Measurement of the Flux of Ultrahigh Energy Cosmic Rays from Monocular Observations by the High Resolution Fly's Eye Experiment.

R. Abbasi[1], T. Abu-Zayyad[1], G.C. Archbold[1], J.A. Bellido[2], K. Belov[1], J.W. Belz[3], D.R. Bergman[4], J. Boyer[5], Z. Cao[1], R.W. Clay[2], B.R. Dawson[2], A.A. Everett[1], J.H.V. Girard[1], R.C. Gray[1], W. Hanlon[4], B.F Jones[1], C.C.H. Jui[1], D.B. Kieda[1], K. Kim[1], B. Knapp[5], W. Lee[5], E.C. Loh[1], K. Martens[1], G. Martin[6], N. Manago[7], E.J. Mannel[5], J.A.J. Matthews[6], J.N. Matthews[1], J.Meyer[1], S.A. Moore[1], P. Morrison[1], A.N. Moosman[1], J.R. Mumford[1], L. Perera[4], K. Reil[1], R. Riehle[1], M. Roberts[6], M. Seman[5], S.R. Schnetzer[4], P. Shen[1], K.M. Simpson[2], J.D. Smith[1], P. Sokolsky[1], C. Song[5], R.W. Springer[1], B.T. Stokes[1], S.B. Thomas[1], G.B. Thomson[4], S. Westerhoff[5], L.R. Wiencke[1], A. Zech[4], X. Zhang[5]

1) University of Utah, Department of Physics and High Energy Astrophysics Institute, Salt Lake City, Utah, USA

2) University of Adelaide, Department of Physics, Adelaide, South Australia, Australia

3) Montana State University, Department of Physics, Bozeman, Montana, USA

4) Rutgers - The State University of New Jersey, Department of Physics and Astronomy, Piscataway, New Jersey, USA

5) Columbia University, Department of Physics and Nevis Laboratory, New York, New York, USA

6) University of New Mexico, Department of Physics and Astronomy, Albuquerque, New Mexico, USA

7) University of Tokyo, Institute for Cosmic Ray Research, Kashiwa, Japan

Abstract

We have measured the cosmic ray spectrum above 10^{17} eV using the two air fluorescence detectors of the High Resolution Fly's Eye operating in monocular mode. We describe the detector, PMT and atmospheric calibrations, and the analysis techniques for the two detectors. We fit the spectrum to a model consisting of galactic and extragalactic sources. Our measured spectrum shows strong evidence for the GZK cutoff near 6×10^{19} eV.

The highest energy cosmic rays detected so far, of energies up to and above 10^{20} eV, are very interesting in that they shed light on two important questions. How they are accelerated in astrophysical sources, and how they can propagate to us through the cosmic microwave background radiation (CMBR), are not well-understood processes. The production of pions from interactions of CMBR photons and UHE cosmic rays is an important energy loss mechanism above about 6×10^{19} eV, and is called the Greisen-Zatsepin-K'uzmin (GZK) cutoff [1,2]; e^+e^- production in the same collisions is a somewhat weaker energy-loss mechanism above a threshhold of about 7×10^{17} eV. We report here a measurement of the flux of UHE cosmic rays from 2×10^{17} eV to over 10^{20} eV with the High Resolution Fly's Eye (HiRes) experiment.

The HiRes experiment consists of two air-fluorescence detectors separated by 12.6 km and located at the U.S. Army Dugway Proving Ground in Utah. Cosmic rays interacting in the upper atmosphere initiate a cascade of particles known as an extensive air-shower (EAS). Passage of charged particles excites nitrogen molecules causing emission of ultraviolet light. The HiRes experiment was designed to detect this *fluorescence* light stereoscopically. The fluorescence yield per particle has been previously measured in an electron beam [3]. From the longitudinal development of the signal, we can infer the arrival direction, energy, and composition of the primary cosmic ray. In this paper we present the cosmic ray energy spectra, measured in monocular mode, from the two detectors.

The two HiRes detector sites, referred to as HiRes-I and HiRes-II, are operated on clear, moon-less nights. Over a typical year, each detector accumulates up to 1000 hours of observation. The HiRes-I site has been in operation since June of 1997. It consists of 22 detector units, each equipped with a 5 m^2 spherical mirror and 256 photo-multiplier tube

(PMT) pixels at its focal plane. Each PMT covers a 1° cone of sky. Together, the 22 mirrors provide nearly full azimuthal coverage for elevation angles between 3 and 17°. The HiRes-I detectors use sample-and-hold integrators with a gate of 5.6 μs [4]. The HiRes-II site was completed in late 1999 and began observations that year. This site uses the same mirrors and PMT's as HiRes-I, but contains 42 mirrors, in two rings, covering elevation angles from 3 to 31°. HiRes-II uses an FADC data acquisition system operating at 10 MHz [5].

To determine the correct shower energies, the air fluorescence technique requires accurate measurement and monitoring of PMT gains. Two methods of calibration are in use. Pulses from a YAG laser are distributed to mirrors via optical fibers. They provide a nightly relative calibration. A stable, standard light source is used for a more precise monthly absolute calibration. Overall, the relative PMT gains were stable to within 3.5% and the absolute gains were known to within about 10% [6].

A second variable in energy measurement is atmospheric clarity. Light from air showers is attenuated by: (a) molecular (Rayleigh), and (b) aerosol scattering. The former is approximately constant, subject only to small variations due to atmospheric pressure. The aerosol concentration needs to be monitored continually. HiRes measures the aerosol content by observing scattered light from two steerable laser systems. The lasers observed by HiRes-I and HiRes-II have been in operation since 1999 and 2000, respectively. The vertical aerosol optical depth from ground to 4.0 km elevation, τ_A, is measured each hour. These measurements yielded an average τ_A of $0.04 \pm 0.02(stat.)^{+0.02}_{-0.00}(sys.)$ [7]. The statistical errors represent the RMS variation in aerosol content, and the systematic uncertainty reflects the assumption of minimal aerosol content in the clearest data samples. The average horizontal extinction length, Λ_H was determined to be 25 km. Therefore, our analysis used an exponential aerosol density profile with a scale height of $H_A = 1.0$ km and $\Lambda_H = 25.0$ km, corresponding average optical density of $\tau_A = H_A/\Lambda_H = 0.04$.

Between June, 1997 and September, 2001, the HiRes-I detector collected approximately 3100 hours of monocular data. From this set, 2410 hours of good weather data were selected for analysis, containing 125 million triggers, mostly consisting of noise. A subset of 4.7

million downward track-like events were found. For these events, a shower-detector plane was determined from the pattern of PMT hits. We then excluded events containing an average number of photo-electrons (pe) per PMT of less than 25; for these the fluctuations in signals are too great to permit reliable reconstruction of the shower profile. Lastly, we cut out tracks with angular speed in excess of $3.33^\circ/\mu$s, which are typically within 5 km of HiRes-I. For these events, the shower maxima appear above the field of view. A total of 10,968 events were selected for reconstruction.

Determination of the shower geometry is possible using a single detector by fitting the trigger times, t_i, of hits to the following function of the angles, χ_i, of hits above the horizon,within the event plane:

$$t_i = t_0 + \frac{R_p}{c} \tan\left(\frac{\pi - \psi - \chi_i}{2}\right) \tag{0.1}$$

Here R_p is the impact parameter, ψ the in-plane angle between the shower and the horizon, and t_0 the time of closest approach. With limited elevation coverage, HiRes-I monocular events are too short in angular spread for reliable determination of ψ and R_p by timing alone. For this analysis, the expected form of shower development itself was used to constrain the time fit to yield realistic geometries. The shower profile was assumed to be described by the Gaisser-Hillas parameterization

$$N(x) = N_m \left(\frac{x - x_0}{x_m - x_0}\right)^{(x_m - x_0)/\lambda} \exp\left(\frac{x_m - x}{\lambda}\right) \tag{0.2}$$

where $N(x)$, N_m are the number of particles at depth x and at shower maximum depth x_m, respectively. The first-interaction depth and shower elongation constant are denoted by x_0, and λ [8].This technique is called the profile-constrained fit (PCF). Equation 0.2 is in agreement with previous HiRes measurements [9], and with CORSIKA/QGSJET simulations [10–12]. Based on these, we fixed x_0 and λ at 40 and 70 g/cm^2, respectively. We allowed x_m to vary in 35 g/cm^2 steps between 680 and 900 g/cm^2, matching the expected range for proton to iron primaries in this energy range. Provided that the PCF converged, additional cuts were made to require a minimum track arc length of 8.0°, and a maximum depth for the highest elevation hit PMT of 1000 g/cm^2. We also rejected tracks with $\psi > 120°$, and those with two or more bins with >25% Čerenkov light. Significant contamination from direct Čerenkov light degrades the reliability of the PCF result. A total of 5,264 events remained after processing.

Monte Carlo (MC) studies were performed to assess the reliability of the PCF method. Not including atmospheric fluctuations, an RMS energy resolution of better than 20% was seen above 3×10^{19} eV. However, the resolution degrades at lower energies to about 25% at 3×10^{18} eV. These MC results were cross-checked by examination of a small set of stereo events where geometry is more precisely known. Comparing the energies reconstructed using monocular and stereo geometries, we obtained energy resolutions similar to those seen in the MC. The MC simulation is also used to calculate the detector aperture. To verify the reliability of this calculation, we compared the zenith angle (θ) and impact parameter (R_p) distributions from the data and simulation for at different energies. These yielded excellent agreement between data and MC. As an example, we show the comparison of R_p distributions at three energies in Figure 1.

FIGURES

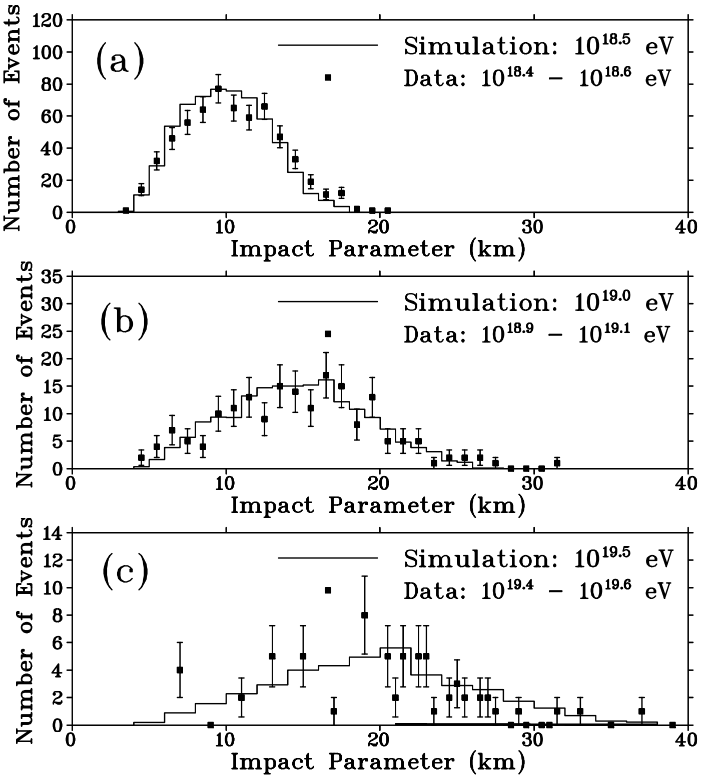

FIG. 1. Comparison of HiRes-I simulated (histogram) and observed (points) R_p distributions at (a) $10^{18.5}$, (b) $10^{19.0}$, and (c) $10^{19.5}$ eV. The MC distributions are normalized to the number of data events.

The analysis of HiRes-II monocular data was similar to that for HiRes-I. However, with greater elevation coverage, it was feasible to reconstruct the shower geometry from timing alone. Since Eqn. 0.1 is linear in R_p and t_0, we find the best value for these variables analytically for each ψ; the best ψ is then found by χ^2 minimization. Only events which were moving down in elevation angle were kept as part of the signal sample. At this stage 104,048 events remained in the sample taken during 142 hours of good weather conditions between Dec. 1999 and May 2000.

With the geometry of the shower known, we fit the observed light signal to the Gaisser-Hillas parameterization of Eqn. 0.2. We collected photo-electrons from all tubes into a sequence of time bins. This exploited the FADC data acquisition system and lessened our sensitivity to PMT acceptance. The events were required to have a good fit to the Gaisser-

Hillas function. They were also required to have a track length greater than 10° for upper ring or multi-mirror events, a track length greater than 7° for lower ring events, an angular speed less than $11°/\mu$s, a zenith angle less than 60°, and a shower maximum visible in our detector. There was also a cut on the size of the Čerenkov light subtraction at $< 60\%$ of signal. There were 781 events left after these cuts. We also found the simulations to give excellent reproduction of data for HiRes-II, as seen, for example, in the comparison of the number of photo-electrons per degree of track in Fig. 2.

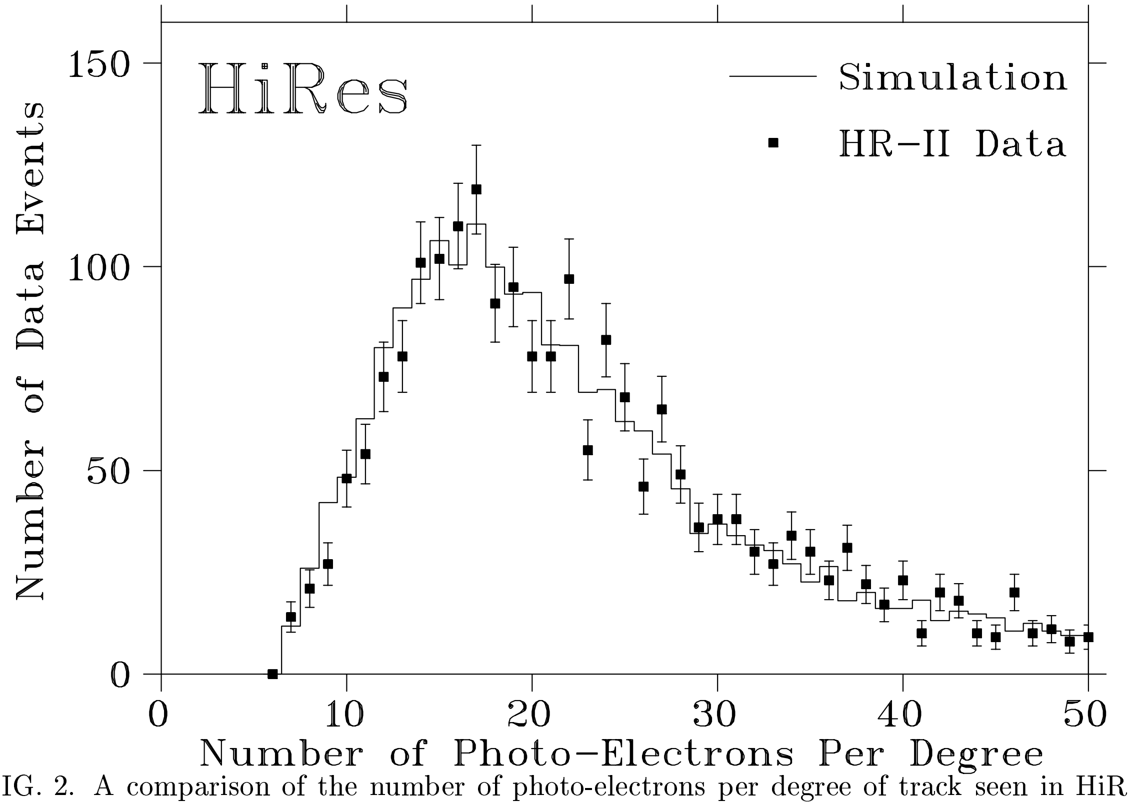

FIG. 2. A comparison of the number of photo-electrons per degree of track seen in HiRes-II monocular events (data points) and in simulation (histogram).

For both HiRes-I and HiRes-II events, the photo-electron count was converted to a shower size at a given atmospheric depth, using the known geometry of the shower, and corrected for atmospheric attenuation. We integrated the resulting function over x (using the determined values of N_m and x_m) and multiply by the average energy loss per particle (2.19 MeV/g/cm^2) to give the visible shower energy. The visible energy was corrected for energy carried off by non-observable particles to give the total shower energy.

The monocular reconstruction apertures are shown in Fig. 3. Values for both HiRes-I and HiRes-II approach 10^4 km^2 sr. above 10^{20} eV. We restrict our result for HiRes-I to energies $> 3 \times 10^{18}$ eV; below this energy the PCF technique becomes unstable. Due to the longer tracks and additional timing information, the RMS energy resolution for HiRes-II remains better than 30% down to 10^{17} eV. However, this data sample becomes statistically depleted at above 10^{19} eV.

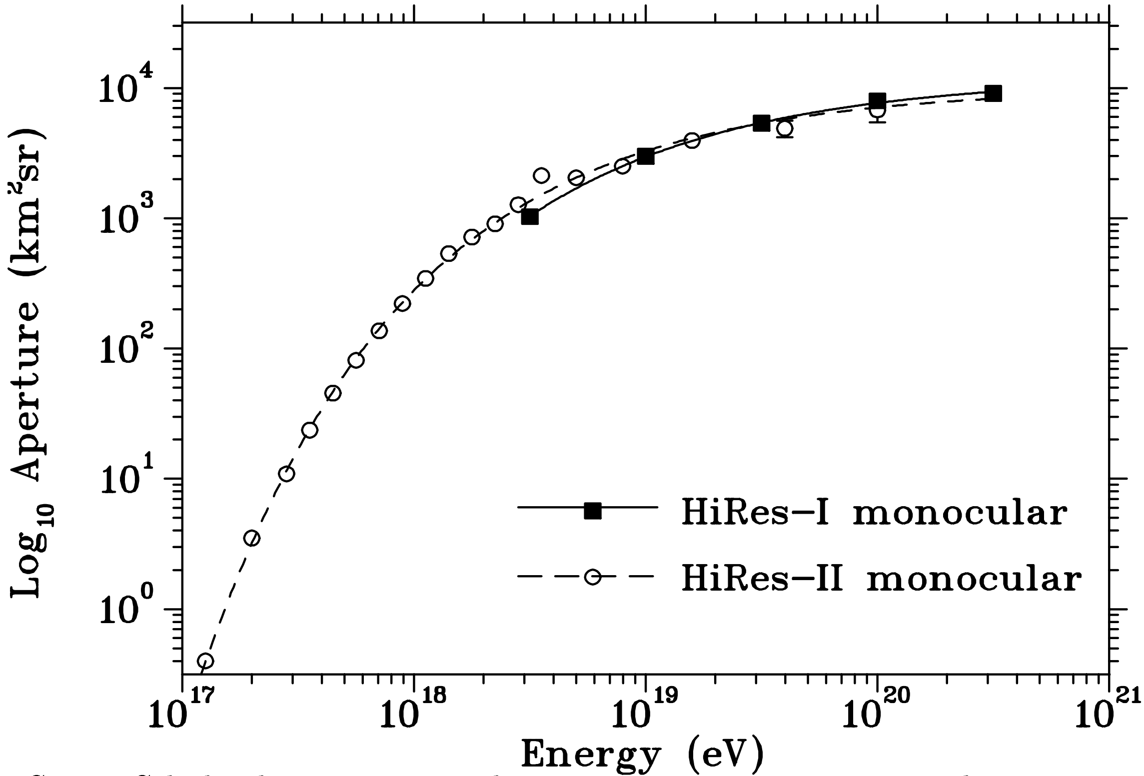

FIG. 3. Calculated HiRes monocular Reconstruction aperture in the energy range $10^{17} - 3 \times 10^{20}$ eV. The HiRes-I aperture is shown by the dashed curve, and the HiRes-II aperture by the dotted curve.

We calculated the cosmic ray flux for HiRes-I above 3×10^{18} eV, and for HiRes-II above 2×10^{17} eV. This combined spectrum is shown in Fig. 4, where the flux has been multiplied by E^3. The error bars represent the 68% confidence interval for the Poisson fluctuations in the number of events only. The HiRes-I flux is the result of two completely independent analyses [13,14], which yielded essentially identical flux values.

The largest systematic uncertainties (and their values) are the absolute calibration of the phototubes (±10%) [6], the yield of the fluorescence process (±10%) [3], the correction for unobserved energy in the shower (±5%) [10,17], and the modeling of the atmosphere [7]. To test the sensitivity of the flux measurement to uncertainties in atmospheric conditions we reanalyzed the data and generated new Monte Carlo samples with τ_A lowered by one (statistical) standard deviation. This lowered J(E) on average by $(15 \pm 5)\%$ and introduced a slope into our results of (-20±5)% per decade of energy. Adding these uncertainties in quadrature yields a net systematic uncertainty in J(E), averaged over energy, of 21%. This uncertainty is common to the fluxes for HiRes-I and HiRes-II. There is an additional relative calibration uncertainty between the two sites which is less than 10%.

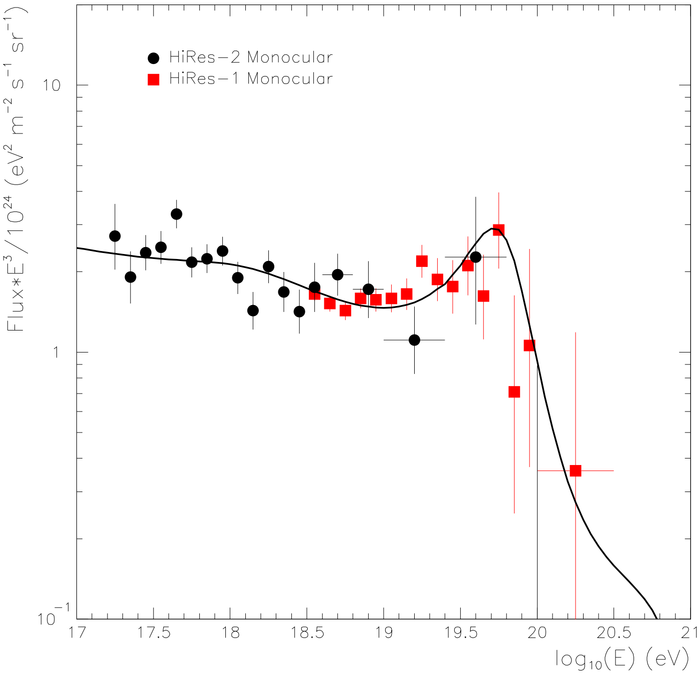

FIG. 4. Combined HiRes monocular energy spectrum. The squares and circles represent the cosmic ray flux measured by HiRes-I and HiRes-II, respectively. The line is a fit to the data of a model, described in the text, of galactic and extragalactic cosmic ray sources.

Our spectrum contains five events above the GZK cutoff at 6×10^{19} eV [1,2], and only one above 10^{20} eV. The observed light curve of the highest energy event is shown in Fig. 5. Its energy is measured at 1.8×10^{20} eV. The fitted geometry was found to be insensitive to variations in aerosol parameters. Assuming a purely molecular atmosphere ($\tau_A = 0.0$), we obtain a lower energy limit of 1.5×10^{20} eV.

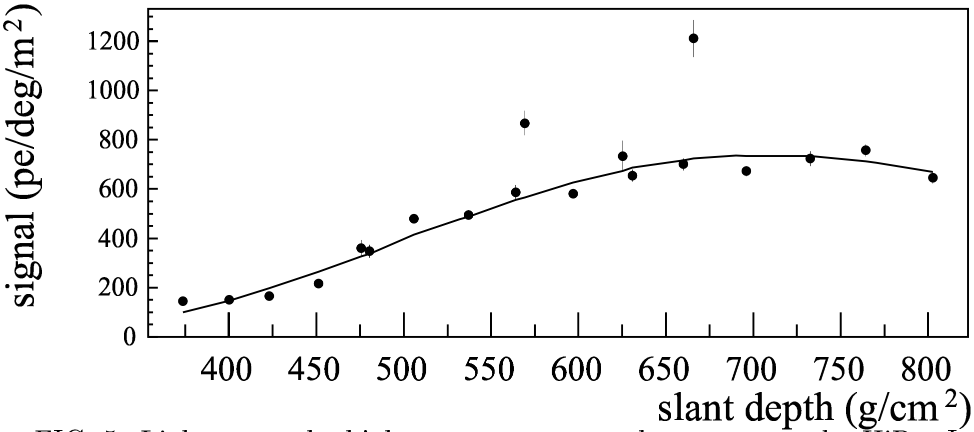

FIG. 5. Light curve the highest energy monocular event seen by HiRes-I.

In the energy range where both detectors' data have good statistical power the results agree with each other very well. The data shows the break in the power law index called the "second knee" at about 7×10^{17} eV, and the dip called the "ankle" at about 4×10^{18} eV.

The HiRes spectrum falls steeply above 6×10^{19} eV as expected if the GZK cutoff were in action. As an example of what one would expect we have fit the data to a model that consists of two sources for cosmic rays, galactic and extragalactic, which includes the GZK cutoff. We use the extragalactic source model of Berezinsky *et al.* [18] which assumes that protons come from sources distributed uniformly across the universe, and lose energy by pion and e^+e^- production from the cosmic microwave background radiation, as well as from the expansion of the universe. Since the measured composition [15] is heavy at the lower end of our energy range, with the iron content decreasing linearly with $\log E$, we approximate the galactic component of cosmic rays as falling with an $E^{-3} \times (19.5 - \log E)$ spectrum between $17.0 < \log E(eV) < 19.5$. The model includes the experimental resolution, and an end to the extragalactic spectrum (at the source) at 1×10^{21} eV. The fitting parameters of the model are the normalization of the galactic events, and the power law index and normalization (at the source) of extragalactic cosmic rays. The fit is excellent with χ^2 of 40.5 for 32 degrees of freedom. In this model the peak at $\log E$ of 19.8 is due to pion production pile-up, the ankle is made by losses due to e^+e^- production, and the second knee comes from e^+e^- production pile-up.

REFERENCES

[1] K. Greisen, Phys. Rev. Lett. **16**, 748, (1966).

[2] G.T. Zatsepin and V.A. K'uzmin, Pis'ma Zh. Eksp. Teor. Fiz. **4**, 114 (166) [JETP Lett. **4**, 78 (1966)].

[3] F. Kakimoto *et al.*, NIM **A 372**, 527 (1996).

[4] T. Abu-Zayyad *et al.*, Proc. 26th Int. Cosmic Ray Conf. (Salt Lake City), **5**, 349, (1999).

[5] J. Boyer, B. Knapp, E .Mannel, and M. Seman, to be published in NIM.

[6] T. Abu-Zayyad *et al.*, to be submitted to NIM.

[7] T. Abu-Zayyad *et al.*, in preparation.

[8] T. Gaisser and A.M. Hillas, Proc. 15th Int. Cosmic Ray Conf. (Plovdiv), **8**, 353, (1977).

[9] T. Abu-Zayyad *et al.*, Astropart. Phys. **16**, 1, (2001).

[10] C. Song, Z. Cao *et al.*, Astropart. Phys. **14**, 7, (2000).

[11] D. Heck, J. Knapp, J.N. Capdevielle, G. Schatz and T. Thouw "CORSIKA : A Monte Carlo Code to Simulate Extensive Air Showers", Report FZKA 6019 (1998), Forschungszentrum Karlsruhe.

[12] N.N. Kalmykov, S.S. Ostapchenko and A.I. Pavlov, Nucl. Phys. B (Proc. Suppl.) **52B**, 17, (1997).

[13] T. Abu-Zayyad, Ph.D Thesis, University of Utah (2000).

[14] X. Zhang, Ph.D Thesis, Columbia University (2001).

[15] D.J. Bird *et al.*, Phys. Rev. Lett. **71**, 3401, (1993).

[16] D.J. Bird *et al.*, Astrophysical J. **441**, 144, (1995).

[17] J. Linsley, Proc. 18th Int. Cosmic Ray Conf. (Bangalore), **12**, 135, (1983).

[18] V. Berezinsky, A.Z. Gazizov, S.I. Grigorieva, hep-ph/0204357.