

Observation of the GZK cutoff by the HiRes experiment

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Abstract

The High Resolution Fly's Eye (HiRes) experiment has observed the GZK cutoff. HiRes' measurement of the flux of cosmic rays shows a sharp suppression at an energy of 6×10^{19} eV, exactly the expected cutoff energy. We observe the "ankle" of the cosmic ray spectrum as well, at an energy of 4×10^{18} eV. However we cannot claim to observe the third spectral feature of the ultrahigh energy cosmic ray regime, the "second knee". We describe the experiment, data collection, analysis, and estimate the systematic uncertainties. The results are presented and the calculation of a five standard deviation observation of the GZK cutoff is described.

1 Introduction: The GZK Cutoff

K. Greisen [1] and G. Zatsepin and V. Kuzmin [2] predicted in 1966 that there would be an end to the cosmic ray spectrum. Caused by the production of pions in collisions between cosmic ray protons and photons of the cosmic microwave background radiation (CMBR), this strong suppression is called the GZK cutoff and should occur at about 6×10^{19} eV. This energy is set by the mass and width of the Δ resonance and the temperature of the CMBR. Several experiments [3, 4] whose exposures were too small to measure the flux of cosmic rays at the cutoff energy nevertheless observed one event each above 10^{20} eV, raising questions about the validity of Greisen's and Zatsepin and Kuzmin's prediction.

The Akeno Giant Air Shower Array (AGASA) was the first experiment large enough to measure the flux of cosmic rays at 10^{20} eV. AGASA consisted of 111 scintillation counters placed in an array of spacing about 1 km, and completed its data collection in 2004. They found that the spectrum continued unabated beyond the GZK cutoff energy: their main evidence consisted of 11 events above 10^{20} eV [5]. These results formed a serious challenge to the expectation that the cosmic ray flux should be cut off. Since the prediction of the existence of the cutoff is based on accepted physics principles this was a truly startling result.

The High Resolution Fly's Eye (HiRes) experiment collected data for nine years (1997-2006), and now has a much higher exposure than AGASA near the cutoff energy. HiRes is a fluorescence experiment; i.e., it observes cosmic ray showers by collecting the fluorescence light emitted by nitrogen molecules excited by shower particles. By using this different technique HiRes has much

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better resolution and better control of systematic uncertainties than AGASA. A fluorescence detector collects much more information about cosmic ray showers (for example it sees the shower development), measures the energy more accurately, and because it depends only on what goes on in the center of the shower one can simulate a fluorescence detector's performance very accurately. This is an important point that has not been lost on new experiments being constructed: the Auger and Telescope Array experiments have both fluorescence detectors and ground arrays.

HiRes sees the GZK cutoff. In this article we describe the measurement of the flux of cosmic rays in which this observation occurs, show the cosmic ray spectrum that we observe, and discuss of our estimates of systematic uncertainties.

2 The HiRes Experiment

The HiRes experiment has been described previously [6]. We have two detectors located atop desert mountains in west-central Utah, separated by 12.6 km, that operate on clear, moonless nights. The older detector, called HiRes-I, consists of a ring of spherical mirrors that collect the fluorescence light. Each mirror focuses the light on a 16x16 array of photomultiplier tubes. As the shower comes down across the sky the image passes over various photomultiplier tubes. A sample-and-hold readout system is used to save the timing and pulse height information from each tube. The mirrors have an active area of 4.2 m², and the 21 mirrors cover elevation angles from 3 to 17 degrees and almost the full azimuthal angle. Each phototube subtends about 1 square degree of sky.

Our newer detector, called HiRes-II, has 42 mirrors arranged in two rings that cover from 3 to 31 degrees in elevation and almost the full azimuthal angle. The front end of the read-out electronics uses a flash ADC (FADC) system with 100 ns period to record the phototube information.

We analyze our data in two ways: in monocular mode we analyze each of our detectors' data independently. This mode gives us the best statistics and the widest energy range: from 10^{17.2} to 10^{20.5} eV. In analyzing the two detectors' data together, called stereoscopic mode, we get the best resolution, but have fewer events, and cover a narrower energy range: 10^{18.5} to 10^{20.5} eV. In this paper we consider our data analyzed in monocular mode. Our stereo spectrum agrees very well with the spectrum being presented here, both in shape and in normalization.

3 Calibration and Corrections

The calibration of our detectors in terms of photons is performed by carrying a very stable xenon flash lamp to each mirror on a monthly basis, and illuminating the phototube cluster. Two methods of analysis of the xenon lamp data, using the absolute intensity and using photon statistics, agree within uncertainties. Ultimately our calibration comes from NIST-traceable photodiodes. We check the calibration with hybrid photodiodes and laser shots fired from the field in the aperture of our detectors. Night-to-night relative variations are monitored with a YAG laser. We achieve 10% accuracy in our optical calibrations.

The atmosphere is not only our calorimeter, it also is the medium through which fluorescence light is transmitted to our detectors. We monitor the transmission of the atmosphere by two methods. Raleigh scattering from the molecular portion of the atmosphere varies little with time. We monitor this through the density of the atmosphere, which is measured by radiosonde

balloons from two neighboring airports. To measure scattering from the aerosol component of the atmosphere we fire lasers into the sky and observe the scattered light with our detectors. A series of laser shots that takes 50 minutes to perform is begun every hour. We measure the vertical aerosol optical depth (VAOD) and the horizontal extinction length and phase function. The average VAOD is about 0.04, with an rms of 0.02. The skies at our site are very clear. An event 25 km distant has an aerosol correction to its energy of about 10% on average. Since 2.5 years of our early data was collected before our lasers were constructed, and we want to have a consistent analysis, the spectra presented here are calculated using a constant-atmosphere assumption, using the average value of VAOD. We have tested this assumption by calculating the spectrum from our later data, using the actual hourly measurements. We get the same answer to within a few percent [7].

The yield of fluorescence photons per minimum ionizing particle per meter of path length is a parameter that enters directly into our calculation of cosmic rays' energies. It has been measured previously [8]. The three measurements in reference [8] agree very well, and a fit to the three measurements indicates that the absolute flux is known to $\pm 6\%$.

4 Data Analysis

The analysis begins with a pattern recognition step. Tubes on a track are identified through being contiguous with other tubes in position and time. The plane that passes through the shower and the detector is found. We make a plot of the time each tube fires vs the angle of the tube in the shower-detector plane. This distribution is not a straight line: the curvature arises due to the geometry of the detector and shower. This curvature is then used in a fit to determine the event geometry. We measure the perpendicular distance to the shower and the angle of the shower in the shower-detector plane. This angle is measured to about 5° accuracy for the HiRes-II detector.

The next step is to calculate the number of charged particles in the shower as a function of the slant depth. This is called the profile of the shower. A fit to the profile is performed using the Gaisser-Hillas function [9], from which the depth of shower maximum is determined. The integral of the Gaisser-Hillas function is used to determine the calorimetric energy of the shower. The left part of Figure 1 illustrates monocular event reconstruction for the HiRes-II detector.

Because tracks seen in the HiRes-I detector are shorter, in the fit for the geometry we also use the shape of the reconstructed profile as a constraint. Again the Gaisser-Hillas function shape is used. An accuracy of about 7° in the in-plane angle is achieved in this fit. The right half of Figure 1 shows the energy of events seen by the HiRes-I detector reconstructed using the profile constrained fit vs the energy when the event geometry is reconstructed stereoscopically (with about 1° uncertainty in the in-plane angle). It is clear that the profile-constrained fit works very well in reconstructing events' energies.

Finally a correction is made for missing energy: for neutrinos and muons that strike the earth and whose energy is not counted in the calorimetric energy. This correction is determined from shower simulations using Corsika [10] and the hadronic generator program QGSJet [11]. This correction is typically about 10%. The hadronic generator program Sibyll [12] predicts the same missing energy correction to 2%.

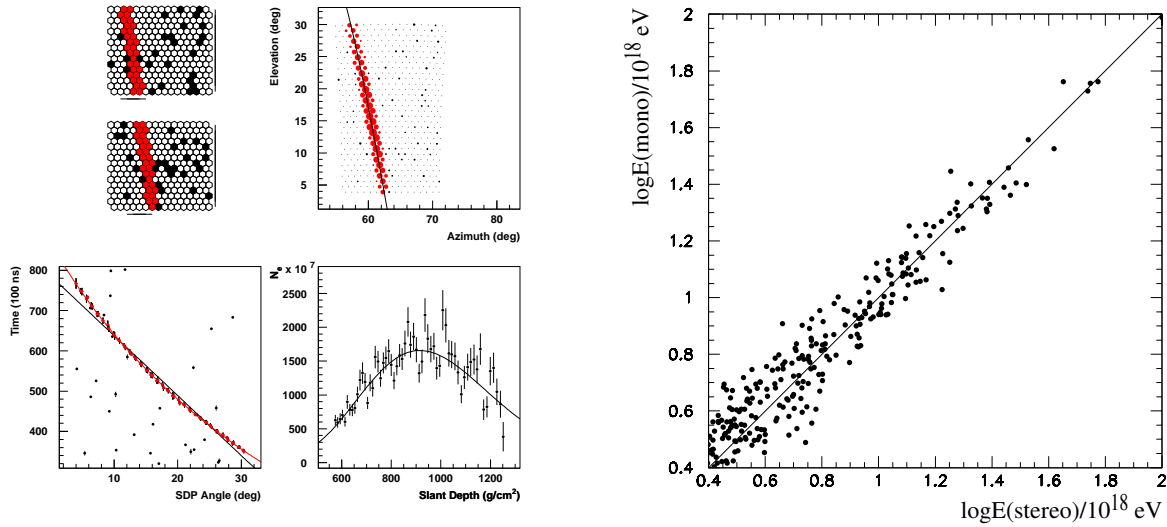


Figure 1: Left figure: Illustration of monocular event reconstruction for one event seen by the HiRes-II detector. The two mirrors that saw the cosmic ray track, all the tubes' elevation vs azimuthal angles, the time of tubes firing vs their angles along the shower-detector plane, and the profile with its Gaisser-Hillas fit are all shown. Right figure: HiRes-I energies calculated with the event geometry reconstructed in stereo, vs. the energy calculated when the geometry is determined using profile-constrained fit.

5 Aperture Calculation

To calculate the aperture of the experiment we perform a full Monte Carlo (MC) simulation, including shower development (using actual Corsika showers), fluorescence and Cerenkov photon generation, propagation through the atmosphere, light collection by our detectors, and the response of our trigger and readout electronics. The MC events are written out in exactly the same format as the data, and are analyzed using the same programs. Previous measurements of the spectrum and composition by the Fly's Eye Experiment [13], the HiRes/MIA hybrid experiment [14], and HiRes stereo (for composition) [15] are used in the simulation.

The way of judging the success of such a simulation is by comparing MC histograms of kinematic and physics variables with those of the data. If they are identical then one says that one understands one's experiment. Our MC simulates the data very well. Two comparison plots with excellent agreement between MC and data, typical of many, are shown in Figure 2. The left part of the figure shows the distance to the shower core for the HiRes-I detector, and the right part shows the number of photoelectrons per degree of track for events seen by the HiRes-II detector, showing that the same amount of light comes from the sky in the MC as in the data.

Figure 3 shows the result of the aperture calculation. The apertures of the HiRes-I and HiRes-II detectors are shown.

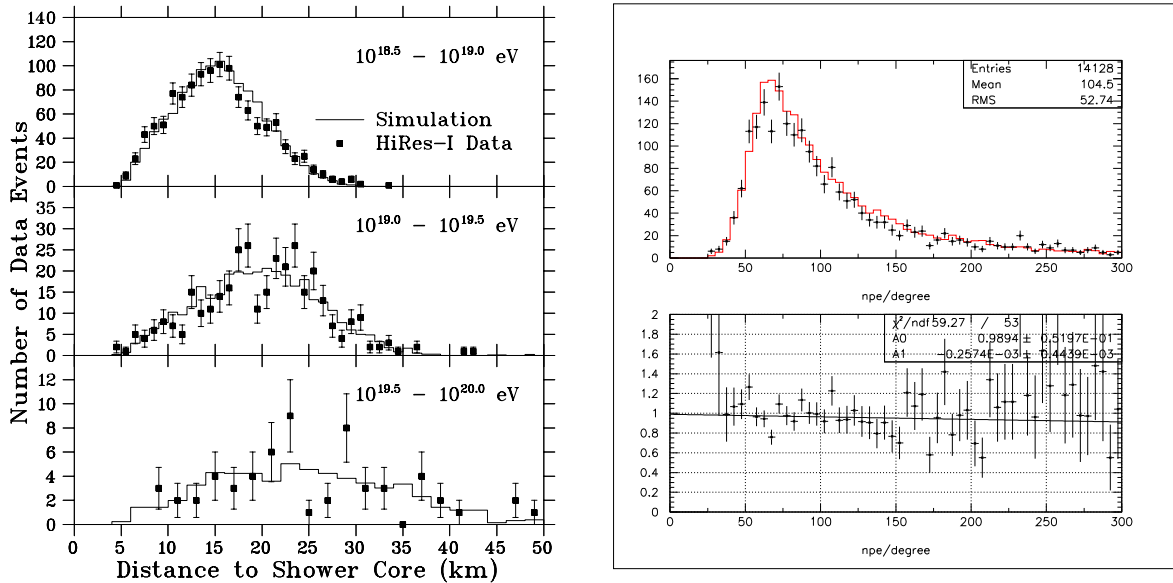


Figure 2: Left figure: Histograms comparing the distance to the shower core in Monte Carlo and data for the HiRes-I detector. Three energy bins are shown. Right figure: Histogram showing the comparison of Monte Carlo to data for the number of photoelectrons per degree of track for events seen by the HiRes-II detector. The lower part of the figure is the bin-by-bin ratio of data events to the Monte Carlo events.

6 The Spectrum

Evidence for the suppression of the flux of cosmic rays at high energies has been published in previous spectrum measurements by our collaboration [16]. Figure 4 shows the current monocular spectra of the two HiRes detectors. The flux times E^3 is shown. The HiRes-I data were collected from May, 1997 to May, 2005, and that from HiRes-II from December, 1999 to August, 2005.

The GZK cutoff stands out clearly as the suppression of the spectrum at $10^{19.8}$ eV. The dip at $10^{18.6}$ eV is a feature known as the “ankle”. Fits to the spectrum [17] show that the ankle is likely caused by e^+e^- pair production in the same interactions between CMBR photons and cosmic ray protons where pion production produces the GZK cutoff. Previous experiments have observed a feature known as the “second knee” [4, 14, 18] near $10^{17.6}$ eV, although there is considerable uncertainty in this energy. The statistical power of our data is poor in this energy range, and below 10^{18} eV systematic uncertainties are growing as well. So HiRes cannot claim to observe the second knee.

At lower energies, the spectrum of cosmic rays can be fit to power laws over ranges of energy. This is also true for the spectrum in Figure 4. Superimposed on the spectrum are three lines fit to the data with break points between the line segments also found by the fitting program. There are two breaks found, at $\log E(\text{eV})$ of 19.75 ± 0.05 for the GZK cutoff, and 18.65 ± 0.05 for the ankle. The χ^2 of this fit is 34.7 for 35 degrees of freedom. A fit with only one break point allowed finds the ankle, and the χ^2 is 68.2 for 37 degrees of freedom. Correcting for the number of degrees of freedom, the difference in χ^2 of 31.5 corresponds to about a 5 1/2 standard deviation statistical significance to our observation of the GZK cutoff.

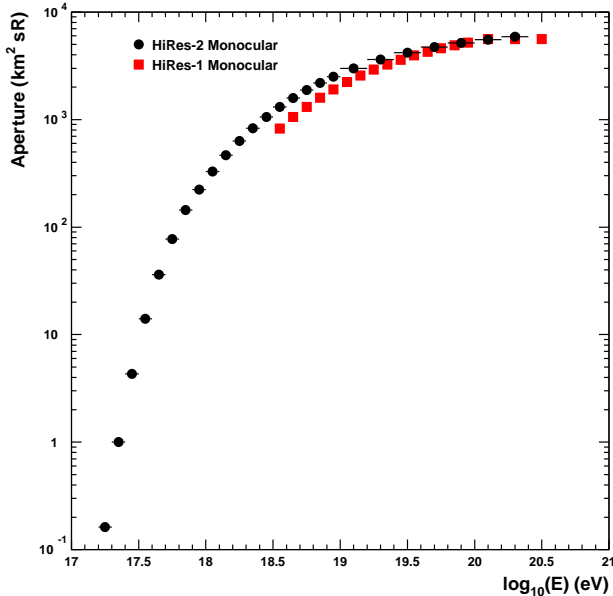


Figure 3: The aperture of the HiRes detectors operating in monocular mode. Apertures of HiRes-I and HiRes-II are shown.

Another way of calculating the statistical significance of the break at $10^{19.8}$ eV is to calculate the number of events that we should have collected if there were no break, and compare it with the true number of events. Using our exposure we should have seen 51.1 events if there were no break, but we actually observed 15. The Poisson probability of seeing 15 or fewer with a mean of 51.1 is 3×10^{-9} , which corresponds to 5.8σ , consistent with the χ^2 calculation in the previous paragraph. Removing the overlapping events seen by both HiRes-I and HiRes-II and redoing the calculation yields a 5.2 standard deviation effect.

7 A “Test Beam” of High Energy Events

Since we do not observe a continuation of the flux of cosmic rays above the GZK energy one might ask whether our experiment is capable of seeing these events. To answer this question we constructed a “test beam” of high energy tracks using a laser. This laser is located at Terra Ranch, 35 km from the HiRes-II detector, at the edge of our aperture, and it fires a beam of light vertically at a wavelength of 355 nm. The atmosphere scatters the light into the aperture of our detectors, and we trigger on it just like a cosmic ray shower. We have measured the efficiency for triggering on the scattered light and reconstructing it as we would do for a shower, and this efficiency is shown in Figure 5. The data for this figure was collected on good-weather nights where the cosmic ray data were used in our spectrum measurement. The laser fires at five energy levels. The specific brightness of a cosmic ray shower, for example measured in photoelectrons per degree of track length, is characteristic of its energy, and we have plotted the five laser energies in Figure 5 at the equivalent cosmic ray energies. Figure 5 proves that we have excellent sensitivity to cosmic ray showers at and above the energy of the GZK cutoff. The fact that super-GZK events are absent in our data is thus due to the GZK cutoff itself,

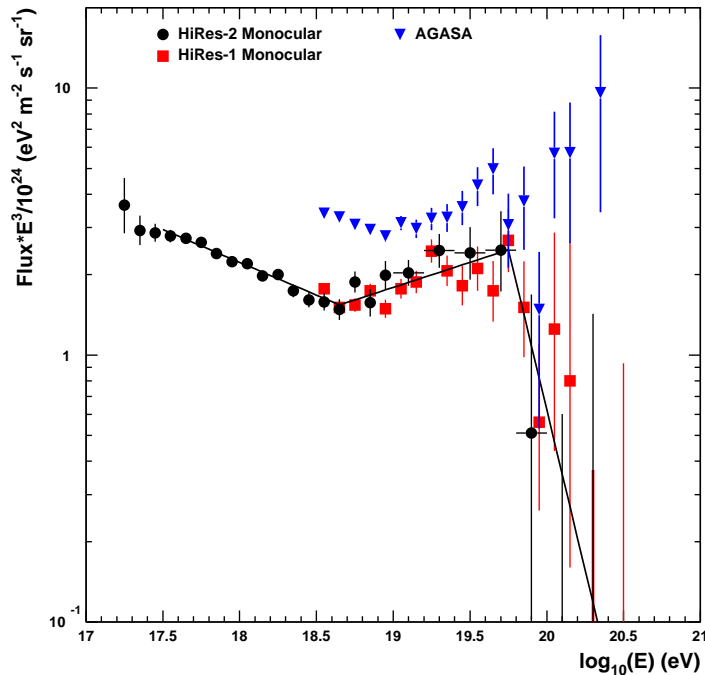


Figure 4: The cosmic ray spectrum measured of the HiRes detectors operating in monocular mode. The spectrum of the HiRes-I and HiRes-II detectors are shown. The spectrum of the AGASA experiment is also shown. The falling-off of the HiRes spectrum above $10^{19.8}$ eV is the GZK cutoff, and the dip at $10^{18.6}$ eV is the “ankle”.

and is not an instrumental effect.

8 Systematic Uncertainties

The main contributions to the systematic uncertainty in the HiRes energy scale and flux measurements are: phototube calibration (10%), fluorescent yield (6%), missing energy correction (5%), aerosol part of atmospheric correction (5%), mean dE/dx ¹ (10%), for a total energy scale uncertainty of 17%, and an uncertainty in the flux of 30%.

9 Summary

We have measured the flux of ultrahigh energy cosmic rays by the fluorescence technique, over the energy range $10^{17.2}$ to $10^{20.5}$ eV. We observe the GZK cutoff and the ankle of the cosmic ray spectrum. We cannot claim to observe the second knee. The statistical power of our observation of the GZK cutoff is just over 5σ . The systematic uncertainty in our energy scale is about 17%, and the uncertainty in the flux is about 30%.

¹The two newest versions of QGSJet yield mean dE/dx estimates for showers that differ by 10%.

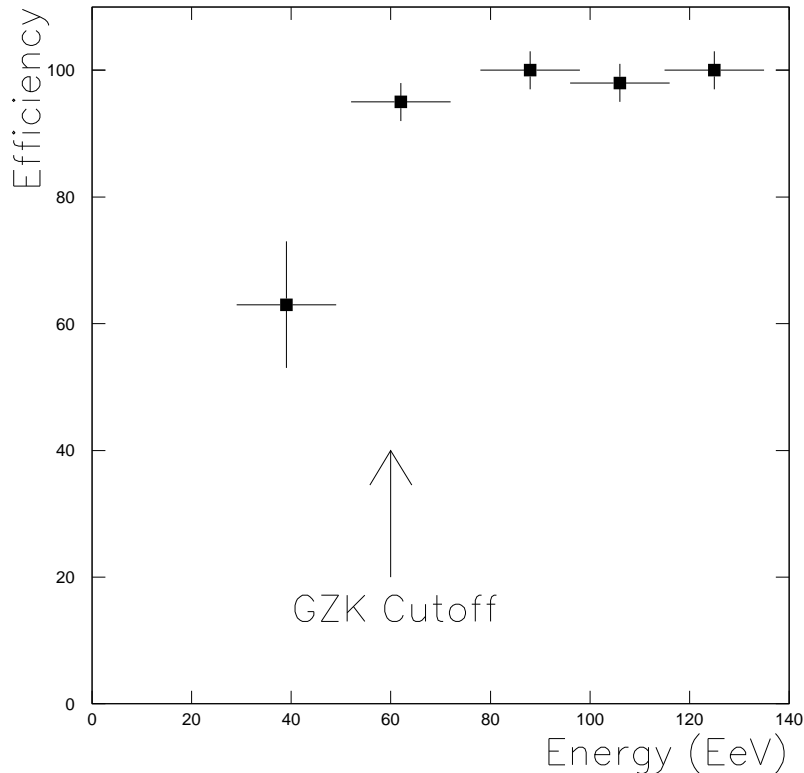


Figure 5: The efficiency for triggering on and reconstructing Terra Ranch laser shots by the HiRes-II detector. The five laser energies are plotted on the ordinate at the equivalent energy a cosmic ray shower of that brightness would have. This figure proves that HiRes has excellent sensitivity to cosmic ray showers at and above the GZK energy, even though those showers are not present in our data; i.e., the absence of these events is due to the GZK cutoff, and is not an instrumental effect.

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