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Fluoresence Detection of Cosmic Ray Air Showers Between $10^{16.5}$ eV and $10^{18.5}$ eV with the Telescope Array Low Energy Extension (TALE)

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Abstract: The TA Collaboration has completed construction of a low-energy extension to its Middle Drum telescope station. Ten new telescopes were added observing 31-59 degrees in elevation above the original telescopes. A graded array of scintillators detectors (SDs) with spacings of 400-600-1200m is being installed in front of the telescope station. With these upgrades, the physics threshold will be lowered below $10^{16.5}$ eV. The TA Low Energy Extension(TALE) will explore the regime corresponding to the LHC center-of-mass energy. This is also where the transition from galactic to extra-galactic cosmic ray flux is suspected to occur. A brief overview of the physics will be presented as well as a report on the progress toward measuring the cosmic ray spectrum between $10^{16.5}$ eV and $10^{18.5}$ eV.

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1. Cosmic Ray Measurements in the Region of the Second Knee

Observations of cosmic ray air showers with energies above $10^{18}eV$ by the Fly's Eye and HiRes experiments resulted in measurements of the average composition and the flux of cosmic rays. The composition of cosmic rays was determined by measuring the average depth of shower maximum also known as $< X_{MAX} >$. Cosmic rays of larger atomic number have a larger cross section and will interact higher in the atmosphere than lighter cosmic rays. Compared to protons of the same energy, heavier cosmic rays also have a smaller energy per nucleon and higher multiplicity. The difference beteween particle types results in the $< X_{MAX} >$ of protons being deeper than the $< X_{MAX} >$ of iron cosmic rays. The results of the Fly's Eye experiment are shown in Figure 1. [6] [3]

The Fly's Eye result indicated that the composition of cosmic rays transitions from being dominated by heavy components at $10^{18}eV$ to light components at $10^{19}eV$. This transition in composition indicates that there is a change in the size of accelerators, specifically that the source of cosmic rays is changing over from galactic sources to extragalactic sources [1]. A two component fit of the Fly's Eye spectrum to a falling heavy component and a light extragalactic component fit the measured energy spectrum. This result is shown in Figure 2. [6]

The HiRes experiment was a second generation Ultra High Energy Cosmic Ray observatory which had better X_{MAX} resolution and better control of systematics than the Fly's Eye experiment. HiRes reported having an X_{MAX} resolution of $35\frac{g}{cm^2}$ versus the Fly's Eye resolution of $55\frac{g}{cm^2}$ [3] [7] . The HiRes experiment measured the composition of cosmic rays in the same range as the Fly's Eye experiment and found no evidence of a transition of composition in the $10^{18}-10^{19}eV$ decade. However, the HiRes experiment overlooked a muon infill array (MIA). By operating at the lower end of the sensitivity of the HiRes detector and the higher end of the sensitivity of the Mia detector cosmic rays with energies as low a $10^{17}eV$ were measured. The composition measurement of the HiRes experiment are shown in Figure 3. [7] [8]

By extending the measurement to lower energies the transition which is attributed to a galactic to extragalactic transition was observed. This transition in measured composition occurs at the same energy as an observed spectral feature known as the second knee. The spectrum of cosmic rays has been measured by many different experiments in the $10^{17}-10^{18}eV$ and aside from uncertainties in the different experiments energy scales they agree [7, 8, 9, 11, 10]. The spectrum measurements for cosmic rays in this energy range are shown in Figure 4.

Having evidence for a change in both the spectrum and composition of cosmic rays in the $10^{17}-10^{18}eV$ decade motivates further detailed study of the cosmic rays in this energy region.

2. Introduction to the TALE Detectors

The Telescope Array Low Energy Extension (TALE) is an addition to the Telescope Array (TA) cosmic ray observatory. TA was designed to measure cosmic ray air showers with energies above $10^{18}eV$ using three Fluorescence Detector (FD) stations (Black Rock, Long Ridge and Middle Drum) overlooking a ground array of scintillation Surface Detectors (SDs). TALE lowers the minimum sensitivity of the TA observatory by adding an additional FD station, named TALE FD, which observes higher in elevation than the original TA FD stations. Observing higher in elevation allows measurement of the shower maximum of lower energy showers. Additionally, a graded infill array of SDs is added in order to adequately sample the footprint of lower energy showers. The graded array has spacing of 0.4 km, 0.6 km, and finally 1.2 km.

The TALE FD station is collocated with the Middle Drum FD. The Middle Drum Fluorescence detector observes the atmosphere between 3° and 32° in elevation and the TALE FD observes between 32° and 59° in elevation. The two FD stations look in the same azimuthal direction and together provide coverage between 3° and 59° in elevation. The TALE SD array is still being deployed. The TALE FD is a newly designed and deployed FD stations that digitizes Photomultiplier Tube (PMT) waveforms at 10 MHz with 8-bit resolution. The TALE FD is photometrically calibrated using the same Roving Xenon Flasher (RXF) light source as the MD detector.

3. Cosmic Ray Air Shower Observations with the TALE FD Detector

Cosmic ray air showers are measured with the TALE FD detector in coincidence with the MD detector. An example display of an event is shown in Figure 5.

In fluorescence detection observatories ,Cherenkov light produced in the air shower was considered to be a contamination to the fluorescence signal and events that had high fractions of Cherenkov light in the signals were discarded [4, 5]. The FADC electronics of the TALE detector allow for better tube timing resolutions than the sample and hold electronics used in previous experiments. This allows events with large Cherenkov fractions to be accurately reconstructed. Events that are closer to the detector typically have larger fractions of their signal from Cherenkov light than event removed from the FD station. Events observed closer to the FD station also tend to be of lower energy. Events with energies below $10^{17.5} eV$ are dominated by Cherenkov light while scintillation light dominates the signal above $10^{17.5} eV$. This changeover in event type is shown in Figure 6.

Events are recorded on clear moonless nights and reconstructed by finding a monte carlo event that best matches the data.

4. Measurement of the Cosmic Ray Flux With TALE

The TALE FD collected a first epoch of data from September 2013 - January 2014. During this time 242 hours of good weather data were acquired by the detector. The following measurement of the cosmic ray flux was performed using only the TALE FD detector. No information from the MD FD or the SD array was used in the analysis. Looking only at the results of the TALE FD detector provide an end to end check of the detector electronics and the event reconstruction toolchain. Since SD data is not used in this analysis events were reconstructed using the Profile Constrained Geometry fit method. This method increases the accuracy in recovering the event energy but increases the uncertainty in the reconstructed X_{MAX} [2]. In this energy region of $10^{16.5} - 10^{18.5} eV$ both the aperture and missing energy corrections to events are composition dependent. In order to accurately determine the event energy a composition must be assumed in the reconstruction. In this analysis the H4A model [12] was assumed below $10^{17} eV$ and a HiRes-MIA [8] like transition assumed above $10^{17} eV$. This assumed composition in this analysis is shown in Figure 7.

In this analysis events with all amounts of Cherenkov light in the event signal were allowed. The resulting measured flux of cosmic rays as measured by the TALE FD is shown in 8. The TALE FD has been demonstrated to measure a cosmic rays flux that is consistent with previous experiments. Additionally, the modeling of events dominated by Cherenkov light allows for measurement of the cosmic ray flux into the $10^{15}eV$ decade. When the TALE SD array is fully instrumented the TALE detector will be able to make simultaneous measure of the composition and energy of air showers. This hybrid analysis will provide a detailed measurement of cosmic rays in the region of the second knee.

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Figure 1: Fly's Eye Experiment measurement of the composition of the cosmic rays. The top rail indicates the Monte Carlo expectation for protons. The bottom rail indicated the Monte Carlo expectation for iron. The measured values are between the two rails. [6, 3]

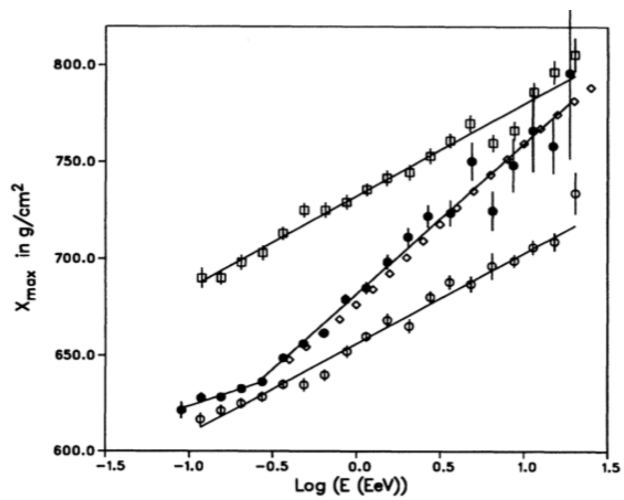

Figure 2: Fly's Eye Experiment measurement of the spectrum of the cosmic rays. The dotted lines indicated a falling iron component to the cosmic ray flux and a rising proton component to the cosmic ray flux. The measured flux is indicated with error bars. [6]

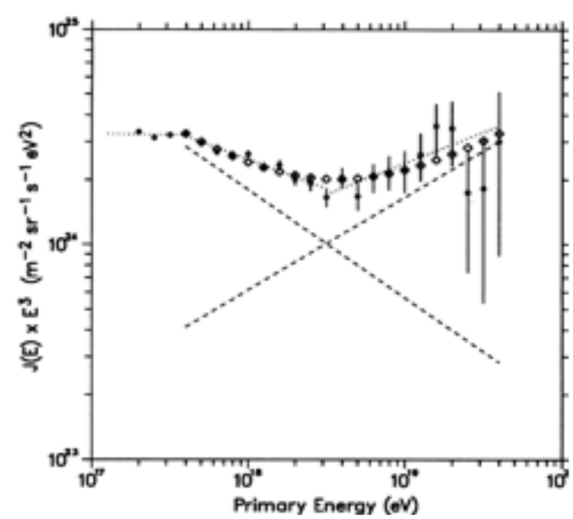

Figure 3: HiRes Experiment measurement of the composition of the cosmic rays. The top rail indicates the Monte Carlo expectation for protons. The bottom rail indicated the Monte Carlo expectation for iron. The measured values are between the two rails. [7] [8]

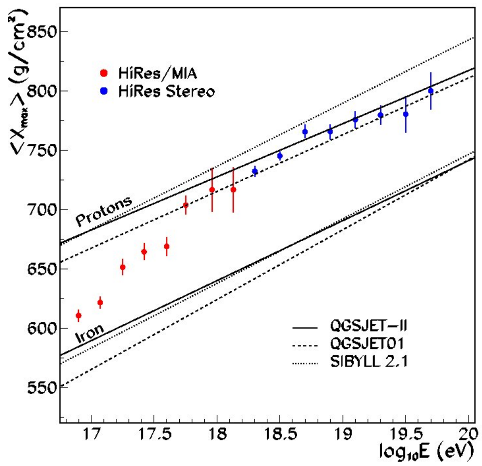

Figure 4: Measured spectrum of the cosmic rays for many experiments including HiRes-Mia. The left panel showed the reported flux measurements for each experiment. The right panel shows the same measurements where the energy scale is corrected to match that of the HiRes experiment. [7] [8]

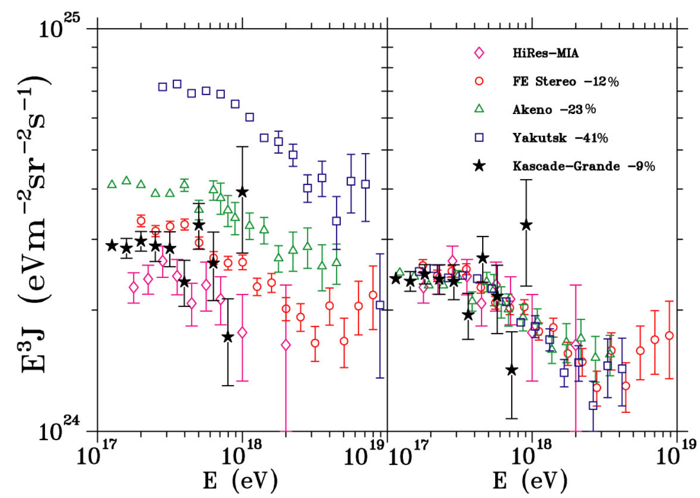

Figure 5: An event display of a cosmic ray air shower observed by both MD and TALE FDs. The region bounded in red indicates the portion of the sky observed by the TALE FD. The region bounded in blue indicates the portion of the sky observed by MD.

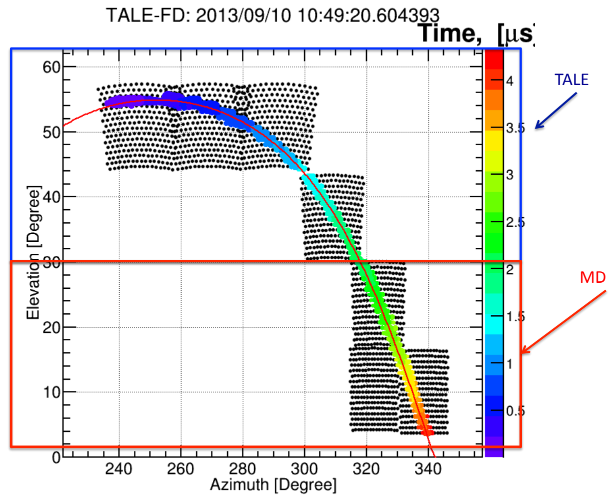

Figure 6: Events where 80% of the signal is from Cherenkov light are shown in blue. Events where 80% of the signal is from Scintillation light are shown in red. Events with intermediate amounts of Cherenkov and Scintillation light are shown in black. Note tat the y-axis is a logarithmic scale.

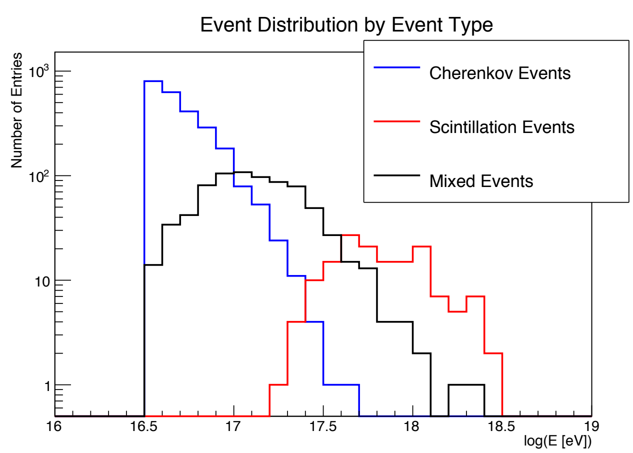

Figure 7: The two component (proton and iron) assumed composition used in calculating the detector aperture and the event missing energy corrections in this analysis.

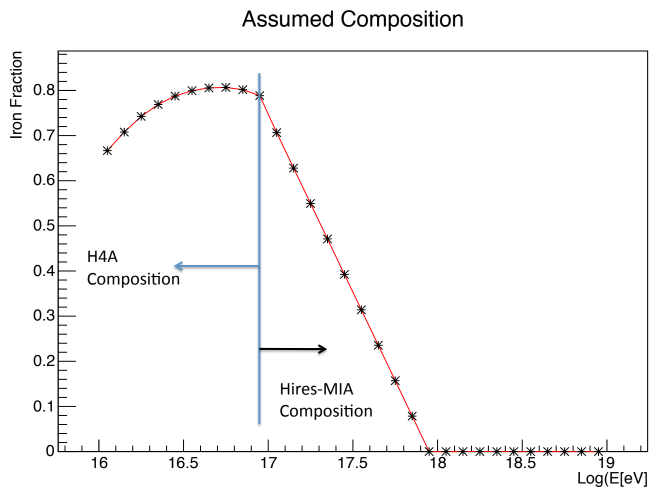

Figure 8: The measured flux of cosmic rays by the TALE FD in this analysis is shown in black. The flux of cosmic rays using only Cherenkov dominant events performed by Tareq AbuZayad is shown in red. The previous measurement of the spectrum reported by the HiRes experiment is shown in blue. Note that the flux has been multiplied by the cube of the energy in order to enhance the features of the spectrum.