PROCEEDINGS OF SCIENCE

Cosmic Ray Energy Spectrum and Mass Composition 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 energy spectrum and mass composition using TALE FD data collected over a period of ∼ 8 years. This contribution provides an update to results on the cosmic-ray energy spectrum and mass composition presented at this conference in 2021. The update includes data collected during 16 additional months of observation and an updated detector simulation sets.

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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 publication on the cosmic ray mass composition [8]. In this proceeding we describe an update to that analysis that essentially increases the data set to include data collected between December 2018 and through the first few days of September 2022.

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 start of September 2022 brings the total good-weather on-time to ∼ 4130 hours. The published energy spectrum [7] was based on a ∼1080 hours of observation.

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 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].

When looking at the energy spectrum; Despite the increase in observation time, the event statistics at ~ 10^{18} eV energies and higher are smaller than the 2018 publication. This is due to the fact that fluorescence dominated events, which form the majority of observed events above 10^{18} eV, are not suitable for use in the mass composition analysis. To measure the shower X_{max}, we require accurate geometrical reconstruction, which in the case of TALE monocular observations, requires that a certain fraction of the observed shower signal, $> 35\%$, be direct-Cherenkov light. This requirement and other smaller changes to the quality cuts applied to the data lead to the rejection of a large fraction of the events that would have passed the event selection of the original analysis.

Another significant difference relative to the 2018 energy spectrum results is the use of the EPOS-LHC hadronic model for shower missing energy correction. Compared to QGSJetII-03, the estimated total-energy of a shower changes by a few percent, resulting in a small change in the overall energy scale and consequently changes the absolute normalization of the observed flux. This shift in energy is within the systematics of the measurement and is expected given the two hadronic models.

We employ a database driven detector simulation, which uses nightly detector files and GDAS atmospheric profiles. The updated analysis presented here includes corresponding simulations to all the added data obervations. The detector simulations are used to study the detector efficiency and reconstruction resolution. The simulations are also used to calculate the detector aperture and exposure for the observation period. The aperture calculation used in this proceeding has been updated and is therefore slightly different from that obtained in the two-year or four-year publications.

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_{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.

The shower simulations are based on the EPOS-LHC[9] hadronic model. 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_{max} distributions for each primary type were used to fit the observed data X_{max} distribution, using the TFractionFitter [11, 12] utility.

3. Results

Results for mass composition will be presented first, follwed by results for the energy spectrum. TALE apperture is composition dependent, especially at the lowest energies. The overall aperture is therefore calculated based on the reconstructed primary fractions, i.e. the results of the mass composition analysis.

The results of the primary fraction fits and the values of the "Mean log(A)" derived from them are shown in Figure 1.

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

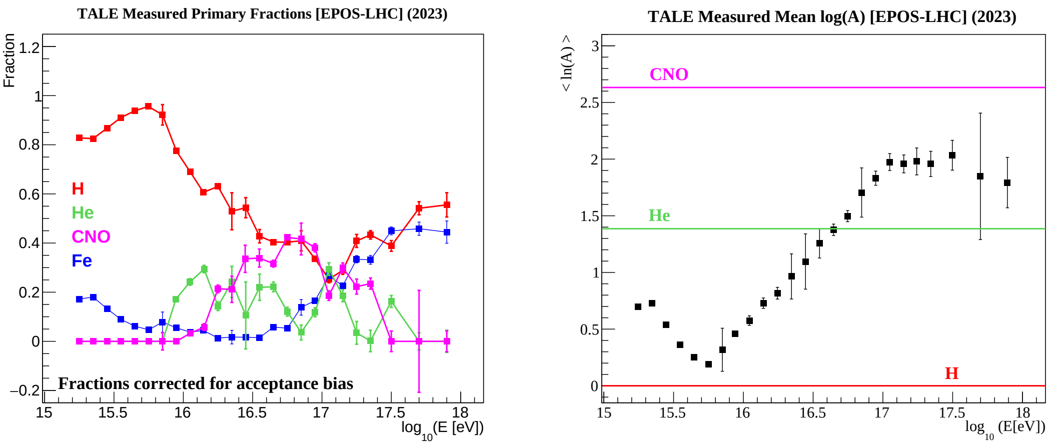

Figure 1: Fit results to the data $X_{\max}$ distributions (per energy bin) to a four component MC distributions. Primary fractions using the EPOS-LHC based simulations are shown on the left. Right plot shows the derived $\langle \ln(A) \rangle$ from four component fits. Horizontal lines show calculated $\ln(A)$ values for H, He, and N, for reference.

in the left-side plot of Figure 2. 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 2. This figure also shows the mean $X_{\max}$ measured by the Telescope Array detectors at higher energies [13]

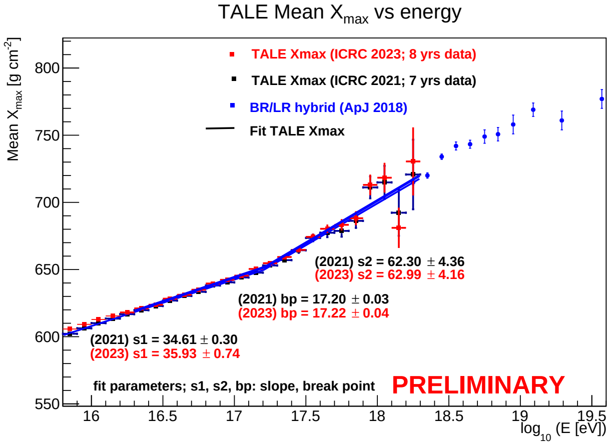

Figure 2: Reconstructed TALE events mean $X_{\max}$ as a function of shower energy. Results from the last update to the data, presented at the 2021 ICRC are also shown in the figure. Shower energy estimate using EPOS-LHC missing energy correction. The plot shows a broken line fit to the elongation rate. The blue points at higher energies come from a hybrid measurement by TA [13].

The event energy distribution for the final data set is shown in Figure 3. As already noted, the requirement of direct-Cherenkov contribution to the observed signal limits the acceptance for high energy events. Below $\sim 10^{17}$ eV, the observed events signal is dominated by direct-Cherenkov light.

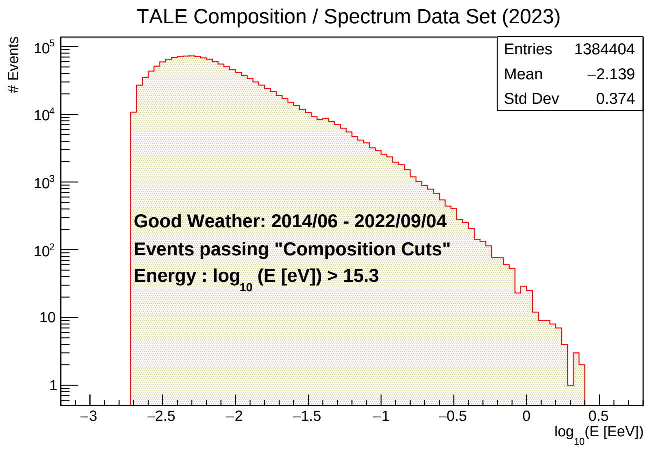

Figure 3: TALE “eight-year” data set event energy distribution.

To calculate an energy spectrum, or a flux, we first calculate the exposure of the detector over the observation period. We do this using a database-driven MC simulation of the detector response that incorporates details of the run conditions, including atmosphere and telescope live times and calibration. The simulation used here covers the four-year run period, up to November 2018, and was adapted for the remaining time period by a applying a small correction. The correction of the order of 3% was made such that the flux normalization for the two subsets was consistent. The updated energy spectrum shown with the 2018 published spectrum can be seen in Figure 4.

Figure 4 shows that the two measurements are similar for energies above $\sim 10^{15.8}$ eV. The difference in overall normalization is expected from the use of the different hadronic models. Below $\sim 10^{15.8}$, the new flux has a lower absolute normalization than expected. This is likely due to the updated composition assumption in the aperture calculation. At lower energies especially, the aperture estimate is sensitive to primary composition, with protons having almost double the acceptance as iron primaries at an energy of $10^{15.3}$ eV. The TALE composition result based on the EPOS-LHC analysis showed a slightly higher preference for protons at the low end of the energy range than the QGSJetII-03 based analysis. Consequently, the composition averaged aperture was slightly higher and the estimated flux came down, as seen in the figure. Below $\sim 10^{15.5}$, the new flux looks different from the previous result. The dicrepancy at energies below the knee are likely due to the rapidly changing acceptance and the strong composition dependence of the aperture.

Lastly, we perform a broken power-law fit to the updated flux, with the fit results shown in Figure 4. Qualitatively, the fit results are very similar.

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_{max} versus energy, shows a change in the X_{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].

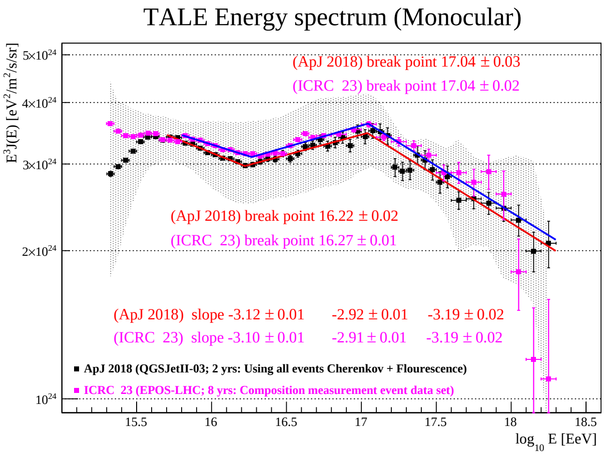

Figure 4: TALE updated energy spectrum along with 2018 spectrum. Note that the change in normalization is partly due to the changed shower missing energy correction, now using EPOS-LHC versus the original using QGSJetII-03. Fit results for the new spectrum and original spectrum are shown.

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