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Cosmic Rays Energy Spectrum observed by the TALE detector using Cerenkov light

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We report on a cosmic ray energy spectrum measurement by the Telescope Array Low-Energy extension (TALE) fluorescence detector (FD). The TALE FD is an air fluorescence detector which is also sensitive to the Cerenkov light produced by shower particles. Low energy cosmic rays, in the PeV energy range, are detectable by TALE as "Cerenkov Events". Using these events, we measure the energy spectrum from a low energy of 4 PeV to an energy greater than 100 PeV. In this talk, we will describe the detector, explain the technique, and present results from a first measurement of the spectrum in this energy range by the Telescope Array experiment.

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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 (FD's) [3, 4] and a large array of surface detectors [5]. TA is located in Millard County, Utah, $\sim$ 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, TALE adds an additional set of telescopes with high-elevation angle view to the site. These complement the existing telescopes at Middle Drum. 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.

As an air fluorescence detector, the TALE FD has an energy threshold of $\sim 3 \times 10^{16}$ eV. However, the detector is also sensitive to Cerenkov light produced by air showers, and if we think of the TALE FD as an Imaging Air Cerenkov Telescope (IACT) we find that we can extend the energy threshold of the detector down to $\sim 3 \times 10^{15}$ eV, i.e. a full decade of energy lower than the original design goal of the experiment. We exploit this capability to measure the cosmic rays energy spectrum using the Cerenkov events observed by the TALE FD. We refer to this measurement as the TALE Cerenkov spectrum.

2. Cerenkov Events Observed by TALE

The following is an overview of the qualitative differences between fluorescence and Cerenkov events, illustrated in Figure 1. The light signal recorded by a fluorescence detector contains a contribution from Cerenkov light generated by the shower particles. In event reconstruction, we distinguish among four contributes to the total observed light signal:

- Direct Air Fluorescence light (FL).
- Direct Cerenkov light (CL).
- Rayleigh Scattered Cerenkov light (first order)
- Aerosols Scattered Cerenkov light (first order)

The relative contribution of the first two determines whether the event is counted as a Fluorescence or Cerenkov event. The amount of scattered light is to be accounted for, however we seek events for which it is minimal.

Traditionally we require that FL constitute at least $\sim 80\%$ of the received signal, although in some analysis this figure is relaxed to 60%. In the new study described in this proceeding we require that the *Direct* CL contributes more than 80% of the received signal. This requirement insures good event reconstruction quality. It also guarantees that we can divide the observed data into two distinct data sets, one Cerenkov and one fluorescence. We can then perform a physics analysis, such as the energy spectrum measurement, using either set collected by a single detector and during the same time period, and compare the results in an overlap region as a systematic check on the results.

CL generated by a shower shares a trait with FL in that both are directly proportional to the number of shower particles for any given point in the shower development. This property means that the observed CL signal can be used to infer the shower properties (energy and x_{max}) in a similar way to how the FL is used. A significant difference between the CL and FL is that CL emitted by the shower particles is strongly peaked forward along the shower direction, and falls off rapidly as the shower viewing angle changes. In contrast, FL is emitted isotropically. As a result, Cerenkov events are seen only if the shower geometry with respect to the detector is such that the shower is moving towards the detector (viewing angle $\sim 10^\circ$ or smaller). Fluorescence events are recorded at all viewing angles. This fact has a number of consequences for the observation:

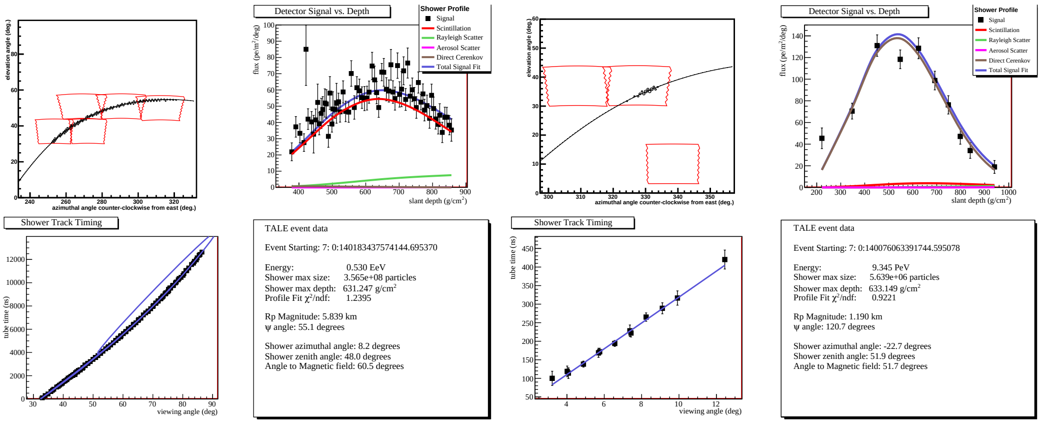
- Cerenkov events are much “faster” (total event duration is much shorter) than fluorescence events.
- At any energy/distance Cerenkov events are more intense (bright) than the fluorescence counterpart, which is why the detector energy threshold is lower for Cerenkov events.
- The detection volume for Cerenkov events is limited and does not grow with energy the same way it does for fluorescence events. The shower core must fall in the vicinity of the detector for the viewing angle condition to be met.

While the amount of CL emitted at the shower is proportional to the shower size, the amount of light observed at the detector depends strongly on the emission (viewing) angle at which the light is received from the shower. This results in two significant consequences for the event reconstruction as will be explained in section 3:

- It is precisely this property which makes the monocular event reconstruction possible.
- It makes the reconstructed shower energy/x_{max} highly sensitive to the error in the reconstructed geometry, and also to the light emission model assumed in the reconstruction

3. Monocular Event Reconstruction

Event reconstruction refers to the determination of the shower geometry with respect to the detector and obtaining a best fit for the shower energy and the depth of shower maximum, x_{max}. It



TALE event data

Event Starting: 7: 0:140183437574144.695370

Energy: 0.530 EeV
Shower max size: 3.565e+08 particles
Shower max depth: 631.247 g/cm^2
Profile Fit χ^2/ndf: 1.2395

Rp Magnitude: 5.839 km
ψ angle: 55.1 degrees

Shower azimuthal angle: 8.2 degrees
Shower zenith angle: 48.0 degrees
Angle to Magnetic field: 60.5 degrees

TALE event data

Event Starting: 7: 0:140076063391744.595078

Energy: 9.345 PeV
Shower max size: 5.639e+06 particles
Shower max depth: 633.149 g/cm^2
Profile Fit χ^2/ndf: 0.9221

Rp Magnitude: 1.190 km
ψ angle: 120.7 degrees

Shower azimuthal angle: -22.7 degrees
Shower zenith angle: 51.9 degrees
Angle to Magnetic field: 51.7 degrees

Figure 1: Qualitative difference in observed Fluorescence events (left) and Cerenkov events (right). Four panels per event show the event display (PMT trigger pattern), the time progression of triggered PMTs, and reconstructed shower profile with relative contributions of FL/CL and scattered CL. (with the fit results displayed in panel 4)

is preferable and simpler to divide this problem into a separate calculation of the best fit shower geometry followed by the calculation of the shower development for the best fit shower energy and x_{max}. Events recorded in monocular mode *and* which have short angular track-lengths do not afford the simple division of the reconstruction task, instead they require a combined geometry/profile reconstruction procedure. Such a procedure, referred to as the Profile Constrained Geometry Fit (PCGF) [7] was developed for the analysis of HiRes-I data, and was successfully used to produce a significant physics result [8].

When applied to the TALE Cerenkov events, it was found that the profile constraint method works extremely well. In particular, it was found that the accuracy of the geometrical reconstruction, section 5, is comparable with what's expected from a hybrid or a stereo observation. Noting the accurate reconstruction of the shower zenith angle, a possibility to extend the PCGF method opens up. By definition, the PCGF precludes obtaining a fit for the shower x_{max}. However, after examining the results from multiple fits with different "trial" x_{max} parameters we noticed that the reconstructed geometry was essentially independent from the assumed trial values. This means that an additional step can be added to the reconstruction procedure in which the PCGF determined geometry can be fixed and a profile/energy fit following standard techniques can be performed.

4. Detector Simulation

A detailed simulation of the detector optics and electronics response to fluorescence and Cerenkov light is employed to calculate the detector acceptance as a function of shower energy, and also to study the resolution and biases of the event reconstruction procedure. As is customary with Air Fluorescence telescope MC's, the shower development curves and the lateral spread of the shower particles are described using parametrization based on fits to output from CORSIKA/AIRES or another shower simulation package. While this methodology remains necessary, we also make use of the IACT package [9], which comes with CORSIKA to do a direct simulation of the Cerenkov light production by showers fully simulated in CORSIKA. The latter option has a few very important features that give us confidence in the measurements we make with TALE. First, No parametrization of the lateral extent or the angular distribution of the produced light needs to be made. Second, and this follows from the first point, namely the inclusion of shower-to-shower fluctuations in the simulations instead of average behavior. Third, the inclusion of the Geomagnetic field deflection of the shower particles, (an effect which is not included in our standard simulation/reconstruction as of yet).

Prior to studying the Cerenkov events, we employed the NKG function to describe the lateral spread of the shower. We found however, that the use of the original NKG function was not consistent with CORSIKA/IACT simulations, and that the more detailed (NKG-like) parametrization provided by [10] gave a better agreement. We therefore updated the shower parametrization accordingly.

5. Reconstruction Performance

We use the CORSIKA/IACT simulations to quantify the reconstruction resolution. This represents a more stringent test than would be had we used parametrized showers; since the same parametrization are used in the reconstruction. Also, this serves as a test of the magnitude of the error introduced by ignoring the geomagnetic field in the reconstruction. An interface to our detector simulation program was developed to allow it to read in the photons arriving at the site as calculated by the external simulation, and was used to connect the two simulation packages. Figure 2 shows the reconstruction results for a shower sample. We find that the reconstruction gives accurate geometry and energy estimation, the x_{max} resolution is acceptable, however we see a bias for iron showers the cause of which is still under investigation.

6. Results and Discussion

The detector aperture/exposure is calculated using a composition assumption based on the H4a model [11]. Simulated showers are reconstructed using the same procedure applied to real data, and event selection is done in the same way as well. A missing energy correction is applied to the reconstructed data and MC showers based on the same composition assumption, with the correction for each primary type and energy is estimated from the CONEX [13] generated showers (cross checked against CORSIKA [14] predictions). CONEX version 4.37 with QGSJet II-4 was used. A separate MC set using QGSJet II-3 (CONEX version 4.36) was produced as well. The measured spectrum using data from the four months of operation is shown in figure 3. This result is based on an analysis using QGSJet II-3. Results from both QGSJet II-3/II-4 based analysis will be shown at the conference. In addition, while a small correction to the H4a model, we also use a composition assumption based on the HiRes-MIA measurement above 10^{17} eV [12].

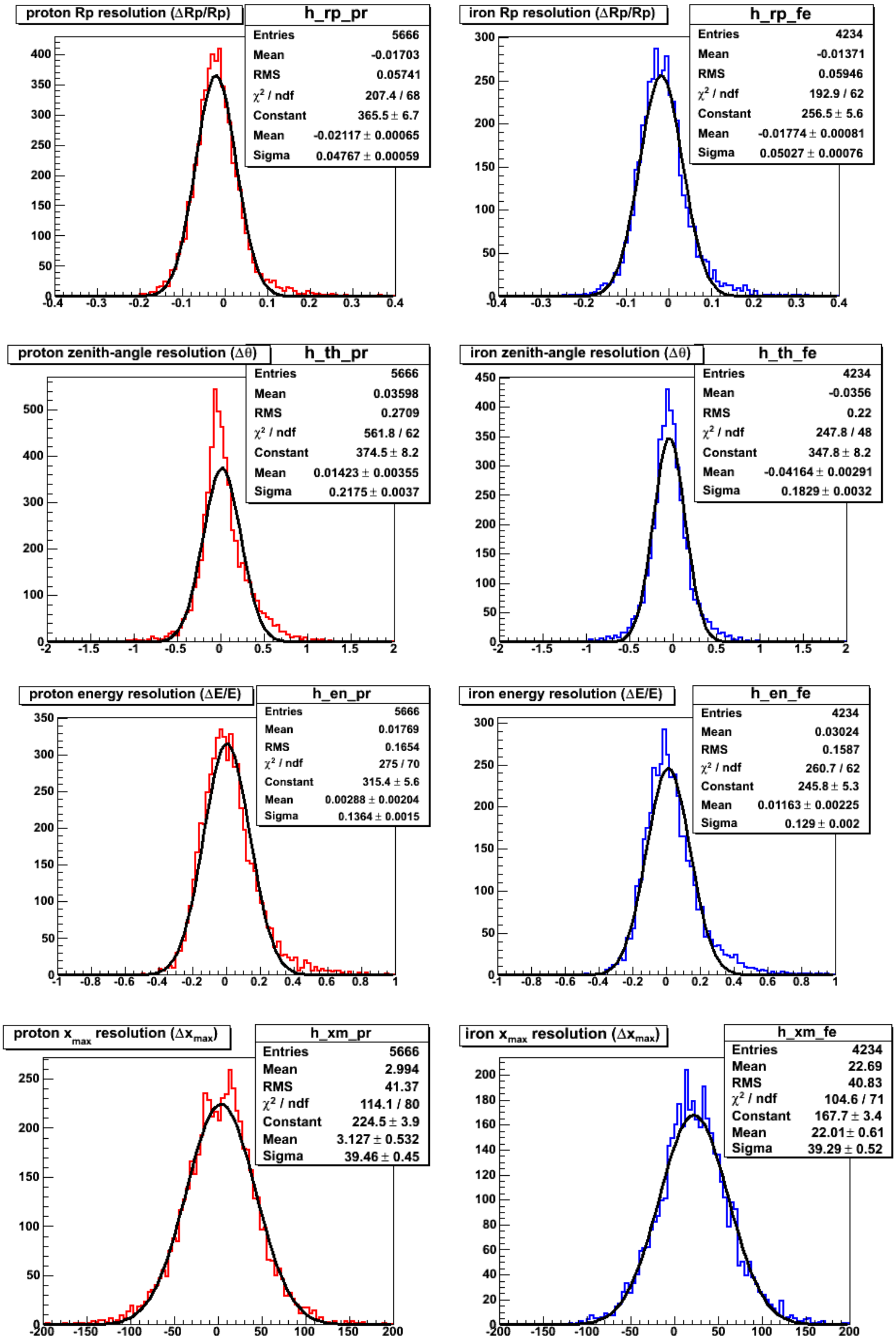


Figure 2: Shower geometry, energy and xmax resolution after all quality cuts are applied. The MC was thrown using the CORSIKA/IACT package, including shower particle deflections by the geomagnetic field. Mono-energetic showers at 2, 3, 6, and 10 PeV contribute to the histograms.

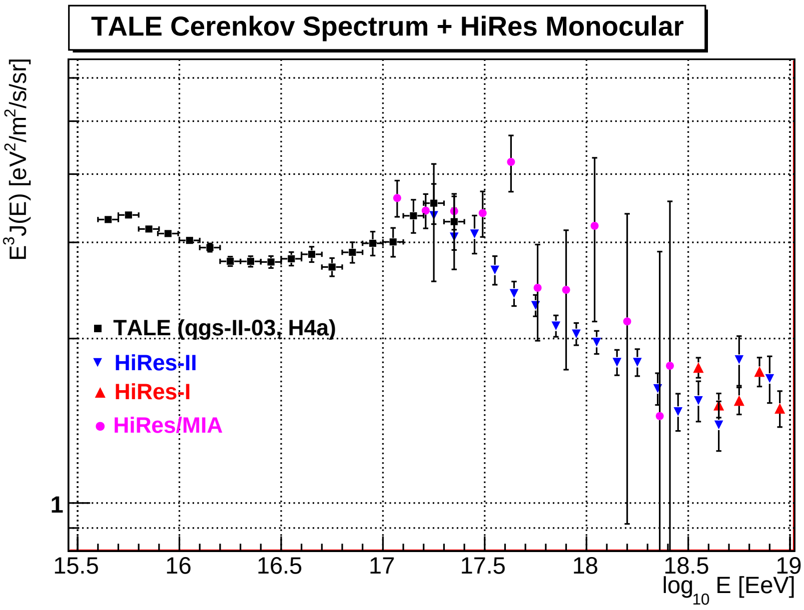


Figure 3: TALE Cerenkov cosmic rays energy spectrum measured with four months of data. The result is based on a QGSJet II-3 hadronic model assumption. A mixed primary composition given by the H4a model was used to calculate the detector aperture.

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