Observation of the GZK Cutoff by the HiRes Experiment

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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. We describe the experiment, data collection, analysis, and estimate the systematic uncertainties. The results are presented and the calculation of a ~ 5 standard deviation observation of the GZK cutoff is described.

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In 1966, Greisen [1], and Zatsepin and Kuzmin [2], proposed an upper energy limit to the cosmic ray spectrum. Their predictions were based on the assumption of a proton dominated extra-Galactic cosmic ray flux which would interact with the photons in the Cosmic Microwave Background (CMB) via photo-pion production. From the temperature of the CMB and the mass and width of the Δ resonance, a "GZK" threshold of $\sim 6\times10^{19}$ eV was calculated, and a suppression in the cosmic ray flux beyond this energy was predicted. This is a strong energy-loss mechanism that limits the range of cosmic protons above this threshold to less than ~ 50 Mpc.

Several earlier experiments [3, 4, 5, 6] have reported the detection of one event each above 10^{20} eV. A continuing, unbroken spectrum beyond the predicted GZK threshold was later reported by a larger experiment, the Akeno Giant Air Shower Array (AGASA) [7, 8].

The High Resolution Fly's Eye (HiRes) experiment was operated on clear, moonless nights over a period of nine years (1997-2006). During that time, HiRes collected a cumulative exposure 4-5 times that collected by AGASA above the GZK threshold. Using the fluorescence technique, the HiRes experiment observes cosmic rays by imaging the Extensive Air Shower (EAS) generated by a primary cosmic ray. Ultraviolet (UV) light is emitted by nitrogen molecules in the wake of the EAS and collected by our detector.

Forty years after its initial prediction, the HiRes experiment has observed the GZK cutoff. In this article we describe our measurement of the flux of cosmic rays, the resulting cosmic ray spectrum, our analysis of this spectrum to infer the existence of the cutoff, and our estimate of systematic uncertainties.

The HiRes project has been described previously [9, 10]. The experiment consists of two detector stations (HiRes-I and HiRes-II) located on the U.S. Army Dugway Proving Ground in Utah, 12.6 km apart. Each station is assembled from telescope modules (22 at HiRes-I and 42 at HiRes-II) pointing at different parts of the sky, covering nearly 360° in azimuth, and 3°–17° (HiRes-I), and 3°–31° (Hires-II) in elevation. Each telescope module collects and focuses UV light from air showers using a spherical mirror of 3.7 m^2 effective area. A cluster of 256 photomultiplier tubes (PMTs) is placed at the focal plane of each mirror and serves as the camera for each telescope. The field of view of each PMT subtends a one degree cone on the sky.

HiRes data analysis is carried out in two ways. In *monocular* mode, events from each detector site are selected and reconstructed independently. The combined monocular dataset has the best statistical power and covers the widest energy range. The dataset consisting of events seen by both detectors, analyzed in *stereo*, has the best resolution, but covers a narrower energy range and has less statistics. This article presents the monocular spectra from our two detectors.

The photometric calibration of the HiRes telescopes has been described previously [11]. It is based on a portable, high-stability ($\sim 0.5\%$) xenon flash lamp carried to each mirror on a monthly basis, which is referenced to NIST-traceable photodiodes. Relative nightly calibrations were performed using Yag laser light brought to each cluster of phototubes through optical fibers. In addition the overall optical calibration of the HiRes detectors is validated by reconstructing scattered light from laser shots fired from locations that surround, and are within ~ 3.5 km of the two detector sites. We achieve $\sim 10\%$ accuracy in our photometric scale.

We monitor the UV transmission properties of the atmosphere to make a correction for attenuation of fluorescence light. Steerable lasers fire patterns of shots that cover the aperture of our fluorescence detectors, and the detectors measure the intensity of the scattered light. The most important parameter we measure is the Vertical Aerosol Optical Depth (VAOD). The mean value of the VAOD is 0.04 with an RMS variation of 0.02. On average, an event at 25 km from a HiRes detector has an aerosol correction to its energy of about 15%. Because ~ 3 years of early HiRes-I data were collected before the lasers were deployed, the spectra presented here are calculated using a constant-atmosphere assumption, using the measured average value for the VAOD. We have tested this assumption by calculating the spectrum from our later data, using the actual hourly measurements. Comparing the resulting spectra from the two methods, we obtain flux values that agree to within a few percent [12].

Another important parameter in our analysis is the fluorescence yield: the number of photons generated per ionizing particle per unit path length. Fluorescence yield measurements have been made by several groups [13, 14, 15, 16]. For the spectrum determination used in this paper, we have used the spectral shape of Bunner [13], and the integral yield reported by Kakimoto *et al.* [14]. Our systematic studies have shown that this set of assumptions produces absolute flux values that are within $\sim 6\%$ of those obtained using the other results cited.

The details of HiRes event selection have been described previously [17, 18]. The event reconstruction procedure begins with the determination of the shower axis. A Shower-Detector Plane (SDP) is determined from the pointing direction of triggered PMTs. For the HiRes-II monocular dataset, the PMT times are then used to find the distance to the shower and the angle, ψ of the shower within the SDP. This *timing fit* measures ψ to $\sim 5°$.

The number of shower particles as a function of slant depth, the *shower profile*, is then determined. This calculation uses the fluorescence yield and corrects for atmospheric attenuation. We fit the shower profile to the Gaisser-Hillas function [19], subtracting scattered Čerenkov light iteratively. This *profile fit* yields both the calorimetric energy of the shower and the slant depth at the shower maximum, $X_{\max}$. A typical HiRes profile is displayed in [11].

The HiRes-I detector, with its limited elevation coverage, does not typically observe enough of the shower for a reliable timing fit. For this reason the HiRes-I monocular reconstruction combines the timing and profile fits in a *Profile-Constrained Fit* (PCF). The PCF reconstructs ψ with an accuracy of $\sim 7°$. The PCF has been validated by comparing the PCF energies to those found using stereo geometries in a subset of the data observed by both detectors as shown in Figure 1.

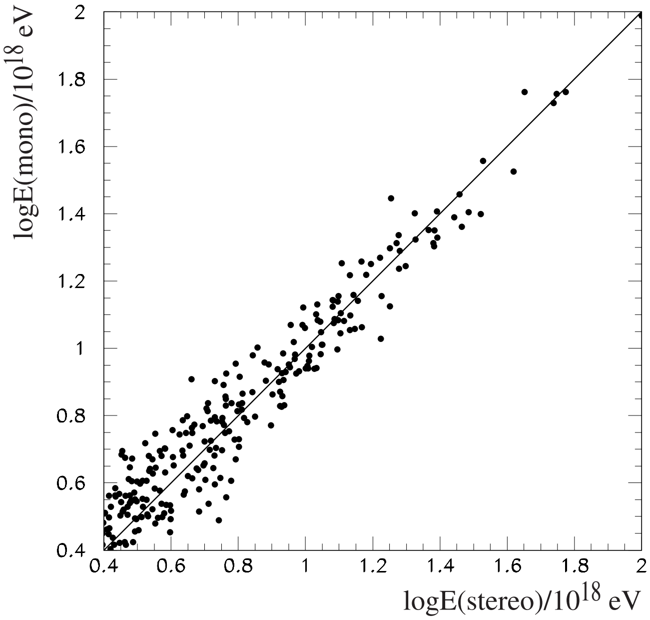

FIG. 1: HiRes-I energies calculated with the event geometry reconstructed in stereo vs. the energy calculated when the geometry is determined using the PCF.

Finally, a correction is made for *missing energy*, the energy carried by shower components which do not deposit their energy in the atmosphere. This includes primarily the energy of neutrinos and muons that strike the earth. The correction is calculated using shower simulations in CORSIKA [20] with hadronic interaction simulated by QGSJet [21]. The correction is $\sim 10\%$. Simulations using Sibyll [22] find a correction within 2% [12] of that found via QGSJet.

The measurement of the cosmic ray flux requires a reliable determination of the detector aperture. The aperture of the HiRes detectors has been calculated using a full Monte Carlo (MC) simulation. The MC includes simulation of shower development (using CORSIKA), fluorescence and Čerenkov light production, transmission of light through the atmosphere to the detector, collection of light by the mirrors, and the response of the PMTs, electronics and trigger systems. Simulated events are recorded in the same format as real data and processed in an identical fashion. To minimize biases from resolution effects, MC event sets are generated using the published measurements of the spectrum [23] and composition [24, 25, 26].

To ensure the reliability of the aperture calculation, the MC simulation is validated by comparing key distributions from the analysis of MC events to those from the actual data. Several of these comparisons were shown in reference [27]. Especially noteworthy are comparisons of the distribution of distances to the showers, which shows that the simulation accurately predicts the coverage of the detector, and the brightness of the signal, which demonstrates that the simulation of the optical characteristics of the detector, and of the trigger and atmospheric conditions, accurately reproduce the data collection environment. The excellent agreement between the observed and simulated distributions shown in these cases is typical of MC-data comparisons of other kinematic and physical quantities, and demonstrate that we have a reliable MC simulation program and aperture calculation. Figure 2 shows the result of the aperture calculation for both HiRes-I and HiRes-II in monocular mode.

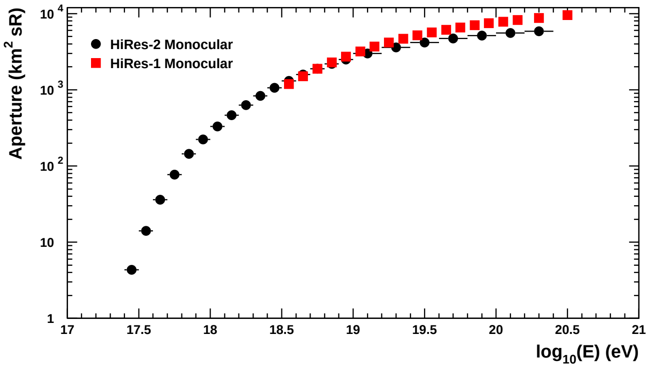

FIG. 2: The apertures of the HiRes-I and HiRes-II detectors operating in monocular mode.

Figure 3 shows the monocular spectra from the two HiRes detectors [28]. The data included in the figure were collected by HiRes-I from May, 1997 to June, 2005, and by HiRes-II from December, 1999 to August, 2005. Figure 3 shows the flux multiplied by E^3, a shear transformation which does not change the statistical interpretation of the results. Two prominent features seen in the figure are a softening of the spectrum at the expected energy of the GZK threshold of $10^{19.8}$ eV, and the dip at $10^{18.6}$ eV, known as the "Ankle". Theoretical fits to the spectrum [29] 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. The observation of both features is consistent with the published HiRes results of a predominantly light composition above 10^{18} eV [26].

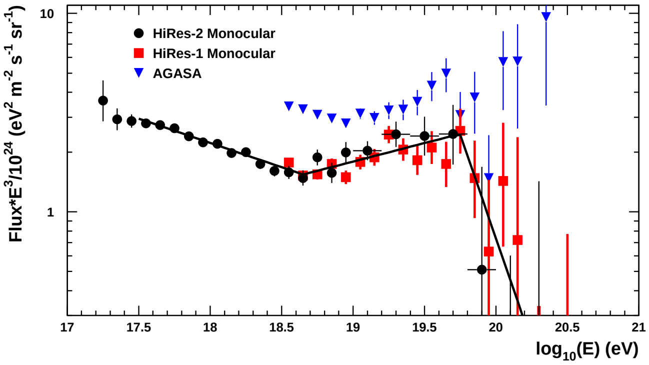

FIG. 3: The cosmic ray spectrum measured by the HiRes detectors operating in monocular mode. The spectrum of the HiRes-I and HiRes-II detectors are shown. The highest two energy bins for each detector are empty, with the 68% confidence level bounds shown. The spectrum of the AGASA experiment is also shown.

At lower energies, the cosmic ray energy spectrum is well fit by a piece-wise power law model. A similar fit also gives an excellent representation of the spectrum in Figure 3. The three straight line segments shown represent the result of a fit of the measured flux to a triple-power law. The model contains six free parameters: one normalization, the energies of two floating break points, and three power law indices.

We performed a binned maximum likelihood fit [30] to the data from the two detectors. The fits include two empty bins for each monocular dataset. We found the two breaks at $\log E$ (E in eV) of 19.75 ± 0.04, and 18.65 ± 0.05, corresponding to the GZK cutoff and the Ankle, respectively. When the datasets were made statistically independent by removing events seen by both detectors from the HiRes-I dataset, we obtained a χ^2 of 39.5 in this fit for 35 degrees of freedom (DOF). In contrast, a fit to a model with only one break point, while able to locate the Ankle, yielded a χ^2/DOF=62.9/37. The χ^2 difference of 23.4, while adding two DOF, implies that the two break point fit is preferred at a confidence level corresponding to 4.5σ.

Another measure of the significance of the break in the spectral index at $10^{19.8}$ eV is made by comparing the actual number of events observed above the break to the expected number for an unbroken spectrum. For the latter, we assume the power law of the middle segment to continue beyond the threshold. Folding the exposures with the overlap between the detectors removed, we expect 39.9 events above $10^{19.8}$ eV from the extrapolation, whereas 13 events were actually found in the data. The Poisson probability for the observed deficit is $\sim 7.1 \times 10^{-7}$, which corresponds to a significance of 4.8σ, consistent with the χ^2 calculation above. Thus we conclude that there is a definite break in the UHE cosmic ray spectrum at an energy of $(5.6 \pm 0.7) \times 10^{19}$ eV. Since the break occurs at the expected energy of the GZK cutoff, we conclude that it is the GZK cutoff.

A test of this interpretation is provided by the $E_{1/2}$ method suggested by Berezinsky and Grigorieva [31]. $E_{1/2}$ refers to the energy at which the integral spectrum falls to half of what would be expected in the absence of the GZK cutoff. Figure 4 shows the integral HiRes spectra divided by the integral of the power law spectrum used above to estimate the number of expected events above the break. From this plot, we find $E_{1/2} = 10^{19.73 \pm 0.07}$. Berezinsky and Grigorieva predict a robust theoretical value for $E_{1/2}$ of $10^{19.72}$ eV for a wide range of spectral slopes [31]. These two values are clearly in excellent agreement, supporting our interpretation of the break as the GZK cutoff.

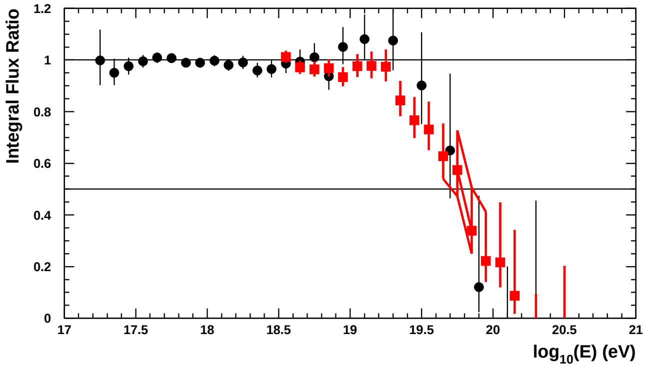

FIG. 4: Integral version of the two HiRes monocular spectra, divided by a fit from the Ankle to the break at $10^{19.8}$ eV. Only the HiRes-I values (in red)are used to make an estimate of $E_{1/2}$, interpolating between the central value and 1σ uncertainty limits.

We measure the index of the power law between the Ankle and the GZK cutoff to be 2.81 ± 0.03. Above the GZK cutoff the fall-off is very steep: we measure a power law index of 5.1 ± 0.7. This may have implications for the local density of extragalactic cosmic ray sources [29].

For the monocular analyses, the main contributions to the systematic uncertainty in the energy scale and flux measurements are: PMT calibration (10%), fluorescence yield (6%), missing energy correction (5%), aerosol component of the atmospheric attenuation correction (5%), and mean dE/dx estimate [32] (10%). These give a total energy scale uncertainty of 17%, and a systematic uncertainty in the flux of 30%.

In summary, we have measured the flux of ultrahigh energy cosmic rays with the fluorescence technique, in the energy range $10^{17.2}$ to above $10^{20.5}$ eV. We observe two breaks in the spectrum corresponding to the GZK cutoff and the Ankle. The statistical significance of the break identified with the GZK cutoff is $\sim 5\sigma$. We measure the energy of the GZK cutoff to be $(5.6 \pm 0.7 \pm 0.9) \times 10^{19}$ eV, where the first uncertainty is statistical and the second is systematic.

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