

The TA and TALE Experiments

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Abstract. The TA/TALE experiment is under construction, and is being deployed in Millard County, Utah. It will consist of a suite of detectors covering four orders of magnitude in energy, from $10^{16.5}$ to $10^{20.5}$ eV, and will observe cosmic ray showers with fluorescence detectors and arrays of scintillation counters. Events will be seen by multiple detectors and cross calibration of detectors' energy scales will be possible. TA/TALE will observe all three features of the spectrum of ultrahigh energy cosmic rays, observe the galactic/extragalactic transition, study the cosmology of cosmic ray sources, and perform anisotropy studies with unprecedented accuracy.

1. The Physics of TA/TALE

The motivation of the TA/TALE experiment is to study ALL the physics in the ultrahigh energy cosmic ray regime. The Telescope Array (TA) is an experiment funded by the Japanese government which is being constructed and deployed in Millard County, Utah. TALE is a proposal for a low energy extension to TA from American and Chinese groups. Together they will make an experiment that has good sensitivity over four orders of magnitude in energy, from $10^{16.5}$ eV to $10^{20.5}$ eV, where the same events will be seen by different detectors and cross normalization of energy scales will be possible.

1.1. Spectrum

The spectrum of cosmic rays in this energy range is very rich in features, in direct opposition of what is seen at lower energies. The HiRes experiment has observed a feature known as the ankle at 3×10^{18} eV, and a high-energy suppression of the flux at an energy consistent with the GZK cutoff (see the presentation by C. Jui in these proceedings). Several experiments have seen the second knee at about 4×10^{17} eV. The HiRes monocular spectra are shown in Figure ??.

An interpretation of these features that is gaining in acceptance is that the ankle is excavated by e^+e^- pair production in collisions of cosmic ray protons with photons of the cosmic microwave background radiation (CMBR), similar to the pion-production mechanism of the GZK cutoff (see the presentations by V. Berezhinsky and D. Bergman in these proceedings). The second knee is a complicated area in these models. The

galactic cosmic rays are dying away, with the pileup of the e^+e^- pair production process occurring at the same energies producing the second knee.

But no single experiment has observed all three spectral features, and even the relative energies of the features are not known. Because of the unknown energy scales and systematic uncertainties between experiments it is impossible to understand in detail the ultrahigh energy cosmic ray regime. An experiment sensitive to a very wide range of energies is badly needed to remedy this situation.

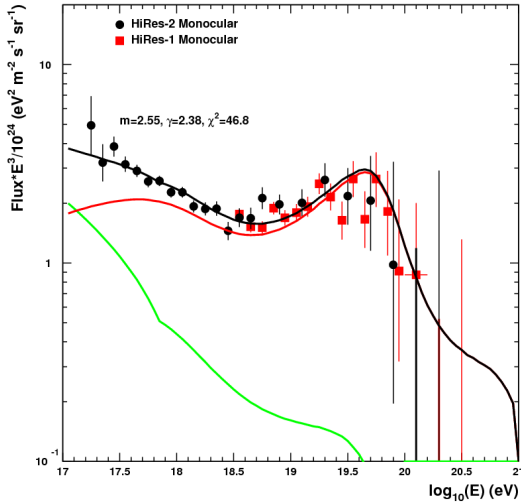


Figure 1. The HiRes Monocular Spectra. Results from the HiRes-I and HiRes-II detectors are shown, plus a fit to a model including extragalactic sources (red), galactic sources (green) and the total (black).

1.2. Composition

The composition of cosmic rays in this energy range is changing. Cascade results from energies below 10^{17} eV show a change through the energy range of the knee from mixed to a heavy composition. This is widely interpreted as the signature of the endpoint of galactic sources' ability to accelerate cosmic rays (or of the galactic magnetic field's ability to contain them). The HiRes/MIA and HiRes stereo results, at a higher energy, show a change back to light composition. Figure ?? shows the HiRes/MIA and HiRes stereo results. The elongation rate measured by HiRes/MIA is $93 \text{ g/cm}^2/\text{decade}$ below about 10^{18} eV. Above this energy the elongation flattens out to $53 \text{ g/cm}^2/\text{decade}$, similar to the slopes of both QGSjet and Sibyll predictions for a constant composition. An interpretation of these data is that the cosmic rays at the end of the galactic spectrum, which are likely to be of heavy composition, are giving way to extragalactic cosmic rays which are likely to be of light composition, with the end of the galactic cosmic ray spectrum occurring at about 10^{18} eV.

Again we are in the same situation as the spectrum case, where no single experiment has seen the whole picture of the composition change. The Cascade Grande experiment (see the submission by A. Haungs in these proceedings) seeks to remedy this situation coming up from lower energies. But they do not make a direct observation of shower max as a fluorescence experiment would. What is needed is a fluorescence experiment

with a wide energy range, with good statistics throughout that range, to measure the mean depth of shower maximum.

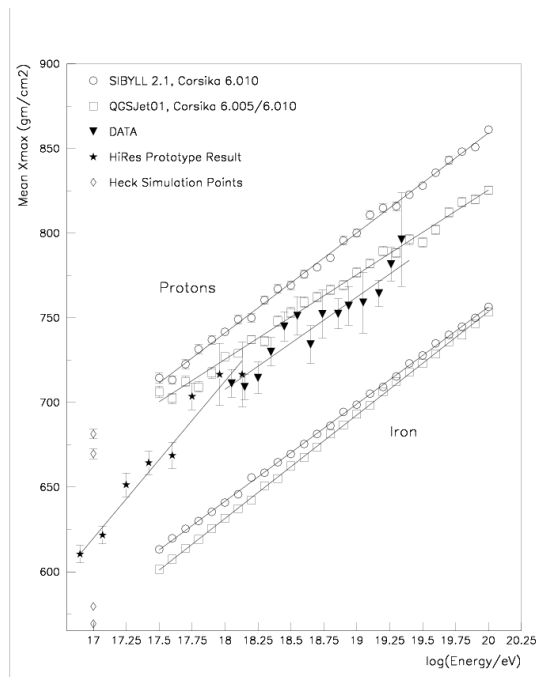


Figure 2. Mean Depth of Shower Maximum, X_{max} , measured by the HiRes/MIA and HiRes Stereo experiments. The data, plus predictions of Corsika and QGSjet or Sibyll are shown.

1.3. Cosmology

Figure ?? shows a decomposition of the extragalactic spectrum from D. Bergman's energy-loss model for sources grouped in shells of redshift, z . This figure shows clearly the way the GZK cutoff develops, plus the way the ankle and pileup in the second knee region occur. Amazingly it also shows that extragalactic events fractionate in energy and redshift. For example, at $z=1$, where the energy at the peak is about $10^{17.8}$ eV, that shell contributes most to the flux, but the contribution of the shell at $z=0.1$ is lower by an order of magnitude. The correlation between energy and redshift is not one-to-one, but it is significant.

This correlation can be used to determine the evolution of extragalactic sources of cosmic rays. Fits to extragalactic sources always include a factor of $(1+z)^m$, where m is called the evolution parameter, to take the overall evolution of sources into account. To go further than this, using the energy/redshift correlation, one could fit the data to a model with varying redshift evolution. The current state of the world's data is not good enough for this.

A hint of what might happen exists in the HiRes spectra shown in Figure ?. Below an energy of about $10^{17.6}$ eV other experiments have shown that the spectrum is proportional to E^{-3} ; i.e., look like a horizontal line on this plot, but the model shows a falling spectrum; i.e., the model predicts too many extragalactic protons below this energy.

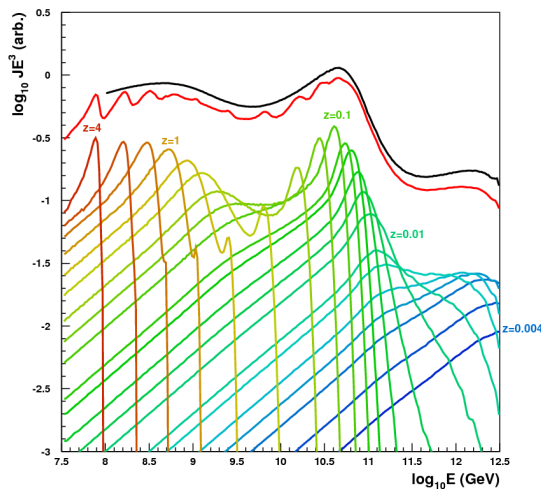


Figure 3. Contributions from sources in shells in redshift to Bergman's energy loss model.

The evolution of QSO's and AGN's has been measured and both types of source show a break in their luminosity densities at about $z=1.6$. If such a break is introduced into D. Bergman's extragalactic source model, then the model yields the correct energy dependence below the second knee.

The lesson to be learned from this study is that an experiment is needed that can go to an order of magnitude lower energy than HiRes, i.e., down to $10^{16.5}$ eV, and cover the entire ultrahigh energy region with good aperture. To do cosmology the energy range from $10^{16.5}$ eV to 10^{20} eV must be covered with good sensitivity.

1.4. Anisotropy

There are several hints of anisotropy in the northern hemisphere that have been seen by the AGASA and HiRes experiments. AGASA has seen clusters of events, one triplet and five doublets, but in only one case has HiRes any independent evidence for their assignment as cosmic ray sources. Interestingly, that case is the triplet, where a HiRes event observed in stereo, with much better angular resolution than AGASA, is in the center of the triplet. Unfortunately the chance probability for this "quartet" is hard to calculate.

The Akeno and AGASA experiments (see the submission by N. Sakaki in this conference proceedings) have seen a hint of extended structure along the Cygnus arm of the Milky Way in events close to 1×10^{18} eV, which is very interesting for the subject of this conference. This excess will be tested by HiRes soon.

The HiRes stereo events show a correlation with BL Lac sources above 10^{19} eV which is very interesting also. Surprisingly the correlation persists for events below this energy as well. This could be a signal of something unexpected: neutral particles that interact with hadronic cross sections. BL Lacs are sufficiently far away that gamma rays and neutrons they emit cannot reach the earth. Since the Milky Way galaxy obscures much of the southern sky, many fewer BL Lacs have been identified there. So this is

inherently a northern hemisphere observation.

Again we see that an experiment with a large aperture and a wide energy range is needed to study the properties of ultrahigh energy cosmic rays.

2. The TA/TALE Experiment

The TA and TALE experiments will consist of a ground array, four fluorescence detectors, and an infill ground array. Figure ?? shows the layout of the TA and TALE detectors. The ground array will have 576 scintillation counters, each 3 m² in area separated by 1.2 km. Three fluorescence detectors will overlook the ground array, and consist of mirrors sensitive to elevations from 3 to 31 degrees, and will provide excellent aperture above 10^{17.5} eV.

An additional fluorescence detector will look from 3 to 71 degrees, have an infill array in front of it, and be located 6 km from one of the TA fluorescence detectors. This detector will provide additional high energy aperture. Importantly, it will have an almost flat stereo aperture in the energy region of the ankle. This will be very important in light of the important physics occurring in this energy range. The mirrors looking at higher elevations, called a tower detector, will have three times larger area, and will observe down to a threshold energy of 10^{16.5} eV. The infill array will be in the aperture of the tower detector and will cover an energy range from 10^{16.5} eV to 10¹⁸ eV.

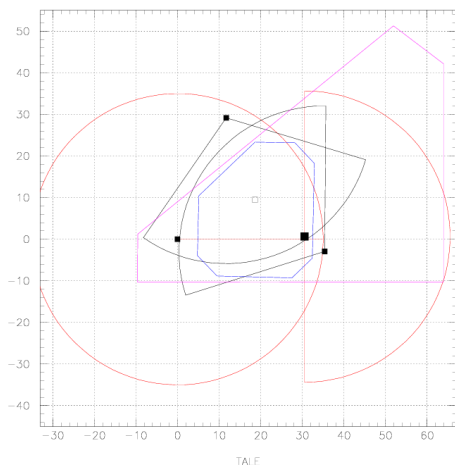


Figure 4. Layout of the TA/TALE Experiment. The surface array is shown in blue, the Japanese TA fluorescence detectors' high energy apertures are shown in black, the U.S. fluorescence detectors high energy apertures are shown in red, and the outline of the proposed Northern Auger surface detector is shown in magenta. The scale is in km.

The result will be the capability of making very accurate measurements of cosmic rays' spectrum, Xmax, and pointing directions over four decades in energy, from 10^{16.5} to 10^{20.5} eV. The apertures of the TA/TALE detectors are shown in Figure ??, and the number of events seen per year in Figure ??.

An interesting feature shown in Figures ?? and ?? is that the TA ground array will have better statistical uncertainty in the energy range 10^{17.5} – 10^{18.5} eV than the fluorescence detectors will. The situation is reversed when one considers systematic

uncertainties. A ground array without a well-designed infill array suffers serious biases in the energy range where its efficiency is below the plateau. This does not happen with a fluorescence detector. What this indicates is that in this energy range the best spectrum measurements will be made using mono, stereo, and hybrid events, while the best statistical power for anisotropy measurements will come from the ground array. Only the combination of these detectors will make this multiple-optimization possible.

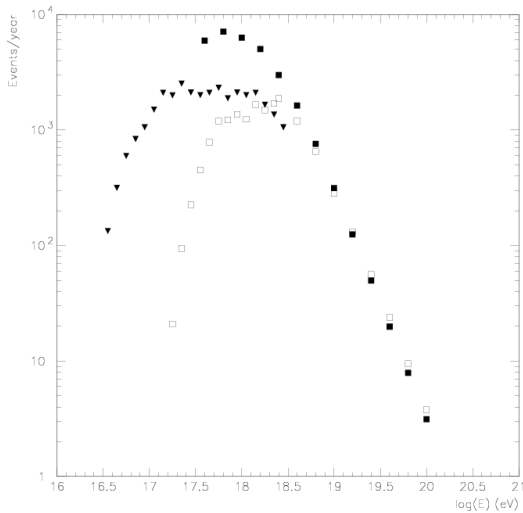
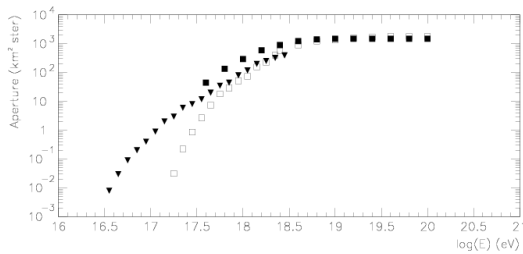
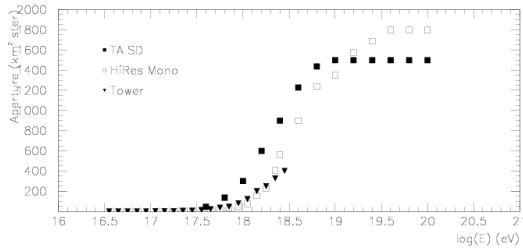


Figure 5. Aperture of the TA/TALE Experiment. The surface array, fluorescence detector, and tower detector apertures are shown as a function of energy.

Figure 6. Events collected per year by the TA/TALE Experiment. The surface array, fluorescence detector, and tower detector statistics are shown.

3. TA/TALE Detector Construction and Deployment

The first Japanese fluorescence building has been constructed in Millard County, Utah, and the first fluorescence telescope will be deployed this fall. The locations of the TA

ground array detectors have been determined and staked, and the first 18 have been deployed. Further deployment and construction will proceed until TA is complete about the beginning of 2007.

4. TALE Prototypes

We are building two prototype detectors for TALE. The first consists of two mirrors in moveable housings that will be placed at the HiRes-I site, pointed toward the HiRes-II detector, and will observe between 18 and 31 degrees in elevation. The addition of these mirrors to the HiRes detectors will give us two detectors of two rings each (for an azimuthal angle coverage of about 30 degrees), like the 6 km stereo detector, and provide valuable test data for the 6 km stereo detector. These prototypes will be deployed in the summer of 2005.

We have also begun building a prototype tower detector. Its mirror will collect three times more light than a HiRes mirror. We plan to put this mirror at the HiRes-I site, in ring 4 (centered on an elevation angle of 52 degrees), also pointing at HiRes-II. The aim of this prototype study is to see just how low in energy we can go. Our calculations of noise from the night sky, plus bright stars, indicate that we will see events down to $10^{16.5}$ eV, but it is important to actually measure this. This detector should be constructed and deployed in summer, 2005.

5. Summary

The HiRes experiment clearly observes the ankle of the cosmic ray spectrum. We also have good evidence for a high-energy suppression of the cosmic ray flux at an energy consistent with the GZK suppression.

Our measurement of the composition of cosmic rays consists of making a direct observation of the slant depth of shower maximum, X_{\max} . It indicates the composition is light above 10^{18} eV. Taken with the measurement made by the HiRes prototype - MIA hybrid experiment, it shows that the galactic - extragalactic transition occurs in the 10^{17} eV decade, with an approximately 50/50 mixture occurring just above 10^{17} eV. This is a surprising result because how galactic sources can reach this high an energy is unknown. Paradoxically, this also upsets many researchers' idea that the ankle marks the transition. Since this measurement depends on two different experiments' results - even though the apparatus and personnel were the same in the two experiments - confirmation is needed for this important result. The best experiment to test this result would be one, like TA/TALE, with a wide energy coverage.

We have used our spectrum and composition results to construct a model of galactic and extragalactic cosmic rays, plus their propagation through the flux of CMBR photons. This model gives the first view of the evolution of the sources of cosmic rays through the $(1+z)^m$ evolution factor in the density of sources. Our data indicate that $m = 2.6$, similar to that of QSO's and to the star formation rate. A remarkable feature of

extragalactic cosmic rays is that they fractionate in energy and source redshift; i.e., cosmic ray protons of a given energy come predominantly from a certain region in redshift. We have a hint that more features of extragalactic cosmic ray source evolution should be measurable by an experiment with a very wide energy coverage like TA/TALE.

HiRes anisotropy studies have not confirmed the existence of the AGASA clusters, with perhaps one exception: the AGASA triplet has a HiRes stereo event on top of it. The chance probability of such an overlap is not definitive. More data is needed - in the northern hemisphere - by TA/TALE.

A surprising correlation between BL Lac's and the pointing directions of HiRes stereo events has been observed. The stereo events have about 0.6 degree angular resolution, so it is unlikely that charged particles could exhibit this correlation because of bending by extragalactic magnetic fields. Since these BL Lac's are quite distant it is also very unlikely that the events are gamma rays or neutrons. This startling result badly needs confirmation by future HiRes and TA/TALE data. Because of the obscuration by the Milky Way galaxy very few BL Lac's have been identified in the southern hemisphere, so this question must be answered by a northern hemisphere experiment.

The perfect experiment to address the physics questions listed above is TA/TALE. This detector will have a very large high-energy aperture, and cover a very wide energy range. Cross normalization between the detectors will minimize systematic uncertainties. The choice of scintillator for the surface detector and infill array makes energy determination relatively model-independent.