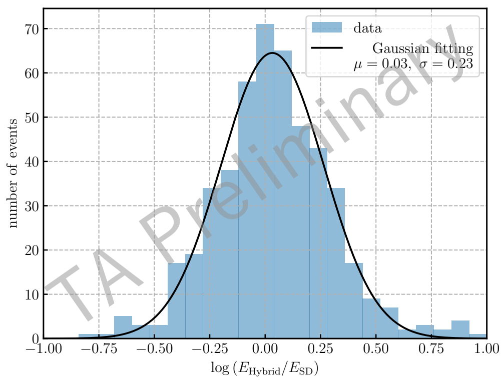



**Figure 4:** Comparison of the primary energy obtained from this analysis with the primary energy obtained from the TALE-Hybrid analysis. The black line is the result of a Gaussian fit to the histogram.

## 3. Monte Carlo simulation

We generated air showers using the CORSIKA-based Monte Carlo simulation code developed for the TA experiments [12]. These simulations first simulate an air shower using the hadronic interaction model QGSJETII-04 [13], followed by the detector response of the TALE-SD, which is calculated using GEANT4 [14]. In this analysis, the primary particle is assumed to be a proton, and the air showers are generated with energies from $10^{16.65}$ eV to $10^{18.95}$ eV where $\mathrm{d}N/\mathrm{d}E$ is proportional to $E^{-3.3}$. The azimuth angle was uniformly selected from 0° to 360°, the zenith angle was sampled from a $\cos\theta \sin\theta$ distribution between 0° to 65°, giving an equal number of events per solid angle, and the core positions were uniformly selected within a 5.5 km radius circle that completely includes the TALE-SD array, as shown in Figure 5.

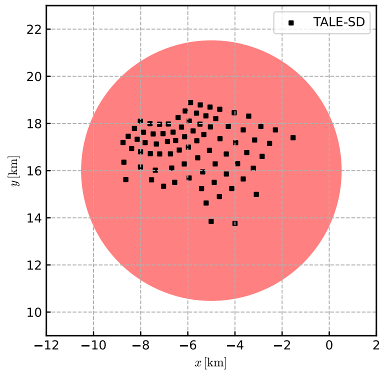


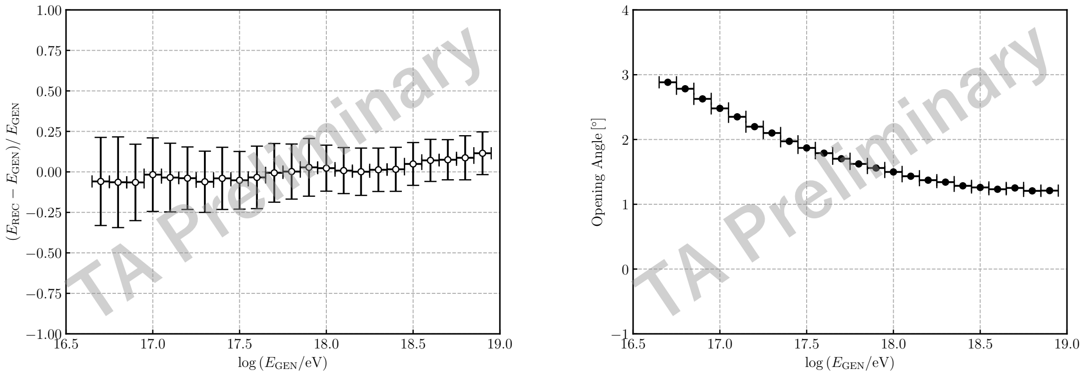

**Figure 5:** Distribution of the shower core positions. The shower core positions were uniformly selected within a 5.5 km radius circle that completely includes the TALE-SD array.

Comparing the reconstruction to the Monte Carlo simulated values estimates the analysis resolution. Figure 6 shows the reconstruction performance. The energy resolution is 25% at $10^{16.7}$ eV and 15% at $10^{18.9}$ eV. The angular resolution is 3° at $10^{16.7}$ eV and almost 1° at $10^{18.9}$ eV.

To check whether the Monte Carlo simulation reasonably simulated the TALE-SD data, the distribution of the measurable parameters were plotted. Figure 7 shows data and Monte Carlo comparisons for primary energy, zenith angle, azimuthal angle, $S_{600}$, the shower core position in $x$ and the shower core position in $y$. The data is shown as black points with error bars. The Monte Carlo is represented by the blue histogram. The Monte Carlo simulation is a good representation of the data. The two are consistent.

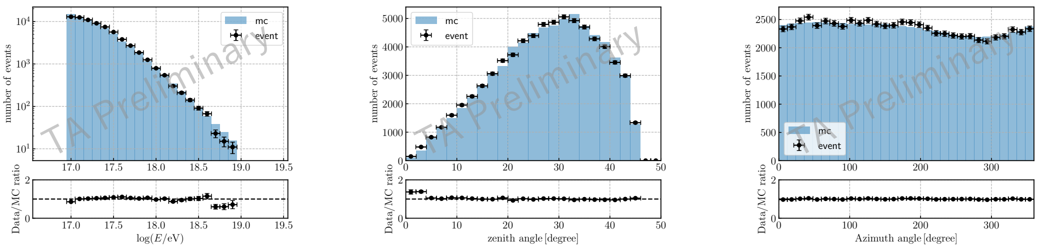
**Table 1:** Quality Cuts Applied in this study.

| Variable | cut condition | Variable | cut condition |
|---|---|---|---|
| # of SDs | ≥ 5 | $\chi^2_{\mathrm{Geom}}/$ d.o.f | ≤ 4 |
| zenith angle [°] | ≤ 55° (To create Energy Estimation Table) | $\chi^2_{\mathrm{LDF}}/$ d.o.f | ≤ 2 |
| | ≤ 45° (To analyze data) | $\left(\sigma_\theta^2 + \sin\theta^2\sigma_\phi^2\right)^{1/2}$ [°] | ≤ 2.5° |
| $D_{\mathrm{border}}$ [m] | ∼ 100 m | $\sigma_{\mathrm{S600}}/$ S600 | ≤ 0.25 |

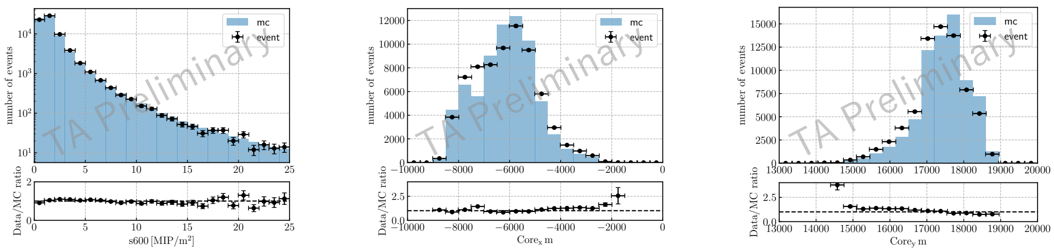



**(a)** Bias and resolution of the primary energy. **(b)** Angular resolution.

**Figure 6:** Result obtained by Monte Carlo simulation. (a): Bias (open circles) and $\pm 1\sigma$ resolution (error bars) of the primary energy obtained by Gaussian fitting. (b): Opening angle at 68% of the number of events at a given energy.




**(a)** Primary energy **(b)** Zenith angle **(c)** Azimuth angle




**(d)** $S_{600}$ **(e)** The shower core position in $x$ **(f)** The shower core position in $y$

**Figure 7:** Data/Monte Carlo comparisons. The Monte Carlo simulation is a good representation of the data.

## 4. Energy spectrum analysis with TALE-SD array

To obtain the energy spectrum, the exposures must first be calculated. The exposures cannot be calculated with a simple geometric factor because it depends on the performance of the surface detectors and also on the primary particles. Therefore, these dependencies are taken into account by the Monte Carlo simulations to estimate the aperture of the detector. In this analysis, the exposures were calculated under the assumption that the composition of primary cosmic rays is pure proton, using the following equation:

$$\begin{aligned}
\text{Exposure} &= A_{\text{GEN}} \times \Omega_{\text{GEN}} \times \frac{N_{\text{REC}}^{\text{all cut}}}{N_{\text{GEN}}} \times T, & (4)\\
A_{\text{GEN}} &= \pi \times 5.5^2\ [\text{km}^2], & (5)\\
\Omega_{\text{GEN}} &= \int_0^{2\pi} \mathrm{d}\phi \int_{0^\circ}^{65^\circ} \mathrm{d}\theta \sin\theta\cos\theta, & (6)\\
T &= 1093\,\text{days}, & (7)
\end{aligned}$$

where $A_{\text{GEN}} \times \Omega_{\text{GEN}}$ is the simulated aperture, $N_{\text{REC}}^{\text{all cut}}$ is the number of reconstructed events, $N_{\text{GEN}}$ is the number of simulated events and $T$ is the number of days of data used in the analysis. The exposures calculated in this way are shown in Figure 8. The bins from $10^{16.7}$ eV to $10^{16.9}$ eV were not used in this analysis to remove the effect of migration from the lower bins.

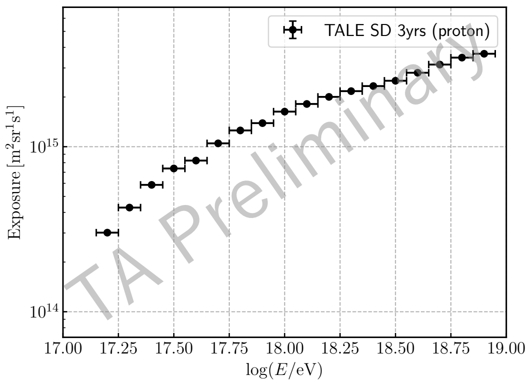



**Figure 8:** The exposure obtained by Monte Carlo simulation.

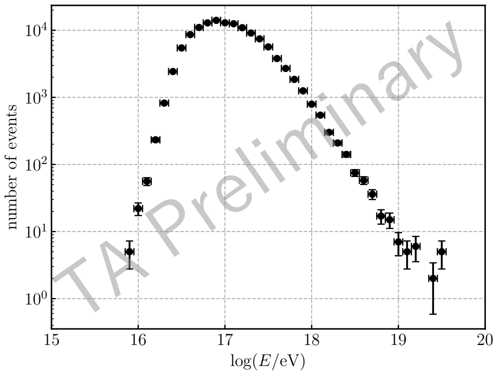
Figure 9a shows the energy histogram of events measured with the TALE-SD array. Dividing the value of each bin of this histogram by the value of the corresponding energy bin exposure and bin width yields the energy spectrum:

$$J = \frac{N(E)}{(\text{Exposure}) \cdot \mathrm{d}E}. \tag{8}$$

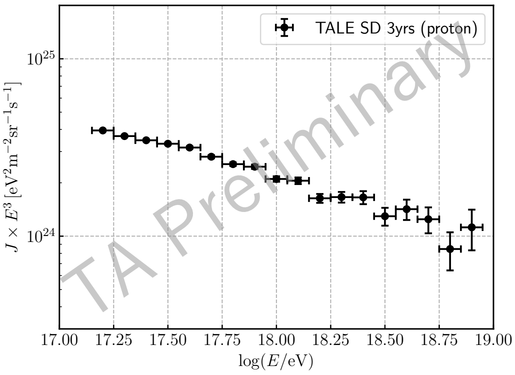
The energy spectrum is shown in Figure 9b.

## 5. Conclusion

The TALE-SD array has been in operation since February 2018 with 80 SDs. The TALE-SD array DAQ is now running stably. The energy resolution is 25 % at $10^{16.7}$ eV and 15 % at $10^{18.9}$ eV, and the angular resolution is 3° at $10^{16.7}$ eV and almost 1° at $10^{18.9}$ eV. We compared the Monte Carlo and data and we have confirmed that they are consisent. And we evaluated the preliminary energy spectrum assuming a pure proton. In the future, we plan to obtain the energy estimation table, the exposure, and the energy spectrum that take into account the composition of cosmic rays.




**(a)** Energy histogram




**(b)** Energy spectrum

**Figure 9:** (a): The energy histogram of events measured with the TALE-SD array. (b): The energy spectrum from the actual data obtained by the TALE-SD array from October 2nd, 2019 to the end of September 28th, 2022.

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