



## Physics of the TALE Experiment

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**Abstract:** The Telescope Array Low Energy Extension (TALE) is a series of detectors to be added to the Telescope Array (TA) experiment to extend its energy coverage to lower energies and increase its aperture at high energies. The combination of TA and TALE will be able to measure the spectrum of ultrahigh energy cosmic rays from  $10^{16.5}$  to  $10^{20.5}$  eV, and study all three features of the spectrum: the second knee, the ankle, and the GZK cutoff. At each energy in this range, TA/TALE will be able to measure, in a model independent way, the average depth of shower maximum - and hence the composition of cosmic rays. TA/TALE will have excellent pointing resolution for anisotropy studies.

The TALE detectors will consist of two fluorescence detectors located 6 km from two TA fluorescence detectors (6 km spacing produces a flat stereo aperture in the region of the ankle), a third fluorescence detector with larger mirrors observing at higher elevation angles (which will observe cosmic rays at lower energies), and an infill array.

## Introduction

The TA and TALE experiments are being built by a collaboration of research groups from Japan, the United States, China, and Korea. The experiment is designed to study the spectrum, composition, and anisotropy of ultrahigh energy cosmic rays, over a wide energy range, with a large aperture, and with good control of systematic uncertainties.

The experiments will be located in Millard County, Utah. They will consist of TA detectors (a large ground array with three fluorescence detectors overlooking it) which will be sensitive to cosmic rays from about  $10^{18.5}$  to  $10^{20.5}$  eV, two TALE fluorescence detectors, and a TALE infill array. The TALE detectors will extend the sensitivity to cosmic rays down to about  $10^{16.5}$  eV. The TALE fluorescence detectors will be located a distance of 6 km from two of the TA fluorescence detectors. This spacing is optimum for studying the ankle of the cosmic ray spectrum with a nearly flat stereo aperture. These detectors will allow cosmic rays above  $10^{17.5}$  eV to be seen. These fluorescence detectors will observe at elevation angles from 3 to 31 degrees above the horizon. Associated with one

of the TALE detector sites will be a “tower detector” which will observe at higher elevations, from 31 to 72 degrees. The tower detector will have larger mirrors and be able to detect cosmic rays down to about  $10^{16.5}$  eV. A ground array of about 100 scintillation counters, of 400 m spacing, will be deployed in front of the tower detector for hybrid coverage at low energies.

Together the TA and TALE detectors will make an experiment that has good sensitivity over four orders of magnitude in energy,  $10^{16.5}$  to  $10^{20.5}$  eV, where the same events will be seen by different detectors and cross normalization of energy scales will be carried out.

Addition of the TALE detectors will enhance the high-energy aperture of TA by about a factor of 2. This aperture will be about  $3000 \text{ km}^2$  ster, and the events collected will be about half surface array events and half fluorescence events (where the fluorescence events are seen in mono, stereo, hybrid, or hybrid stereo).

This suite of detectors will study cosmic rays over a very wide energy range, from well below the second knee through the region above the GZK cutoff [1].

## Physics of TA/TALE

The aim of the TA/TALE experiment is to study ALL the physics in the ultrahigh energy region. Measuring the spectrum over four orders of magnitude will allow the experiment to see the three features in this region: the second knee, the ankle, and the GZK cutoff. No experiment has seen all three features. The HiRes experiment has observed the ankle and the GZK cutoff at  $10^{18.65}$  and  $10^{19.75}$  eV, respectively [2]. However, the energy at which the second knee occurs is very poorly known: it is somewhere in the middle of the  $10^{17}$  eV decade.

The presence of the GZK cutoff shows that at the highest energies most cosmic rays are protons which interact with the cosmic microwave background radiation. The GZK cutoff is observed at just the predicted energy, and is an important calibration point for future experiments' energy scales. The steepness of the fall-off above the GZK threshold energy of  $10^{19.75}$  eV will give information on the local density of extragalactic sources.

The ankle is very important for learning about extragalactic sources of the highest energy cosmic rays. Many physicists now think that the ankle is made by  $e^+e^-$  pair production when photons of the cosmic microwave background radiation strike cosmic ray protons. Studies of the detailed shape of the ankle allow one to determine the average spectral index of these sources, and also their average evolution.

The origin of the second knee is completely unknown. Some theories ascribe its origin to galactic and some to extragalactic effects. Similarly there are theories in each case where the second knee is a source effect and theories where it is a propagation effect. More and better data is badly needed to untangle the situation. Although seemingly making things worse, in the  $10^{17}$  eV decade the galactic-extragalactic transition is also occurring. This may actually be a virtue, because we should be able to determine whether the second knee shows up in the heavy (light) part of the cosmic ray flux, which would make it a galactic (extragalactic) effect.

The TA/TALE experiment is designed to measure the spectrum from well below the second knee (so one has a long lever arm for fitting the spectrum

in the region of the second knee) to well above the GZK cutoff.

Composition studies are very important, and will continue to be so in the future. The HiRes stereo measurement of mean depth of shower maximum,  $\langle X_{max} \rangle$ , and that of the HiRes/MIA hybrid experiment, show an important change in the elongation rate at about  $10^{17.9}$  eV. The elongation rate is 93 g/cm<sup>2</sup>/decade at lower energies and 55 g/cm<sup>2</sup>/decade at higher energies. All models with a constant composition give elongation rates between 50 and 60 g/cm<sup>2</sup>/decade, indicating that the composition is approximately constant above about  $10^{18}$  eV. Below this energy the composition has more heavy elements, but is becoming lighter, hence the larger elongation rate. The heavier composition giving way to the lighter is considered a sign of the transition from galactic cosmic rays to ones from extragalactic sources.

The TA/TALE experiment is designed to measure  $\langle X_{max} \rangle$  in hybrid and stereo modes over its entire four-decade-wide energy range.

The direct observation of  $\langle X_{max} \rangle$  by the fluorescence detectors of TA/TALE is a model-independent measurement. At the lowest energies a mix of heavy elements of galactic origin is expected to be seen. Other experiments will be carrying out model-dependent measurements of the composition in this energy range, e.g., Cascade and Cascade-Grande by measuring the electron and muon component of showers. Checking their observations with TA/TALE data will be very important. In particular, the TA/TALE  $\langle X_{max} \rangle$  measurement can be used as a (model-independent) constraint by the (model-dependent) Cascade and Cascade-Grande experiments.

Through the  $10^{17}$  eV decade the heavy component of the composition steadily disappears, and at higher energies a light composition dominates, with the transition being complete by  $10^{18}$  eV. This observation by the HiRes stereo and HiRes/MIA hybrid experiments is somewhat incomplete because the two experiments' data overlap by only a little bit. Observing this transition all in one experiment will be very important.

HiRes has seen correlations between arrival directions of events (seen in stereo, over a wide energy range) with BL Lac sources [3]. There are

also events that point back to sources seen in TeV gamma ray experiments. If true, these correlations would be startling since these are extragalactic sources and one would expect galactic magnetic fields to wash out these correlations at the 2 degree level. But they are seen at the level of the 0.5 degree angular resolution of HiRes stereo events. It may be that there are pointing directions with smaller magnetic fields - or that some cosmic rays are neutral. The BL Lac correlations are also a northern hemisphere effect since most identified BL Lac sources are in the northern hemisphere.

TA/TALE will have excellent angular resolution. The stereo aperture will be larger than that of HiRes, and about 85% of stereo events will also be seen in hybrid mode, improving the angular resolution from 0.5 to about 0.1 degrees. If the BL Lac correlations are confirmed then TA/TALE, which will collect the largest number of hybrid stereo events in the world, will be just the experiment to study anisotropy of this kind.

## TALE Detectors

The TA detectors will be completely deployed in 2007. The ground array and two of the fluorescence detectors have been built in Japan, and are mostly deployed at this time. Fourteen HiRes mirrors have been moved to the Millard County site, to become the third TA fluorescence detector overlooking the ground array.

The remaining 50 HiRes mirrors will be redeployed to two locations near the other TA fluorescence detectors to form stereo pairs with the TA detectors. The spacing for stereo will be about 6 km, which is optimized for studies of the ankle region. These detectors will be observing partly in directions away from the TA detectors, and will increase the aperture of TA at high energies by about a factor of 2. The energy range covered by these detectors will be from about  $10^{17.5}$  to  $10^{20.5}$  eV.

We plan to build a tower detector to extend the coverage to lower energies. This will consist of 15 mirrors that will cover elevation angles from 31 to 72 degrees, and cover about 90 degrees in azimuth. Looking higher in elevation with HiRes mirrors would lower the minimum energy observed to about  $10^{17}$  eV. The tower mirrors will be about

$12.6 \text{ m}^2$  in area, three times larger than HiRes mirrors, which will lower the minimum energy to about  $10^{16.5}$  eV.

We plan to deploy an infill array of about 110 scintillation counters in front of the tower detector. With about 400 m separation (1/3 of the separation of the TA scintillation counters) they will have good efficiency at  $10^{16.5}$  eV. The infill array will be used for hybrid observation with the tower detector, and will improve its energy resolution, its  $X_{max}$  resolution, and its pointing resolution. The infill array will reach up in energy to about  $10^{18}$  eV.

Events between  $10^{16.5}$  and  $10^{18}$  eV will be collected by the tower detector, infill array, and TA and TALE fluorescence detectors. Many will be seen in stereo with one of the TA fluorescence detectors and in hybrid with the main TA ground array. Cross calibration of all of these detectors will be performed using these events. At higher energies, events will be seen monocularly, in stereo, in hybrid, and in hybrid and stereo, between the TA and TALE fluorescence detectors and the TA ground array. Thus cross calibration will be possible throughout the entire energy range of the experiment.

## Conclusions

The physics of ultrahigh energy cosmic rays in the energy range above  $10^{16.5}$  eV is very rich. Three spectral features are present, in contrast to the almost featureless spectrum at lower energies. In addition the galactic - extragalactic transition occurs here.

The composition of the primaries at the lower end of this energy range should be heavy and of galactic origin, then make a transition to become light and of extragalactic origin at higher energies. This will occur just where the TALE detectors are at their optimum efficiency. Indications are that the highest energy events continue this light composition.

By making composition-tagged measurements of the spectrum we will be able to study both galactic and extragalactic sources independently. We will determine the maximum energy of galactic sources, and how their composition varies. For ex-

tragalactic sources we will measure the spectral index at the source, the evolution of the sources, and the density of nearby sources.

The TA/TALE detector will be very powerful for anisotropy studies. The experiment has a large aperture and excellent pointing accuracy at all energies. The large fraction of events seen in stereo and hybrid modes simultaneously, with pointing accuracies about 0.1 degrees, is an unprecedented advantage of the TA/TALE design. The northern hemisphere sky is a very rich field for anisotropy studies. The possible observation of the first point sources by AGASA and HiRes will be pursued by TA/TALE, and the correlation with BL Lac sources will be investigated.

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