Evidence for a High-Energy Cosmic-Ray Spectrum Cutoff

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We report a measurement of the ultrahigh-energy cosmic-ray spectrum using an atmospheric fluorescence technique for extensive–air-shower detection. The differential spectrum between 0.1 and 10 EeV (1 EeV $= 10^{18}$ eV) is well fitted by a power law with slope 2.94 ± 0.02. Above 10 EeV evidence is presented for the development of a spectral "bump" followed by a cutoff at 70 EeV.

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In 1966, Roll and Wilkinson[1] reported the first confirmation that the intense isotropic radiation observed earlier by Penzias and Wilson[2] was thermal in nature and all pervasive, characteristic of a universe cooled to a temperature of 2.7 K. Given the previous report by Linsley[3] of the detection of a primary cosmic ray with an energy estimated to be in excess of 100 EeV, Greisen[4] astutely realized that the spectrum of such energetic cosmic-ray primaries, if their sources were predominantly of extragalactic origin, should steepen abruptly. Such a steepening results naturally from the rapid onset of opacity to passage through the universe of ultrahigh-energy cosmic rays due to energy degradation from photopion production off the 2.7-K blackbody radiation. Thus, the cosmic-ray spectrum would appear to terminate at energies near production threshold at 60 EeV. Here we present evidence confirming the early prediction of Greisen and the more recent calculations of Hill and Schramm[5] which indicate the development of a spectral "bump," due to pileup of the recoil protons, prior to the onset of the "Greisen cutoff."

We report here the energy spectrum obtained using the Fly's Eye detector situated at 41° N latitude in the western Utah desert at an atmospheric depth of 852 g cm^{-2}. The detector differs from conventional extensive–air-shower (EAS) detectors in that it is essentially a calorimetric device which observes the passage of EAS through the atmosphere by means of the nitrogen fluorescence light given off upon ionization and excitation by the relativisitic charged particles in the shower.[6] Events have been detected with impact parameters as far away as 22 km. The effective collecting aperture is thus very large. However, since the apparatus must detect a very low light flux, observing periods are restricted to clear, moonless nights which greatly negates the benefits of large aperture. The data collected for this analysis were obtained during a total elapsed time of 33 months and an actual live time of 0.145 yr. The duty cycle is 6.3%.

The techniques of track reconstruction and conversion of measured photoelectron yields into shower size versus atmospheric slant depth have been described elsewhere.[6] Shower energies are assigned by integration of the resultant longitudinal shower development curve to obtain the total track length. Track lengths are then converted into total "electromagnetic" energy via the relation

$$Eem = (\epsilon/X_0)\int Ne\,(x)dx,$$

where ϵ/X_0, the ratio of the critical energy of an electron to its radiation length in air, represents the total rate of energy loss by ionization and excitation.[7] We take $\epsilon = 81$ MeV and $x_0 = 37.1$ g cm^2 giving an energy loss rate of 2.18 MeV/g cm^{-2}.[8] (Independent estimates of this loss rate were made by integration of dE/dX over the energy distribution of electrons in showers calculated by Hillas,[9] and a value of 2.24 MeV/g cm^{-1} was obtained.) In order to estimate the total energy of the primary cosmic ray, we correct for undetected energy lost via (1) neutrals that fail to decay into detectable charged particles before striking ground, (2) high-energy muons which lose most of their energy in the earth, and (3) nuclear excitations by the hadrons in the shower. The correction factor was obtained by parametrizing the estimates of lost energy derived by Linsley[10] by demanding consistency among a wide variety of cosmic electron and muon size measurements. Application of the correction yields total energy estimates which are larger than the derived electromagnetic energy by factors which range from 13% at 0.1 EeV to 5% at 100 EeV.

Resultant total energies are statistically accurate to within $\pm 15\%$. Systematic inaccuracy is estimated to be less than 15% on the basis of extensive calibration procedures including a detailed analysis of the detection of scattered light generated by nitrogen laser shots used to simulate EAS events.[6]

Confidence that our analysis procedure leads to correct energy assignments can be gained by noting that our measured values of ratio of total energy to maximum shower size, $E/N_{\max}$, and equivalent Gaussian width σ of the shower at $E = 1.0$ EeV are 1.3 ± 0.18 GeV/electron and 220 ± 33 g cm^{-2}, respectively. These values agree favorably with estimates made by Linsley[10] on the basis of cosmic ray data and by Hillas[11] on the basis of Monte Carlo simulations of shower development which incorporate radial scaling and measured high-energy cross sections at accelerators suitably extrapolated to EAS energies.

Differential spectra are calculated in the usual way,

$$j(E) = [tA\,\Omega(E)]^{-1} dN/dE,$$

where $A\,\Omega(E)$ is the efficiency-corrected acceptance in km^2 sr) for events with energy between E and $E+dE$. The acceptance has been calculated from a Monte Carlo simulation of the Fly's Eye experiment in which an isotropic cosmic-ray flux incident upon a model atmosphere is generated from quasirandomly selected trajectories and depths of first interactions. The shapes of the Monte Carlo showers are based upon those obtained from the real data sample in order to ensure self-consistency between the Monte Carlo–derived and the real, but unknown, acceptance. The high degree of success which the Monte Carlo simulation has attained in correctly representing real data distributions has been described elsewhere.[6] The resultant acceptance, obtained from the calculated detection efficiency of the isotropic flux on the simulated experiment and suitably corrected for track reconstruction and longitudinal development fitting efficiencies, is shown in Fig. 1. Overall reconstruction and fitting efficiencies vary from factors of roughly 50% at $E = 0.1$ EeV to 70% at $E = 100$ EeV so that the basic shape of the plotted acceptance is that of the simulated detection efficiency. At the highest energies the acceptance for events in excess of 100 EeV is close to 1000 km^2 sr. Accumulated total Fly's Eye exposure for such events is thus far about 145 km^2 sr yr.

The derived differential spectrum is shown in Fig. 2(a) plotted as $E^3 j(E)$. It is essentially flat with the appearance of a bump roughly between 10 and 50 EeV.

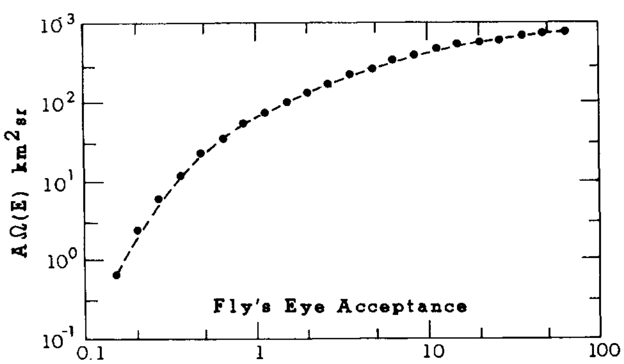

FIG. 1. Fly's Eye acceptance $A\,\Omega(E)$ for events with energy between E and $E+dE$. Acceptance is based on triggering efficiencies obtained from a Monte Carlo simulation of the Fly's Eye experiment (Ref. 6) and then corrected for track reconstruction and longitudinal development fitting efficiencies.

The number of events in that interval is 62. If the spectrum continued with the same slope ($\gamma = 2.94 \pm 0.02$) as obtained for energies < 10 EeV, the number of events between 10 and 50 EeV would be 46. The uncertainty in the extrapolated value is small, and hence the significance of the bump is roughly $16/\sqrt{46} \approx 2.4\sigma$. We also note that the spectrum between 10 and 50 EeV exhibits a slope of 2.42 ± 0.27 which is about 2σ flatter than the lower energy value.

In order to compare our results with those of previous experiments[10,12,13] we plot our derived integral spectrum in Fig. 2(b) as $E^{1.5} I(>E)$. At energies ranging from 1 to 50 EeV the overall agreement between our data and that of the Haverah Park experiment is quite good. Below 1 EeV and above 50 EeV there is disagreement. We note that a shift in energy scale cannot be invoked to raise the lower-energy points relative to the higher-energy ones. The spectral

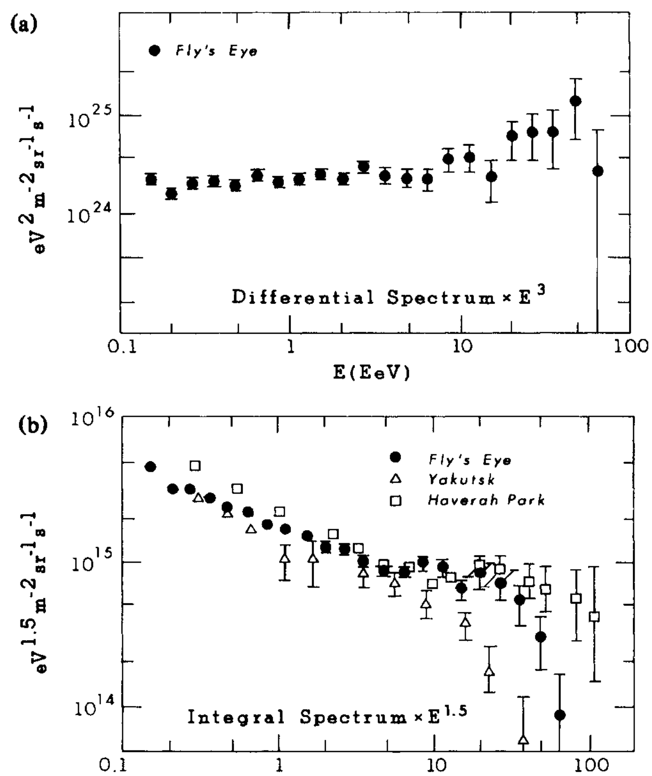

FIG. 2. (a) Differential spectrum $j(E)$ plotted as $E^3 j(E)$. A power-law best fit of the form $j(E) = aE^{-\gamma}$ yields $a = 109.6 \pm 2.2$ EeV^{-1} km^{-2} sr^{-1} yr^{-1} and $\gamma = 2.94 \pm 0.02$ for events at $E < 10$ EeV. Between 10 and 50 EeV we obtain $a = 34 \pm 17$ EeV^{-1} km^{-2} sr^{-1} yr^{-1} and $\gamma = 2.42 \pm 0.27$. The lack of events above 50 EeV indicates that the flattened slope does not continue. (b) Integral spectrum $I(>E)$ plotted as $E^{1.5} I(>E)$. Data from both Haverah Park and Yakutsk (Refs. 10, 12, and 13) experiments are also shown.

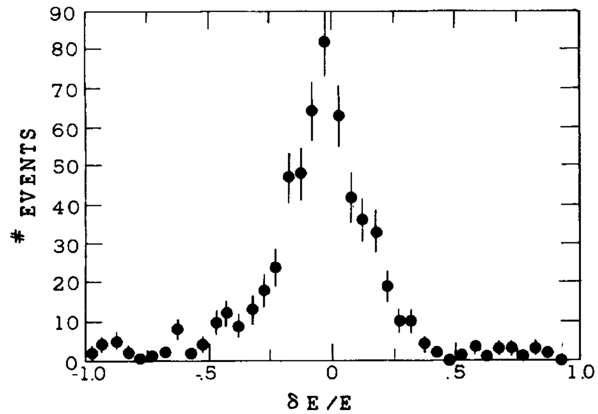

FIG. 3. Monte Carlo response function $(E_{in}-E_{out})/E_{in}$. Virtually no systematic shift is indicated between Monte Carlo assigned energies E_{in} and analyzed energies E_{out}. Resolution of ±15% is identical with assessed resolution of real data and exhibits almost no energy dependence.

shape is invariant under a scale change since the scales of both the event energy and energy-dependent acceptance would change coherently. Only an unknown discrepancy between the Monte Carlo and real-data energy assignments could result in a spectral index shift. This possibility has been tested by subjecting the Monte Carlo data to the same analysis as the real data. The resulting energy response function (energy "out" versus energy "in") of Fig. 3 shows excellent agreement between the two energy scales.[6] Errors in reconstruction and fitting efficiency estimates in the lower energy region $E < 1$ EeV where the acceptance is rapidly changing could account for the differences observed there between our results and those of the Haverah Park group. Such a possibility is currently under investigation although the outcome will not affect our conclusion regarding the discrepancy which appears to be developing in the energy region $E > 50$ EeV where we have detected only one event. An extrapolation of our measured differential spectrum between 10 and 50 EeV indicates that we should have seen 11 ± 5 events at $E > 50$ EeV. Based upon the Haverah Park spectrum we should have detected 7 ± 2 events at $E > 50$ EeV with 2 of them at $E > 100$ EeV. Thus, the discrepancy between detected and anticipated numbers of events above 50 EeV is 2σ below our own expectations if the flattened spectrum continued and 3σ below those based upon the Haverah Park data.

We consider whether or not the apparent termination of the spectrum could be accounted for by a failure of the detector to register events at $E > 50$ EeV. The estimate of numbers of events which should have been detected at $E > 50$ EeV is based on the acceptance at 50 EeV where excellent agreement is obtained between our measured differential spectrum and that of Haverah Park.[12] About 80% of the "missed" events at $E > 50$ EeV should have fallen within the 50-EeV acceptance where they would have been detected with even greater probability than the ones actually registered because of the increased brightness of the resultant EAS.

We also consider whether or not the appearance of a bump or an ankle in our data at the tail end of a steeply falling spectrum could result from a response function that varied with energy. We have extensively investigated the distribution of errors in energy assessment and find no significant behavioral differences between the low-energy and high-energy populations.

Hence, it is our conclusion that the "ankle" in the cosmic-ray spectrum at 10 EeV is most propably a "bump" as predicted by Hill and Schramm[5] which is followed by a spectral "cutoff" at about 70 EeV as originally predicted by Greisen.[3] We note that these spectral features imply that ultrahigh-energy cosmic rays are of extragalactic origin and have traveled distances on the order of 70–150 Mpc or roughly the scale of intercluster spacing. Unequivocal verification of this result requires better statistics and should be augmented by both anisotropy and compositional studies. Such efforts are in progress.

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[1]P. G. Roll and D. T. Wilkinson, Phys. Rev. Lett. **16**, 405 (1966).

[2]A. A. Penzias and R. W. Wilson, Astrophys. J. **142**, 419 (1965).

[3]J. Linsley, Phys. Rev. Lett. **10**, 146 (1963).

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

[5]C. T. Hill and D. N. Schramm, Phys. Rev. D **31**, 564 (1984), and Phys. Lett. **131B**, 247 (1983).

[6]R. M. Baltrusaitis *et al.*, Nucl. Instrum. Methods (to be published).

[7]B. Rossi, *High Energy Particles* (Prentice-Hall, Englewood Cliffs, N. J., 1952), Chap. 5.

[8]O. I. Dozhenko and A. A. Pomanskii, Zh. Eksp. Teor. Fiz. **45**, 268 (1963) [Sov. Phys. JETP **18**, 187 (1964)].

[9]A. M. Hillas, J. Phys. G **8**, 1461 (1982).

[10]J. Linsley, in *Proceedings of the Eighteenth International Cosmic Ray Conference, Bangalore, India,* edited by P. V. Ramana Murthy (Tata Institute of Fundamental Research, Bombay, 1983), Vol. 12, p. 135.

[11]A. M. Hillas, in *Proceedings of the Cosmic Ray Workshop, University of Utah,* edited by T. K. Gaisser (Bartol Research Foundation of the Franklin Institute, University of Delaware, Newark, Del., 1983).

[12]G. Cunningham *et al.*, Astrophys. J. Lett. **236**, L171 (1980).

[13]O. S. Diminstein *et al.*, Bull. Naushno-technithekoj Informasii, Yakutsk, USSR **9**, 537 (1982).