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New Results from the HiRes Experiment

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The High Resolution Fly's Eye (HiRes) collaboration has measured the spectrum of ultrahigh energy cosmic rays in the energy range from $10^{17.2}$ to $10^{20.2}$ eV. Two spectral features appear. We clearly see one, called the "ankle", at about $10^{18.5}$ eV. We also have evidence for a high-energy suppression of the cosmic ray flux at an energy of about $10^{19.8}$ eV, where the GZK suppression is expected to occur. We have also measured the composition of cosmic rays between $10^{18.0}$ and $10^{19.4}$ eV using the X_{max} method. We have searched for anisotropy in the arrival directions of ultra high energy cosmic rays. Results are presented on these topics.

1. Introduction

The spectrum of cosmic rays at energies below 10^{17} eV is nearly featureless, with only the "knee" appearing at about 3×10^{15} eV. This feature has been studied extensively to learn mostly about galactic cosmic rays and their sources.

In the ultrahigh energy regime this situation changes considerably. There are two spectral features observed, called the "second knee" at about $10^{17.6}$ eV, and the "ankle" at about $10^{18.5}$ eV. In addition the "GZK suppression" is expected to be seen at about $10^{19.8}$ eV. The second knee is widely regarded as being caused by the transition from galactic to extragalactic cosmic ray sources, and the ankle and GZK suppression are thought to be caused by energy loss in interactions between cosmic rays and photons of the cosmic microwave background radiation (CMBR).

The composition of cosmic rays above the knee has been measured to be heavy; i.e., mostly iron [1]. The HiRes Prototype / MIA hybrid experiment observed the composition to be changing from heavy to light in the energy range $10^{16.9}$ to $10^{18.2}$ eV [2].

The AGASA experiment has found six clusters of events in their data above 4×10^{19} eV, with an angular resolution of 2.5 degrees [3]. One interpretation of this result is that these clusters represent the brig$10^{17.2}$htest sources in the northern hemisphere sky. If this is correct then we should see them also.

In this submission to the Proceedings of the Cosmic Ray International Symposium of 2004, I would like to present the latest spectrum and composition measurements by the HiRes Collaboration, and describe one search we have made for anisotropy in cosmic ray arrival directions.

The HiRes collaboration consists of research groups from University of Adelaide, Columbia University, Los Alamos National Laboratory, University of Montana, University of New Mexico, Rutgers University, University of Tokyo, and University of Utah. The HiRes detectors measure fluorescence light generated by extensive air showers produced by the interactions of cosmic rays in the atmosphere. About five photons are emitted by nitrogen molecules per charged particle per meter of path length in the wavelength range from 300 to 400 nm. We collect data at night when the moon is down, which gives us about a 10% duty factor.

We have two detectors located atop desert mountains in west central Utah. Our detectors consist of mirrors that collect fluorescence light and focus it on arrays of 256 hexagonal photomultiplier tubes (PMT's). Each PMT subtends

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about one degree of sky. We collect the pulse height and time information from the tubes. The HiRes-I detector consists of 21 mirrors arranged to look from 3 to 17 degrees in elevation and almost 360 degrees in azimuth. The HiRes-II detector, located 12.6 km SW of HiRes-I, consists of 42 mirrors, which cover 3 to 31 degrees in elevation and almost 360 degrees in azimuth.

The absolute calibration of our detector is done with a xenon flash lamp, stable to 2%, which we carry to each mirror and use to illuminate the cluster of PMT's. The xenon flash lamp is calibrated to NIST-tracable photodiodes. Absolute calibrations occur at monthly intervals, and we use a YAG laser system to monitor nightly gains.

The atmosphere is our calorimeter, but it also scatters fluorescence light coming from cosmic ray showers to our detectors. The molecular component of the atmosphere causes Raleigh scattering which is well understood. The aerosol component varies and its scattering properties must be measured while we are collecting data. To monitor the aerosol scattering we have two lasers, one located at each of our detector sites, that fire a pattern of shots covering the aperture of our experiment. The scattered laser light is detected and analyzed to determine the vertical aerosol optical depth, the horizontal aerosol scattering length, and the angular distribution of the scattering cross section.

The result is that we have very clear, stable skies. 2/3 of nights are cloudless; the aerosol levels are less than the standard desert atmosphere, and they vary slowly. Most nights have constant aerosol levels, and often the aerosol levels are constant over several nights. HiRes has an excellent site for a fluorescence experiment.

We use a third laser to test the far reaches of our aperture. This laser is located 35 km from the HiRes-II detector and fires vertically at a brightness equivalent to a cosmic ray shower of energy 3×10^{19} eV. The HiRes-II detector sees 100% of these laser shots when the vertical aerosol optical depth is 0.12 or less, which is true for 99% of cloudless nights. 35 km is about the limit our detectors can see. This limit is set not by the brightness of cosmic ray showers, but by our pixel size. Showers farther away become too short to reconstruct accurately.

2. Data Analysis

Figure 1 shows analysis plots for an event. The upper left shows the hit tubes in three mirrors that triggered; the upper right plot shows all the tubes together in an elevation vs. azimuthal angle plot. Fitting the tubes in the shower defines the "shower-detector plane". The lower left shows the time tubes were hit vs their angular position in the shower-detector plane. From the curvature of the time vs. angle plot the geometry of the event can be determined. The angle in the shower-detector plane is measured to about 5 degree accuracy for HiRes-II events.

Then the pulse height is brought in: the lower right plot shows the number of charged particles in the shower as a function of slant depth (in g/cm^2) traversed. The curve is a fit to the Gaisser-Hillas function [6]. The energy of the event is found from the area under the Gaisser-Hillas function, with corrections for missing energy from neutrinos, etc.

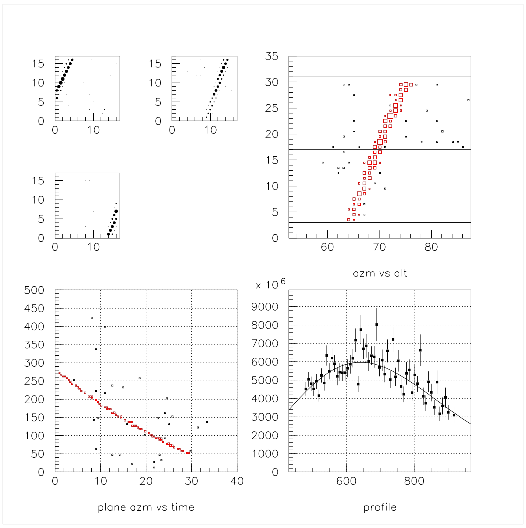

Figure 1. Mirror Views and Analysis Figures for an Event.

For events seen by the HiRes-I detector the track length and time resolution are insufficient for many events to break the fitting correlations between the distance to the shower and the angle in the shower-detector plane, so the tube pulse height is brought in for the geometry determination. A Profile-Constrained Fit (PCF) is performed using the time vs angle information and the χ^2 of the fit to the Gaisser-Hillas function to determine the geometry of the shower. This fit results in a resolution in in-plane angle of seven degrees. In checking events' energies where the geometry is found from the PCF method to Monte Carlo events where the energy is known, excellent agreement results. In performing a similar check with stereo events, where the geometry is known, again events' energies agree with the PCF.

3. Aperture Calculation

We calculate the aperture of our experiment using two Monte Carlo simulation programs. In the first step we use CORSIKA and QGSjet to generate two libraries of cosmic ray showers, one for proton primaries and one for iron. Since a fluorescence experiment is sensitive only to the center of showers, not the tails, this is a simple task and can be accomplished using medium values of the Corsika thinning parameter.

In the second step we use events from the shower libraries and simulate the detector's response to them. The inputs to this Monte Carlo program are the spectrum measured by the Fly's Eye Stereo experiment [4], the composition measurement made by the HiRes/MIA hybrid experiment [2], and the HiRes stereo composition measurement [5]. A complete simulation of the optical path, trigger, and detector electronics is made. A data base of experimental conditions (trigger logic and thresholds, number of live mirrors, etc.) is used to exactly simulate the conditions of the data. The Monte Carlo events are written out in the same format as the data and are analyzed using the same programs.

The way to tell if the aperture is being calculated properly is to compare the distribution of Monte Carlo events against that of the data. One plots many different kinematic and geometrical variables, and if the Monte Carlo plots are identical to those of the data then one has confidence that the aperture is correct. We have done this and, indeed, our data/Monte Carlo comparisons are excellent. As an example, Figure 2 shows a plot from the HiRes-II data of the number of photoelectrons in tracks divided by the track length. This plot shows that the same amount of light is being detected from showers in our Monte Carlo simulation as is in the data.

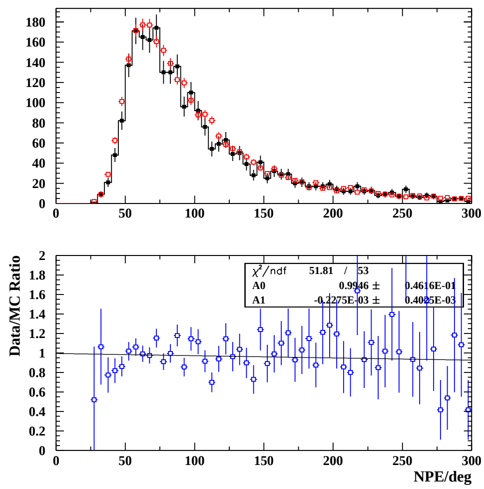

Figure 2. Comparison of Monte Carlo simulation to the data. The number of photoelectrons per degree of track is shown. The upper plot shows the data as a histogram and the Monte Carlo, normalized to the same area as the data as red points. The lower plot shows the ratio of data to Monte Carlo, with a linear fit superimposed.

4. Monocular Spectrum Measurement

We calculate the spectrum, $J(E)$, from the following equation.

$$J(E) = \frac{D(E)}{A(E)} \frac{T(E)}{S\Omega t dE}$$

where $D(E), A(E)$, and $T(E)$ are histograms of the data, Monte Carlo accepted, and Monte Carlo thrown events. S is the area, Ω the solid angle, t the live time, and dE the bin width. Since we simulate the resolution of the experiment correctly in the Monte Carlo, the same fluctuations occur in $D(E)$ as in $A(E)$, and in using their ratio we make a first order correction for resolution. We can calculate biases in our spectrum measurement and they are smaller than our statistical uncertainties.

The spectrum of the HiRes-I and HiRes-II detectors, observing in monocular mode are shown in Figure 3, multiplied by E^3 for clarity. In this figure there is a dip at about $10^{18.5}$ eV, called the "ankle" of the spectrum, and a marked deficit of events above $10^{19.8}$ eV. This energy is the threshold for pion production in interactions between cosmic ray protons and the average photon of the CMBR; i.e., the deficit occurs at the energy of the GZK cutoff. The previous speaker, Prof. M. Teshima, described the results of the AGASA experiment, which seem to indicate that the spectrum continues above the ankle at a constant power law.

To test whether our data are consistent with this interpretation of the Agasa result, we fit our data, from the ankle to the pion production threshold, to a power law, then continue the power law to higher energies. This tests the hypothesis that the GZK cutoff is absent, as the AGASA data seem to show. The power law index is 2.8 ± 0.1. If the cutoff were absent, using our sensitivity calculated as described above, we expect to see 29.0 events above $10^{19.8}$ eV, but we see 11. The Poisson probability of seeing 11 or fewer events, with a mean of 29.0, is 1×10^{-4}. So the break in our data is statistically significant. It is worth emphasizing that our experiment has good sensitivity but the events are not present.

Two additional talks at this conference, by Douglas Bergman and Andreas Zech, describe in more detail our monocular spectrum measurements.

5. Composition Measurement

We have measured the composition of UHE cosmic rays using our stereo data and the X_{max} method. The result is shown in Figure 4. In this figure results of the HiRes Prototype - MIA hybrid experiment are also shown. The two experiments agree in the energy range where both have good sensitivity.

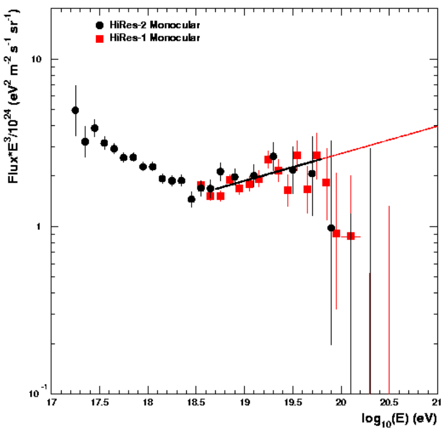

Figure 3. The spectrum of UHE cosmic rays measured by the HiRes-I and HiRes-II detectors observing in monocular mode. The spectrum has been multiplied by E^3 for clarity. Also shown is a power law fit performed from the ankle to the pion-production threshold (in black), and extended to higher energies (in red).

The elongation rate measured by the HiRes/MIA experiment was 93 g/cm^2 per decade, where for the HiRes Stereo data it is 55 g/cm^2 per decade. The break occurs close to $10^{18.0}$ eV.

Also shown in Figure 4 are predictions from the shower simulation program Corsika, using hadronic generators QGSjet and Sibyll. Those predictions, and that of all modern shower generating programs, are for an elongation rate between 50 and 60 g/cm^2 per decade for protons and for iron. The exact value of X_{max} varies by about 25 g/cm^2 among simulation programs.

The HiRes/MIA and HiRes Stereo results are consistent with a changing composition at lower energies (with the light components increasing) becoming a constant composition above $10^{18.0}$

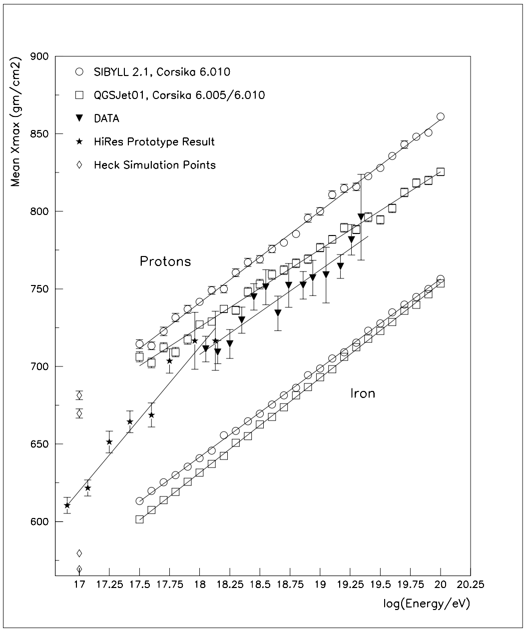

Figure 4. The mean X_{max} of UHE cosmic rays as a function of energy. The triangles are the HiRes stereo data and the stars are the result of the HiRes Prototype - MIA hybrid experiment. Also shown are predictions of the Corsika/QGSjet and Corsika/Sibyll shower programs.

eV, with light components dominating the mixture. This data is consistent with an observation of the transition from galactic to extragalactic sources of cosmic rays.

The HiRes stereo composition measurement was made using our full database of atmospheric conditions: hourly measurements of aerosols, and seasonally adjusted density profiles for the molecular component. We have examined radiosonde (balloon) measurements of atmospheric density made from the Salt Lake City and Denver airports and they show fluctuations of about 5% from the seasonal averages, the effect of which are smaller than our X_{max} resolution.

In the analysis of the HiRes/MIA hybrid experiment, a constant aerosol density with VAOD=0.05 was used. This is slightly larger than our current understanding of aerosols. But the geometry of the events was tightly constrained by the requirement of their showers striking the MIA muon detectors: the distance was always between 3 and 4.5 km from the HiRes prototype detector. At these short distances the aerosol correction is small. Including in the analysis the variation of aerosols might improve the resolution in X_{max}, but it would not move the curve or change its slope.

6. Searching for Overlaps between HiRes Events and the AGASA Clusters

We have searched for the overlap of events in the HiRes-I monocular data set and the AGASA clusters. We are testing the hypothesis that the AGASA clusters represent the six brightest cosmic ray sources in the northern sky. If this hypothesis is correct then we should see events coming from these directions. When we use the AGASA search criteria, that the events have energy greater than 4×10^{19} eV and have a radius of 2.5 degrees on the sky, we have 27 events. We define a HiRes overlap event as one whose three sigma error ellipse overlaps with the AGASA error circle. Two events overlap with the AGASA clusters, where by chance we would observe about 4. 91% of simulated isotropic HiRes data sets show this level of overlaps or more. This analysis does not verify the AGASA clusters.

The HiRes exposure is higher than the AGASA exposure in this energy range, but AGASA has more events. This contradiction could be resolved if there were an energy scale difference between the two experiments of about 30%. If this were the case then we should lower the minimum energy in our search by about this amount. In fact, if we lower the minimum energy to 2.65×10^{19} eV (68% of the AGASA minimum energy) then the density of events in the vicinity of the AGASA clusters is the same in our two data sets. Figure 5 shows the locations on the sky of the HiRes events and the AGASA clusters.

With this lower minimum energy we see nine overlaps where the mean from simulated isotropic data sets is about 8. 45% of simulated data sets have nine or more overlaps with the AGASA clus-

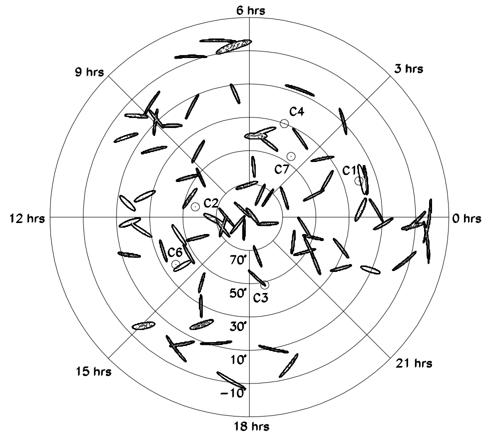

Figure 5. Arrival directions of HiRes-I monocular events above 2.65×10^{19} eV, plotted in polar projection, equatorial coordinates. One sigma error ellipses are shown for each event. AGASA clusters are shown as points with 2.5 degree radius circles labled C1 through C7 (C5 excluded).

ters. Again our data does not indicate that the AGASA clusters represent sources of cosmic rays.

To test the model further we assume that the six sources have constant intensity and a statistical fluctuation (perhaps up for AGASA and down for HiRes) can explain the difference. The joint probability of the AGASA and HiRes observations is 0.004. Again our data does not indicate that the AGASA clusters represent sources of cosmic rays.

7. Summary

We have measured the flux of UHE cosmic rays between $10^{17.2}$ and $10^{20.2}$ eV, observing with the two HiRes detectors in monocular mode. The two spectra agree very well with each other.

In the HiRes monocular spectra we see two features: the ankle at about $10^{18.6}$ eV, and a suppression of the spectrum at about $10^{19.8}$ eV, which is the location of the threshold for pion production in interactions between cosmic ray protons and photons of the CMBR. This suppression is consistent with the GZK cutoff.

We have measured the average depth of shower maximum, X_{max}, for cosmic rays between $10^{18.0}$ and $10^{19.4}$ eV. The elongation rate in this energy range is 55 g/cm^2 per decade. This is to be compared with the measurement by the HiRes-MIA hybrid experiment, at lower energies, which was 93 g/cm^2 per decade. The change in slopes occurs close to $10^{18.0}$ eV. The data of these two experiments, taken together, indicates that the composition at lower energies is becoming lighter, then plateaus at an overall light composition. This is the signature one would expect of the transition from galactic sources to extragalactic ones.

We have searched for anisotropy in the arrival directions of HiRes-I monocular events by testing the hypothesis that the AGASA clusters represent the six brightest sources in the northern hemisphere. The result is that these sources are not seen in the HiRes data, and the probability that constant-intensity sources are the explanation of the AGASA clusters and the HiRes data is 0.004.

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