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Observation of the GZK Cutoff Using the HiRes Detector

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The High Resolution Fly's Eye (HiRes) experiment has observed the GZK cutoff. HiRes observes two features in the ultra-high energy cosmic ray (UHECR) flux spectrum: the Ankle at an energy of 4×10^{18} eV and a high energy suppression at 6×10^{19} eV. The later feature is at exactly the right energy for the GZK cutoff according to the $E_{1/2}$ criterion. HiRes cannot claim to observe a third feature at lower energies, the Second Knee. The HiRes monocular spectra are presented, along with data demonstrating our control and understanding of systematic uncertainties affecting the energy and flux measurements.

HiRes has observed the GZK Cutoff. The GZK cutoff was predicted 40 years ago, Greisen [1] and Zatsepin and Kuzmin [2] predicted the existence of a sharp reduction in the flux of ultra-high energy cosmic rays (UHECR's) at energies above about 6×10^{19} due to photopion production interactions between UHECR protons and the cosmic microwave background radiation (CMBR).

Since the prediction of the GZK cutoff was made, a number of experiments claim to have observed events with measured energies above 1×10^{20} eV. Volcano Ranch[3] observed one event in 1963, even before the GZK Cutoff was proposed. However, the knowledge of the expected lateral distribution function to use in estimating the total number of shower particle was lacking at that time. SUGAR claimed three events[4] and Haverah Park observed four[5]. SUGAR used only muon detectors, however, and had problems with after pulsing in its PMT's. One should "be cautious about taking the energies ascribed to the Sydney events ... as providing definitive evidence against a cutoff in the cosmic ray energy spectrum[6]." The Haverah Park data was later reanalyzed[7] using Corsika to establish the relation between ρ_{600} and the energy; all the high energy events were reanalyzed to lower energies, below the GZK cutoff. More recently, both the

Yakutsk Array[8] and AGASA[9] have claimed to events above 10^{20} eV, but Yakutsk claims that it's events are consistent with what is expected from the GZK process while AGASA had claimed otherwise, but is now reconsidering their energy scale[10].

The point of going through this short history is to note that it is *hard* to measure the energy well with a surface array (which all of the above are), because one is never looking at the *bulk* of the shower. This makes the energy determination subject to the poorly understood systematics of shower modeling, and it is necessary to measure the energy well to observe a break in such a steeply falling spectrum. It is easier, on the other hand, to measure the energy well with a fluorescence detector, such as HiRes. Because a fluorescence detector does observe the bulk of the shower, one is left only with systematic uncertainties which are easier to understand and control.

Two such systematic uncertainties are number of photons emitted by the shower as it passes through the atmosphere, the fluorescence yield, and the clarity of the atmosphere through which one observes those emitted photons. The fluorescence yield has been well studied in the lab, and the differences between three recent measurements is only at the 6% level [11, 12, 13]. The atmospheric uncertainty, on the other hand, can be controlled by going to a site with a clean stable

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atmosphere, like Dugway, Utah, and then by measuring the scattering properties of the air with lasers as we have done in HiRes[14].

A third systematic uncertainty for a fluorescence detector is the size of the aperture as a function of energy. Traditionally, ground arrays were thought to have constant aperture above the energy where the array becomes 100% efficient. In fact, given energy and core location resolutions this is not quite true. Fluorescence detectors, however, have a manifestly changing aperture because higher energy showers are brighter and can be seen farther away. The problem then becomes one of determining the size of the aperture at a given energy by a Monte Carlo simulation. However, this is not a case where we have replaced one poorly understood simulation, extensive air shower development, which is the bane of ground array experiments, with another poorly understood simulation. The aperture calculation for a fluorescence detector uses only well understood physics and, more importantly, is amenable to detailed *verification* through the technique of Data/MC Comparisons. It is just these detailed comparisons that comprise the bulk of this talk and give us the great confidence we have in our aperture calculation.

I will begin this discussion of the aperture calculation by noting that the aperture is, in accelerator physics parlance, the acceptance of the detector, and that acceptances are routinely calculated by MC simulation:

$$\text{Ap}(E') = \frac{N_R(E')}{N_T(E)} \text{Area}_T \Omega_T \quad (1)$$

$$= \text{Acpt}(E') \text{Area}_T \Omega_T \quad (2)$$

where E' is the reconstructed energy, while E is the thrown energy. N_T and N_R are the numbers of events generated (“thrown”) and reconstructed, respectively. For the calculation to be accurate, one must put the right distribution of showers in the right places (to get the area), at the right angles (to the right solid angle), and with the right amount of light (to get the right energy scale). What is more, one must put in the right fluctuations in signal for the difference between reconstructed energy (E') and thrown energy (E) to be significant. Fortunately, these distributions

are easy to check in Data/MC Comparisons.

The first comparisons are for the distances of the showers from both HiRes-I and HiRes-II (events in the right *places*). These are shown in Figure 1 for the distance to the impact point in HiRes-I in three energy bins, and in Figure 2 for the impact parameter for showers from HiRes-II. The second set of comparisons shows the distributions of measured angles (events at the right *angles*): the zenith angle for HiRes-I events in Figure 3, the angle between the shower and the ground in the shower-detector plane, ψ , for HiRes-II events in Figure 4. A third comparison, in Figure 6 shows the brightness distribution for events at HiRes-II (events with the right amount of light). The final comparison, in Figure 5, shows the distribution of χ^2 for a fit of the times of tubes at HiRes-II to a linear function of time vs. angle (for resolution). Since the time vs angle relation should be curved, the χ^2 distribution has a large tail.

Having built confidence in our aperture calculation, we move on to the data measured by HiRes in monocular mode. This is shown in Figure 7. It is *this* distribution which we will be fitting later to determine the significance of our observation of the GZK Cutoff. The calculated exposure (aperture times time) is shown in Figure 8. Dividing the event distribution by the exposure gives the spectrum, which is shown in Figure 9.

We performed a number of systematic cross checks on these data to ensure their accuracy. First we limited the distance to showers to 10 and 15 km. We saw no systematic change in the spectra in these cases, only variations due to reduced statistics. What is more, the Ankle feature is visible in the event distribution in the 10 km case. Second, we made a spectrum from the events which are in both the HiRes-I and HiRes-II samples, using the precision shower geometry measurement available in this case. All the other details of the analysis are the same as in the monocular analyses, and the spectrum agrees with our monocular spectra. This shows that the energy resolution in monocular mode is good enough not to distort the spectrum from the stereo measurement beyond the statistical power of the data we have collected. This was *not* true of Fly’s Eye.

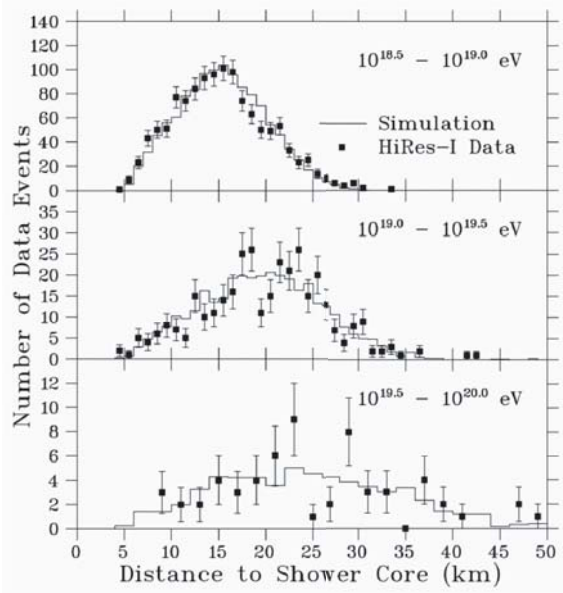


Figure 1. A Data/MC Comparison of the distance to the impact point from HiRes-I. The three panels show events in the different energy ranges as labeled. Data is shown as points with error bars, the MC as a histogram.

We also tested the aperture at 35 km, by reconstructing vertical laser shots at this distance. A variety of laser intensities were used, which we linked to cosmic ray energies based on the brightness of the tracks. Our detector becomes fully efficient for vertical showers at 35 km for showers with energies above 60 EeV.

Because we use a fit the Gaisser-Hillas profile to determine the shower energy, we compared the average shower profile in data to that calculated in MC using the Gaisser-Hillas profile. In each case the showers are normalized by X_{\max} (using the age parameter) and N_{\max} . Then the actual shower measurements are averaged in bins of the age parameter. The comparison is shown in Figure 10. This shows that the Gaisser-Hillas profile is appropriate to use for measuring shower energies.

To check the systematic uncertainty from

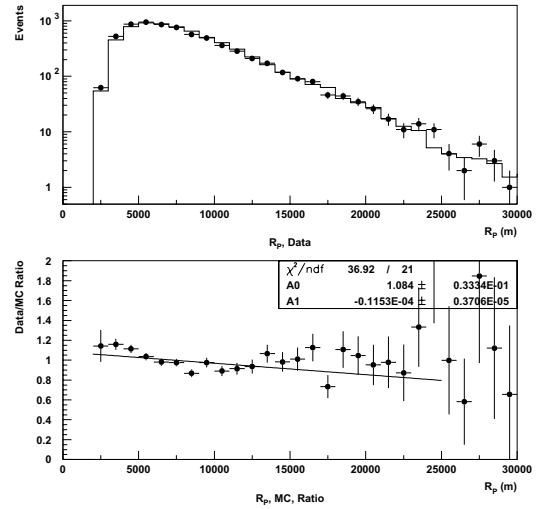


Figure 2. A Data/MC Comparison of the impact parameter, R_P , from HiRes-II. The top panel shows the data as points with error bars, the MC as a histogram. The MC has about five times the statistics as the data. The bottom panel shows the ratio of data to MC, with a linear fit over bins with more than 10 data events.

shower modeling, we calculated the aperture using both QGSJet and Sibyll[15]. It is important to note that we adjust the proton-to-iron ratio in each case to give identical mean X_{\max} values as a function of energy. With this requirement, we calculate identical apertures for both models within the MC statistics ($5\times$ the data) available.

We cannot claim to observe the Second Knee in the HiRes-II spectrum. The data statistics are limited and the aperture has a larger uncertainty than at energies above 10^{18} eV due to composition uncertainties and their effect on the aperture[15]. Because of this, we will only be fitting the spectra above $10^{17.5}$ eV.

We now move on to broken power law fits of the two HiRes monocular spectra. We will be fitting the spectra using a binned maximum likelihood method which uses the number of observed events

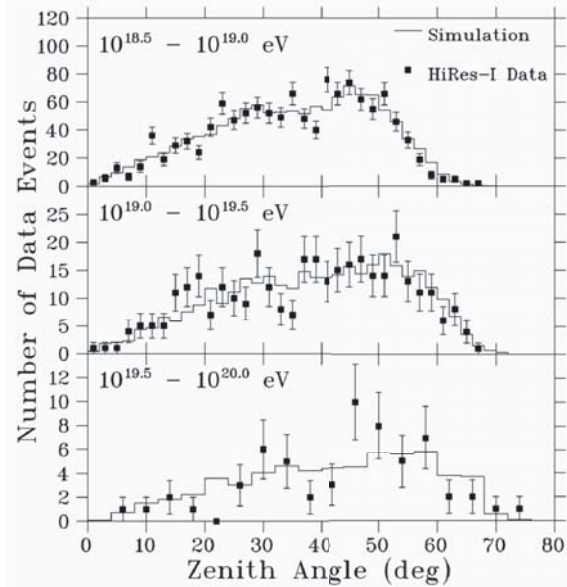


Figure 3. A Data/MC Comparison of the zenith angle in HiRes-I. The three panels show events in the different energy ranges as labeled. Data is shown as points with error bars, the MC as a histogram.

in a bin and the number of events expected. This will allow us to use empty bins in the data where there is a significant number expected from the power law. It also allows us use both data samples independently. A correction will be made at the end for events seen by both detectors. The number of expected events is given by the broken power law flux times the measured exposure. We will begin with no break points and add floating break points until there is no improvement in the χ^2 .

A fit of both datasets to a simple power law gives a χ^2 of 162 for 39 degrees of freedom, with a spectral index γ of 3.13 ± 0.01 . This is clearly not a good fit. Adding one floating break point gives a much better fit, and the break point finds the position of the Ankle. The χ^2 is now 68 for 37 degrees of freedom, with the break point at 4.3 ± 0.5 EeV, a spectral slope below the Ankle

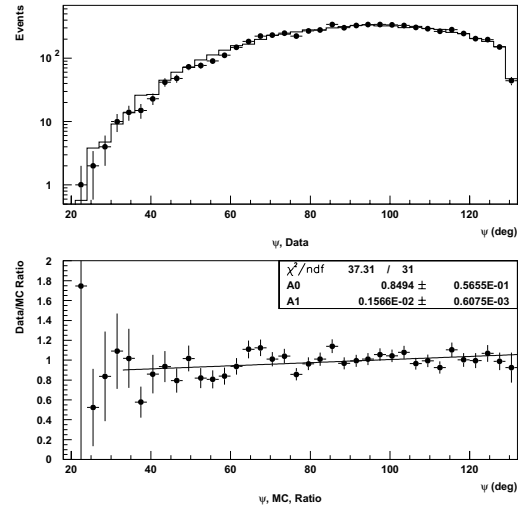


Figure 4. A Data/MC Comparison of the shower-detector plane angle, ψ , from HiRes-II. The top panel shows the data as points with error bars, the MC as a histogram. The MC has about five times the statistics as the data. The bottom panel shows the ratio of data to MC, with a linear fit over bins with more than 10 data events.

of $\gamma_1 = 3.24 \pm 0.02$ and a spectral slope above the Ankle of $\gamma_2 = 2.89 \pm 0.03$. Adding a third break point reduces the χ^2 by 33 to 34.7 for 35 degrees of freedom. The breakpoints are at 4.5 EeV and 56 EeV, while the three spectral indices are 3.24 ± 0.02 , 2.81 ± 0.03 and 5.4 ± 0.7 . This fit is shown in Figure 9. Adding a third breakpoint does not significantly reduce the χ^2 .

We calculate the significance of the break at 56 EeV by comparing the number of events expected above $10^{19.8}$ eV if the spectral index continued at 2.81 to the actual number of events observed. In this case we expect 51.1 events but observe only 15. The Poisson probability of observing 15 or fewer events when expecting 51.1 is 2.9×10^{-9} . In actuality, we have counted one event observed in stereo twice in our 15 observed events and have also counted expected events from overlapping ex-

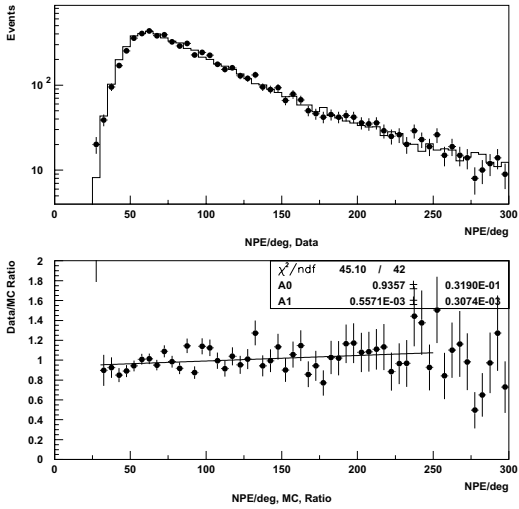


Figure 5. A Data/MC Comparison of the event brightness, total signal divided by track length, for HiRes-II. The top panel shows the data as points with error bars, the MC as a histogram. The MC has about five times the statistics as the data. The bottom panel shows the ratio of data to MC, with a linear fit over bins with more than 10 data events.

posure from the two sites. When each of these is taken into account we get a revised expectation of 44.9 events while observing 14. The Poisson probability in this case is 7×10^{-8} . For comparison the fraction of the area in one tail of a Gaussian beyond 5σ is 3×10^{-7} and beyond 6σ is 1×10^{-9} . Thus we claim a significance of over 5σ for our measurement of a high energy break point in the spectrum.

One way to compare the energy of this break-point to that expected of the GZK Cutoff is to use the $E_{1/2}$ method of Berezhinsky[16]. $E_{1/2}$ is the energy at which the integral spectrum falls to half of what would be expected in the absence of the feature. This HiRes monocular spectra are displayed as integral spectra in Figure 11 along with the two break point fit mentioned above and

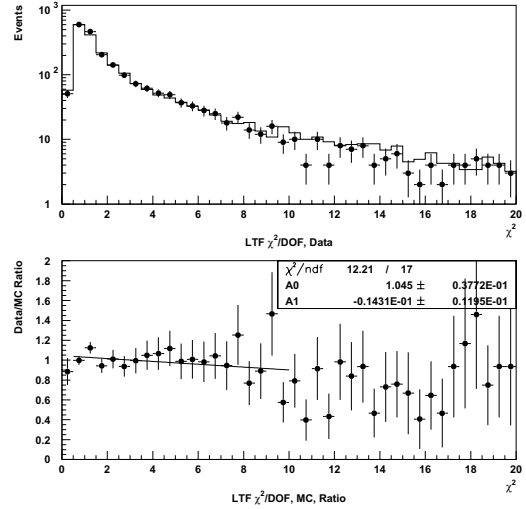


Figure 6. A Data/MC Comparison of the distribution of $\chi^2/rmDOF$ for a linear fit of tube time vs angle, for HiRes-II. The top panel shows the data as points with error bars, the MC as a histogram. The MC has about five times the statistics as the data. The bottom panel shows the ratio of data to MC, with a linear fit over bins with more than 10 data events.

the extension of this fit used to measure the significance of the high energy break point. Taking the ratio of the measured points to the extended fit allows us to measure $E_{1/2}$. This is shown in Figure 12. We find $\log E_{1/2} = 19.73 \pm 0.07$. The prediction Berezhinsky *et al*[16] for the GZK effect for a wide range of spectral indices is $\log E_{1/2} = 19.72$. In this way we have linked the energy of our measurement of a high energy break point to the GZK Cutoff.

In conclusion, HiRes has made a measurement of the UHECR spectrum using its two detectors in monocular mode. The aperture used for this measurement is well understood as verified by Data/MC comparisons. We observe a high energy break in the spectrum at the energy to be the GZK Cutoff and with a significance of over

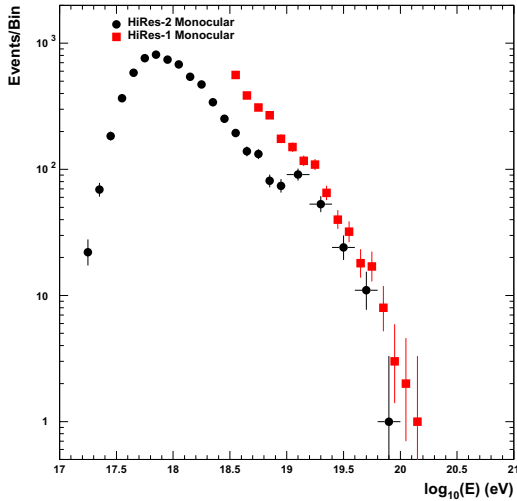


Figure 7. The number of events collected in each energy bin in monocular mode by HiRes-I and by HiRes-II. The jump in HiRes-II statistics at 10^{19} eV is due to the bins being twice as big in $\log E$.

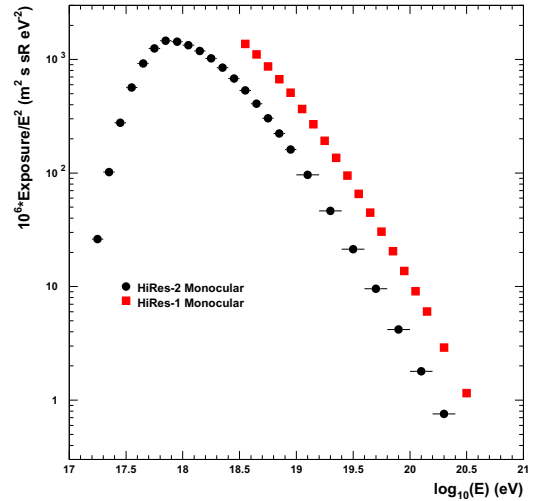


Figure 8. The calculated exposure of HiRes-1 and HiRes-II in monocular mode. The exposure has been divided by E^2 to make direct comparisons to the event distribution easier.

5σ . Thus we claim an observation of the GZK Cutoff.

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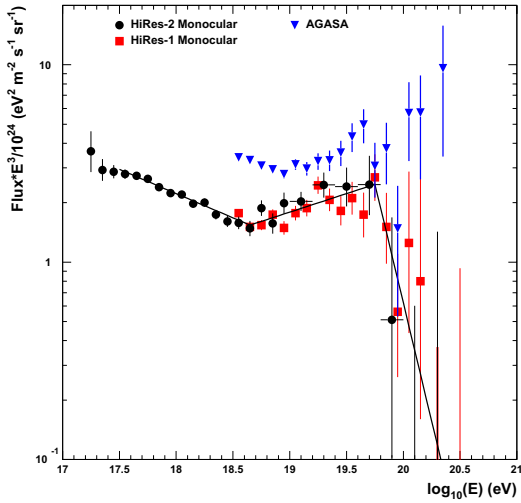


Figure 9. The measured UHECR spectra from HiRes-I and HiRes-II in monocular mode. Also shown is a recent AGASA spectrum for comparison. The HiRes-I and HiRes-II spectra have been fit to a broken power law spectrum with two break points. The result of this fit is also shown.

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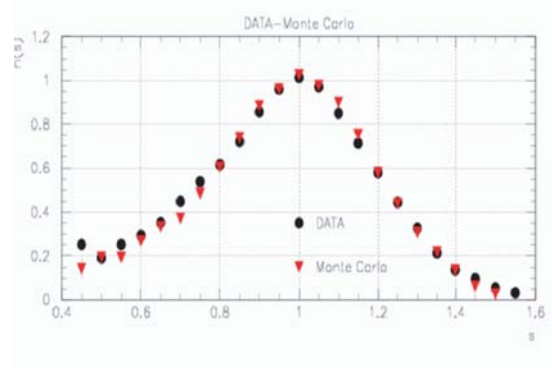


Figure 10. A Data/MC comparison of the average profile for showers in HiRes-II.

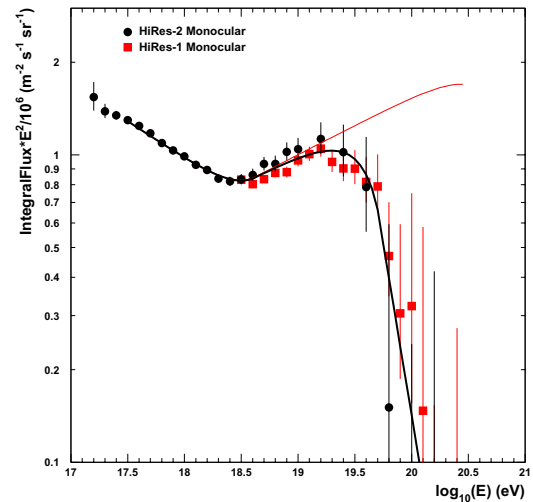


Figure 11. The integral spectra measured by HiRes-I and HiRes-II. Also shown are the integrated broken power law fits to the differential spectra. The black line shows the fit with two break points; the red line shows the same fit in which the high energy break point has been removed with no change in the other parameters.

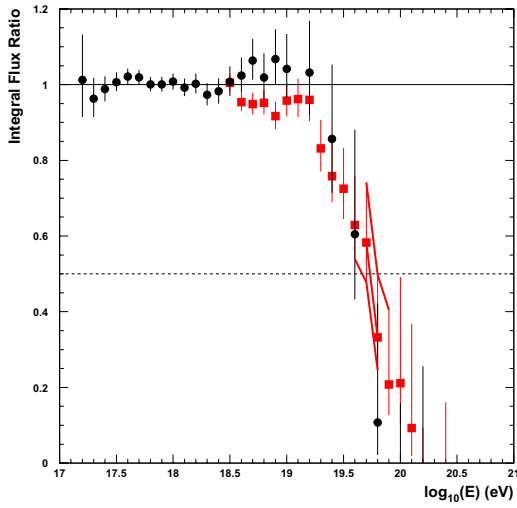


Figure 12. The ratio of the HiRes-I and HiRes-II integral spectra to the expected integral flux in the absence of a GZK cutoff. Only the HiRes-I values are used to make an estimate of $E_{1/2}$ by interpolating between the central value and 1σ uncertainty limits.