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# Cosmic Ray Composition between 2 PeV and 2 EeV measured by the TALE Fluorescence Detector

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The Telescope Array (TA) cosmic rays detector located in the State of Utah in the United States is the largest ultra high energy cosmic rays detector in the northern hemisphere. The Telescope Array Low Energy Extension (TALE) fluorescence detector (FD) was added to TA in order to lower the detector's energy threshold, and has succeeded in measuring the cosmic rays energy spectrum down to PeV energies, by making use of the direct Cherenkov light produced by air showers. In this contribution we present the results of a measurement of the cosmic-ray composition using TALE FD data collected over a period of ~ 7 years. TALE FD data is used to measure the $X_{\mathrm{max}}$ distributions of showers seen in the energy range of $10^{15.3}$ - $10^{18.3}$ eV. The data distributions are fit to Monte Carlo distributions of H, He, N, Fe cosmic-ray primaries for energies up to $10^{18}$ eV. Mean $X_{\mathrm{max}}$ values are measured for the full energy range. TALE observes a light composition at the "Knee", that gets gradually heavier as energy increases toward the "Second-Knee". An increase in the $X_{\mathrm{max}}$ elongation rate is observed at energies just above $10^{17.3}$ eV indicating a change in the cosmic rays composition from a heavier to a lighter mix of primaries.

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## 1. Introduction

The Telescope Array (TA) experiment was designed for the study of ultra high energy (above $\sim 10^{18}$ eV) cosmic rays. TA is the successor to the AGASA/HiRes experiments [1, 2] with the goal of improving on both. TA is composed of three fluorescence detectors (FDs) [3, 4] and a large array of surface detectors [5]. TA is located in Millard County, Utah, ~ 200 km southwest of Salt Lake City. The surface detector array is made up of 507 scintillation counters with 1.2 km spacing on a square grid. The three fluorescence detectors have an elevation coverage of about 30°, and an azimuthal coverage of about 110° overlooking the SD array.

The TA Low Energy extension (TALE) detector [6] aims to lower the energy threshold of the experiment to well below $10^{17}$ eV. This is mainly motivated by the interest in the galactic to extra-galactic transition in cosmic ray flux.

Located at the TA Middle Drum FD site at the northern edge of the main SD array, TALE provides an additional set of telescopes with high-elevation angle view to the site. These complement the existing telescopes at Middle Drum, resulting in an elevation coverage range of 3°-59° for the full detector. In addition, an infill surface detector (SD) located closer to the FD site than the main TA array, and with closer spacing between the SD counters themselves, forms the second component of the "hybrid detector". TALE operates as a hybrid detector (FD/SD) for best event quality in the intended range of operation, but can also operate as two separate detectors. GPS timing allows for an observed cosmic ray shower (an event) observed separately by the FD and SD to be merged into a single event. Events recorded by the FD which fail to trigger the SD, or if we choose to ignore the SD data, are referred to as monocular events. Furthermore, in what follows *we refer to the set of ten telescopes with high-elevation view as the TALE FD*. These telescopes employ FADC electronics which allow for better timing resolution than the older lower-ring telescopes with sample and hold electronics.

## 2. Data Analysis

TALE FD monocular data collected between June 2014 and November 2018 was used in a recent publication on the cosmic ray mass composition [8]. In this proceeding we summarize some of the results from the publication and describe an update to the data set to include data collected through the end of April of 2021.

The total, good-weather, detector on-time in the "four-year" period between June 2014 and November 2018 comes to ~ 2633 hours. The additional data from December 2018 to end of April 2021 brings the total good-weather on-time to ~ 3456 hours.

A high level view of the analysis follows: Air showers register in the detector as events, which are calibrated and reconstructed to obtain the shower geometry, total energy, and the depth of maximum development, $X_{\rm max}$. Quality cuts are applied to the reconstructed data to reduce it to a data set usable for energy spectrum measurement or for cosmic rays composition analysis, the subject of this proceeding.

Observed air showers comprising the "composition" data set used for this study were required to meet the condition that at least 35% of the total observed light signal of the detected event should be direct-Cherenkov light. I.e. not counting the contribution from Rayleigh or Aerosols scattered

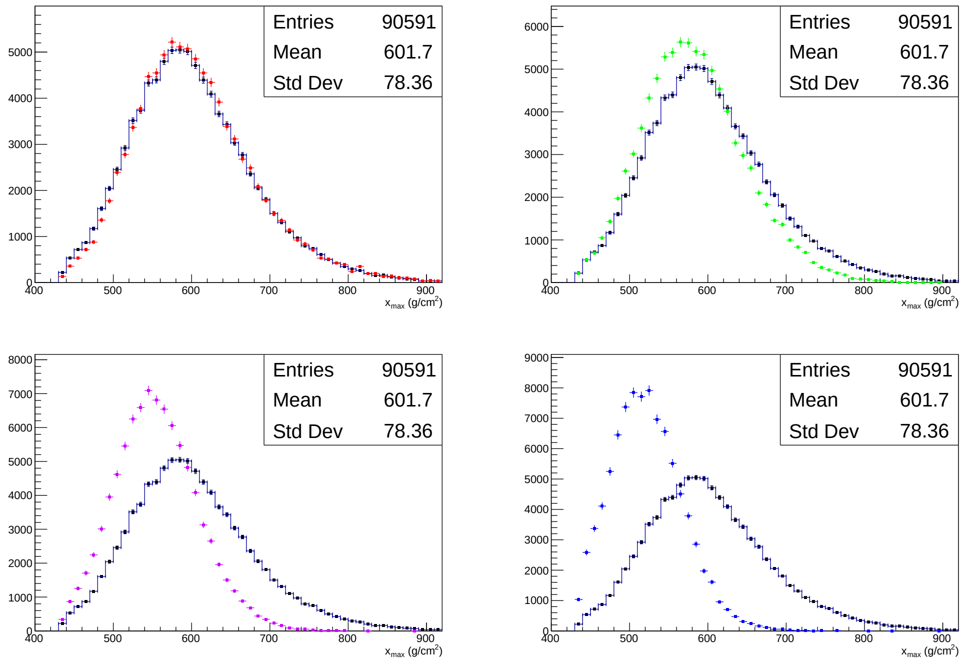


**Figure 1:** Shower $X_{\rm max}$ (g/cm$^2$) distributions for energy bin $15.7 < \log_{10}(E_{cal}/\mathrm{eV}) < 15.8$. Each of four plots shows data histogram (black points / blue line), along with MC primary reconstructed $X_{\rm max}$: upper left plot H (red), upper right He (green), lower left CNO (violet), and lower right Fe (blue)

Cherenkov light. This condition was found to be sufficient for good geometrical reconstruction of the events seen by the TALE FD operating in monocular mode. A detailed description of the event data reconstruction and selection can be found in [7]. A detailed discussion of the "composition" data set, event selection and reconstruction performance can be found in [8].

We use Monte Carlo simulations to study the detector efficiency and reconstruction resolution. Two sets of simulations were used for the analysis. One based on the EPOS-LHC[9] hadronic model and one based on QGSJetII-03[10]. The first model is a post-LHC model, while the second was the model used for the TALE energy spectrum measurement [7]. In this proceeding we focus on the EPOS-LHC based analysis.

Four primary cosmic rays particle types were simulated: proton, helium, nitrogen (CNO), and iron. Equal numbers of each primary type were generated. Simulated showers were processed through the event reconstruction and event selection procedure used for TALE data. The resulting shower $X_{\rm max}$ distributions for each primary type were used to fit the observed data $X_{\rm max}$ distribution, using the TFractionFitter [11, 12] utility. Figures 1 and 2 show the data and MC Xmax distributions at two different energy bins.

## 3. Results

The results of the primary fraction fits and the values of the "Mean log(A)" derived from them are shows in Figure 3.

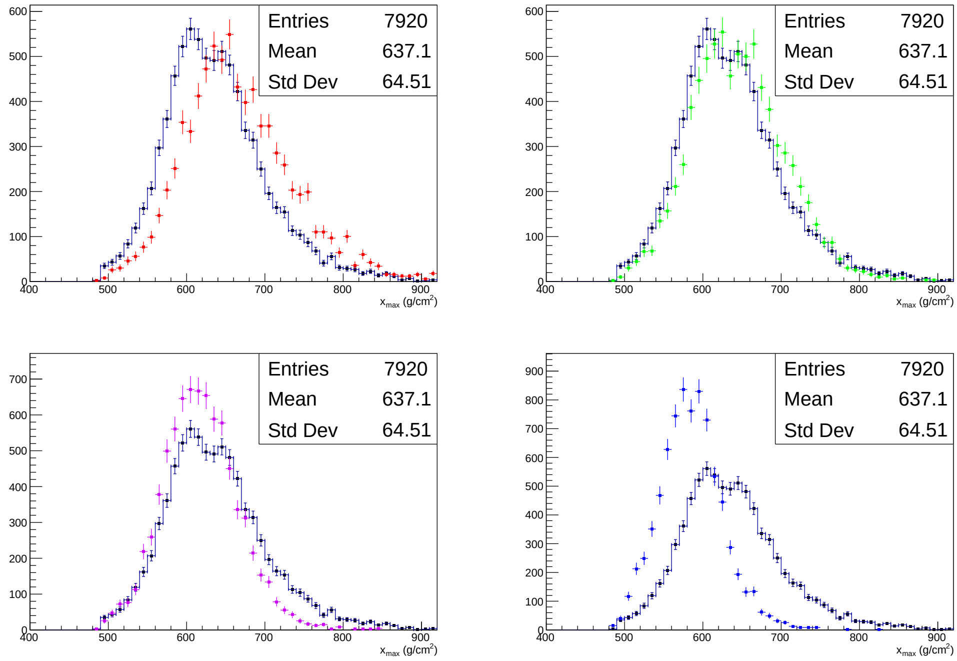


**Figure 2:** Shower $X_{\max}$ (g/cm$^2$) distributions for energy bin $16.7 < \log_{10}(E_{cal}/\text{eV}) < 16.8$. Each of four plots shows data histogram (black points / blue line), along with MC primary reconstructed $X_{\max}$: upper left plot H (red), upper right He (green), lower left CNO (violet), and lower right Fe (blue)

An alternative analysis to estimating mass composition is to examine the mean $X_{\max}$ values of TALE data. A comparison of these observations with those of different MC primaries is shown in the left-side plot of Figure 4. A change in the elongation rate of the mean $X_{\max}$ as a function of energy can be interpreted as a change in composition and we look for such change by using a broken line fit (one floating break point). The results of the fit are shown in the right-side plot Figure 4 and Table 1. This figure also shows the mean $X_{\max}$ measured by the Telescope Array detectors at higher energies [13]

**Table 1:** Fit parameters to a broken line fit to TALE $X_{\max}$ elongation rate: Break point energies are expressed as $\log_{10}(E/eV)$, and the slopes have units of $(g\ cm^{-2})/decade$. Uncertainties are reported as $value \pm \sigma_{stat.} + \sigma_{sys.} - \sigma_{sys.}$.

| | | |
|---|---|---|
| EPOS-LHC | break point | $17.291 \pm 0.060 + 0.077 - 0.084$ |
| | slope before | $35.863 \pm 0.294 + 1.481 - 0.536$ |
| | slope after | $65.413 \pm 6.655 + 0.000 - 3.269$ |

We are now in the process of updating the analysis to include data collected through April 2021. At this point, the detector data has been processed, but the corresponding MC sets are still in production. We therefore show an updated mean $X_{\max}$ result, but not the primary fits. First we compare the mean $X_{\max}$ from the new data to the published result, this is shown in Figure 5. Next we look at the combined set, that is shown in Figure 6. By redoing the broken line fit to the updated set, we see that the result is consistent to the four-year result.

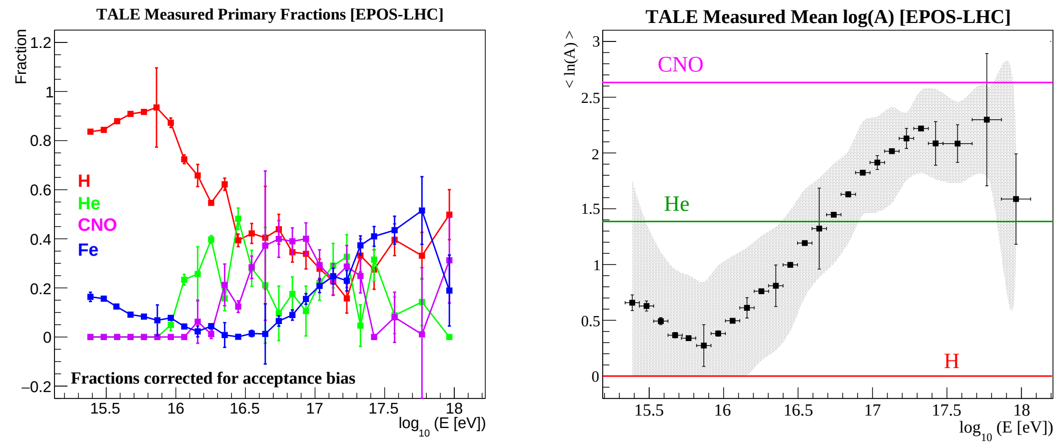


**Figure 3:** Fit results to the data $X_{\mathrm{max}}$ distributions (per energy bin) to a four component MC distributions. Primary fractions using the EPOS-LHC based simulations are shown on the left. Right plot shows the derived $\langle \ln(A) \rangle$ from four component fits. Horizontal lines show calculated $\ln(A)$ values for H, He, and N, for reference.

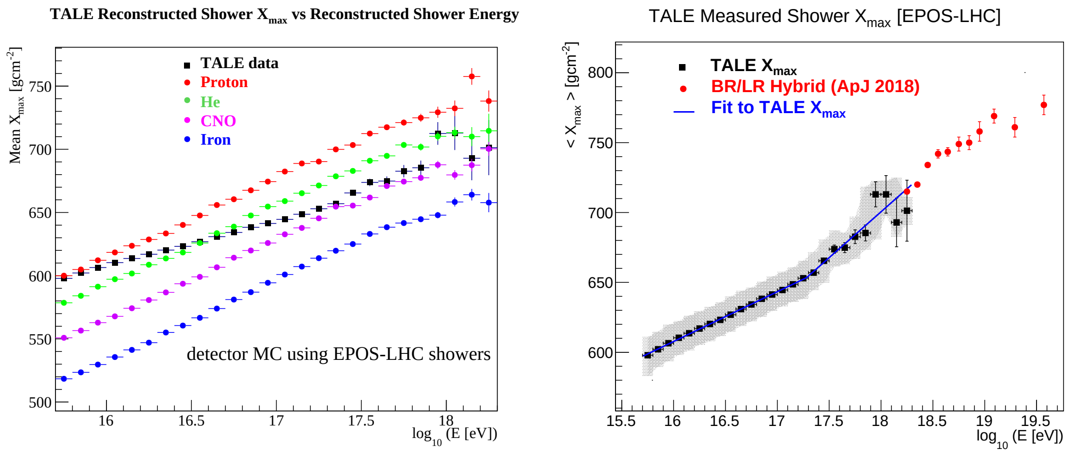


**Figure 4:** Reconstructed TALE events mean $X_{\mathrm{max}}$ as a function of shower energy. Shower energy estimate using EPOS-LHC missing energy correction. Plot on the left shows the reconstructed $X_{\mathrm{max}}$ values for the four MC primaries alongside the data for comparison. Right plot shows a broken line fit with fit parameters given in Table 1. Red points at higher energies come from a hybrid measurement by TA [13].

## 4. Summary

We presented the results of a measurement of the cosmic rays composition in the energy range of $10^{15.3}$ - $10^{18.3}$ eV using data collected by the TALE detector over a period of roughly four years. An examination of the mean $X_{\mathrm{max}}$ versus energy, shows a change in the $X_{\mathrm{max}}$ elongation rate at an energy of $\sim 10^{17.2}$ eV. This "break" in the elongation rate is likely correlated with the observed break in the cosmic rays energy spectrum [7].

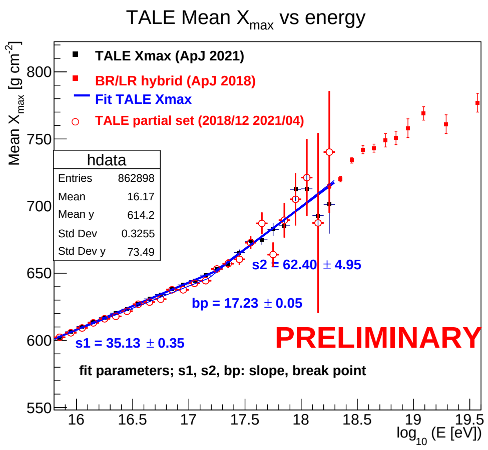


**Figure 5:** Reconstructed TALE events mean $X_{\max}$ as a function of shower energy (New data along with four-year set). Shower energy estimate using EPOS-LHC missing energy correction. A broken line fit with fit parameters displayed on the figure also shown. Red points at higher energies come from a hybrid measurement by TA [13].

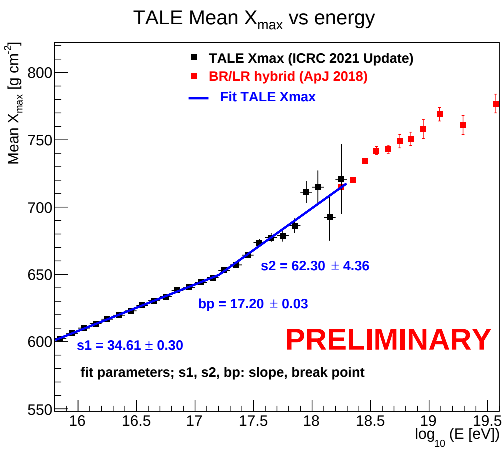


**Figure 6:** Reconstructed TALE events mean $X_{\max}$ as a function of shower energy (Entire data set). Shower energy estimate using EPOS-LHC missing energy correction. A broken line fit with fit parameters displayed on the figure also shown. Red points at higher energies come from a hybrid measurement by TA [13].

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