First Observation of the Greisen-Zatsepin-Kuzmin Suppression

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The High Resolution Fly's Eye (HiRes) experiment has observed the Greisen-Zatsepin-Kuzmin suppression (called the GZK cutoff) with a statistical significance of five standard deviations. HiRes' measurement of the flux of ultrahigh energy (UHE) cosmic rays shows a sharp suppression at an energy of 6×10^{19} eV, consistent with the expected cutoff energy. We observe the "ankle" of the cosmic-ray energy 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 the statistical significance of our observation is described.

In 1966, Greisen [1], and Zatsepin and Kuzmin [2], proposed an upper limit to the cosmic-ray energy 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 $\sim 6 \times 10^{19}$ eV was calculated, and a suppression in the cosmic-ray flux beyond this energy (commonly called the GZK cutoff) 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 energy 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 more than twice that collected by AGASA above the GZK threshold. The HiRes experiment observes cosmic rays by imaging the extensive air shower (EAS) generated by a primary cosmic ray. Ultraviolet fluorescence (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 GZK cutoff has been observed for the first time by the HiRes experiment. In this article we describe our measurement of the flux of cosmic rays, the resulting cosmic-ray energy 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 diameter 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 (stereo mode data) has the best energy resolution, but it covers a narrower energy range and has less statistics[11]. This article presents the monocular energy spectra from our two detectors.

The photometric calibration of the HiRes telescopes has been described previously [12]. It is based on a portable, high-stability ($\sim 0.5\%$) Xenon flash lamp carried to each mirror on a monthly basis. Relative nightly calibrations were performed using Yag laser light brought to each cluster of PMT's through optical fibers. In addition, the overall optical calibration of the HiRes detectors is validated by reconstructing scattered light from a pulsed laser fired into the atmosphere from locations that surround, and are within ~ 3.5 km, of the two detector sites. We achieve $\sim 10\%$ RMS accuracy in our photometric scale.

We monitor the UV transmission properties of the atmosphere to make a correction for the 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. An event at 25 km from a HiRes detector has an average aerosol correction of $\sim 15\%$ upward in energy. Because 2.5 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 energy 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 [13].

Another important parameter in our analysis is the fluorescence yield (FY): the number of photons generated per ionizing particle per unit path length. FY measurements have been made by several groups [14, 15, 16, 17]. For the energy spectrum determination used in this paper, we have used the spectral shape of Bunner [14] and the integral yield reported by Kakimoto *et al.* [15]. Our systematic studies have shown that this set of assumptions produces absolute fluorescence flux values that are equal, within $\sim 6\%$, of those obtained using a fit to all the results cited [18].

The details of HiRes event selection have been described previously [19, 20]. An additional cut on the distance to showers has been applied in the HiRes-II data collected after those shown in [20]. This cut is applied to make the aperture (defined as the product of collection area and solid angle) calculation more robust. The event reconstruction procedure begins with the determination of the shower axis. A plane containing the axis of the shower and the detector, the 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 an accuracy of $\sim 5°$ RMS.

The number of shower particles as a function of atmospheric depth is then determined. This calculation uses the FY and corrects for atmospheric attenuation. We fit this shower profile to the Gaisser-Hillas function [21], after having subtracted scattered Čerenkov light produced by the air shower particles. This profile fit yields both the energy of the shower and the depth at the shower maximum, $X_{\max}$. A typical HiRes profile is displayed in [12]. The energy resolution of the HiRes-II detector is about 12% at high energies.

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 $\sim 7°$ RMS. The PCF has been validated by comparing the PCF energies to those found using stereo geometries in that subset of the data observed by both detectors as shown in Figure 1. The energy resolution of the HiRes-I detector is about 17% at high energies.
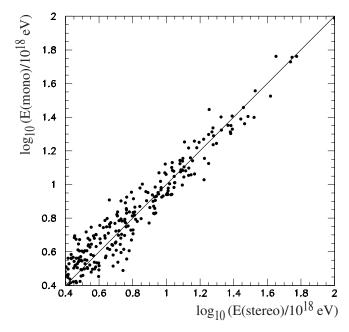

FIG. 1: HiRes-I energies calculated with the event geometry reconstructed in monocular mode using the profile-constrained fit vs. the energy reconstructed in stereo mode.

Finally, a correction is made for the energy carried by shower components which do not deposit their energy in the atmosphere. This correction includes primarily the energy of neutrinos and muons that strike the earth. The correction is calculated using shower simulations in CORSIKA [22] with hadronic interaction simulated by QGSJet [23]. The correction is $\sim 10\%$. Simulations using

Sibyll [24] find a correction within 2% [13] 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 energy spectrum [25] and composition [26, 27, 28].

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 [29]. Two comparisons are especially noteworthy. The data-MC comparison of the distances to showers shows that the simulation accurately models the coverage of the detector. The comparison of event brightness shows that the simulations 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 this agreement demonstrates 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.
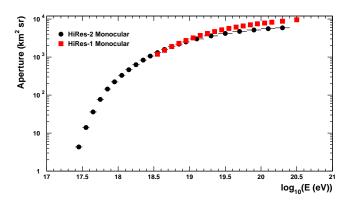

FIG. 2: The apertures (defined as the product of collection area and solid angle) of the HiRes-I and HiRes-II detectors operating in monocular mode.

Figure 3 shows the monocular energy spectra from the two HiRes detectors [30]. 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, 2004. Figure 3 shows the flux multiplied by E^3, which does not change the statistical interpretation of the results but highlights features more clearly. 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, commonly known as the "ankle". Theoretical fits to the spectrum [31] show that the ankle is likely caused by e^+e^- pair production in the same interactions between CMB 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 [28].
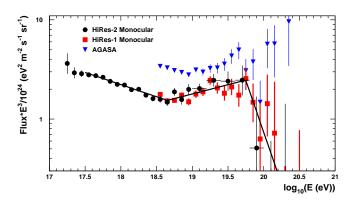

FIG. 3: The cosmic-ray energy spectrum measured by the HiRes detectors operating in monocular mode. The spectrum of the HiRes-I and HiRes-II detectors are shown. The highest two energy bins for each detector are empty, with the 68% confidence level bounds shown. The spectrum of the AGASA experiment is also shown [7, 8].

At lower energies, the cosmic-ray 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 fit 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 [32] 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 35.1 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 (at the same energy), yielded a $\chi^2/\text{DOF}=63.0/37$ [33].

A measure of the significance of the break in the spectral index at $10^{19.8}$ eV can be made by comparing the actual number of events observed above the break to the expected number for an unbroken spectrum. For the lat-

ter, we assume the power law of the middle segment to continue beyond the threshold. From the independant HiRes exposures (with events seen by both detectors removed from HiRes-I), we expect 43.2 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 7×10^{-8}, which corresponds to 5.3 standard deviations. We conclude that we have observed the GZK cutoff with a 5 standard deviation significance.

One question that remains is whether the sources of extragalactic UHE cosmic rays have properties that could change the GZK energy. A study by V. Berezinsky *et al.* [31] found that the density of sources in the local area should change the power law of the energy spectrum above the GZK cutoff, but not the GZK energy itself. The average power law of the sources could change the GZK energy somewhat, but the $E_{1/2}$ method suggested by V. Berezinsky and S. Grigorieva [34] provides a test of whether a break is the GZK cutoff independent of power law over a wide range. $E_{1/2}$ refers to the energy at which the integral energy spectrum falls to half of what would be expected in the absence of the GZK cutoff. To calculate $E_{1/2}$ we used the HiRes monocular energy spectra and the integral of the power law spectrum used above to estimate the number of expected events above the break. We find $E_{1/2} = 10^{19.73 \pm 0.07}$. Berezinsky and Grigorieva predict a robust theoretical value for $E_{1/2}$ of $10^{19.76}$ eV for a wide range of spectral slopes [34]. These two values are clearly in excellent agreement, supporting our interpretation of the break as the GZK cutoff.

We measure the index of the power law to be 3.25 ± 0.01 below the ankle, 2.81 ± 0.03 between the ankle and the GZK cutoff, and 5.1 ± 0.7 above the GZK cutoff.

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 energy loss rate estimate (the flux of fluorescence photons is proportional to the mean dE/dx of the particles in the shower [35]) (10%). Since these uncertainties arise from very different sources, we add them in quadrature, giving 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 energy spectrum consistent with the GZK cutoff and the ankle. The statistical significance of the break identified with the GZK cutoff is 5 standard deviations. We measure the energy of the GZK cutoff to be $(5.6 \pm 0.5 \pm 0.9) \times 10^{19}$ eV, where the first uncertainty is statistical and the second is systematic.

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