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Observation of a Very Energetic Cosmic Ray Well Beyond the Predicted 2.7 K Cutoff in the Primary Energy Spectrum

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A very energetic cosmic ray of energy about $(1.7-2.6) \times 10^{20}$ eV was observed by the Akeno Giant Air Shower Array on 3 December 1993 from the direction of galactic longitude $l = 131°$ and galactic latitude $b = -41°$ within an error circle of 1.0° radius. If this cosmic ray were a proton, its origin could be extragalactic. However, the distance of the source cannot be much more than a few times 10 Mpc due to the energy loss during its travel from interactions with universal background radiation.

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It has been suggested that there might be a cutoff in the energy spectrum of primary cosmic rays around 10^{20} eV, if they are of extragalactic origin, since those cosmic rays lose their energy during traveling in the intergalactic space as a result of their interaction with universal background radiation. This cutoff is called the "GZK cutoff" after predictions by Greisen [1] and Zatsepin and Kuźmin [2].

By combining all data accumulated for more than 30 years from the experiments at Volcano Ranch [3], at Haverah Park [4], at Sydney [5], at Yakutsk [6], at Dugway [7], and at Akeno [8], the significance of evidence for the GZK cutoff has increased. That is, only several cosmic rays exceeding 10^{20} eV have been observed, compared with an expectation of more than 25 if there is no cutoff and the spectrum extends beyond 10^{20} eV with the same slope [9]. The extragalactic origin of the highest energy cosmic rays is supported by their uniform distribution over the celestial sphere and the flattening of the primary energy spectrum around 10^{19} eV.

Modifications of the injected energy spectrum of extragalactic cosmic rays in intergalactic space have been studied in detail by many authors [10–13]. It is now generally accepted by these calculations that there will be a cutoff in the energy spectrum below 10^{20} eV, unless the sources are relatively near to our galaxy (within a few times 10 Mpc).

Therefore detection by the Fly's Eye detector [7] of a 3×10^{20} eV cosmic ray, well beyond the expected cutoff energy, has posed a puzzle concerning its origin. We report here in some detail another big extensive air shower (EAS) produced by a cosmic ray exceeding 10^{20} eV which was observed at Akeno on 3 December 1993.

In the Akeno Giant Air Shower Array (AGASA), 111 scintillation detectors of 2.2 m^2 area are arranged on the surface with detector separation of approximately

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1 km. Proportional counters shielded by concrete or iron-lead plates are also deployed at 27 positions of the 111 surface detectors. The threshold energy of muons is about 0.5 GeV. The AGASA is divided into four branches, the "Akeno Branch," the "Sudama Branch," the "Takane Branch," and the "Nagasaka Branch." The largest event reported here hit near the center of the Akeno Branch with a zenith angle of 22.9 deg. The details of the array are described by Chiba *et al.* [14].

The details of the event are summarized in Table I. In Fig. 1 a map is shown of the particle density distribution at each detector position, where the radii of the circles represent the logarithm of the particle densities (per m^2). It is seen that the shower core hits near the center of the Akeno Branch. Figure 2 is a lateral distribution of charged particles (LDF), whose core is determined by fitting particle densities to the following function:

$$S(R)=C\left(\frac{R}{R_M}\right)^{-1.2}\left(1+\frac{R}{R_M}\right)^{-(\eta-1.2)}\left[1.0+\left(\frac{R}{1000}\right)^2\right]^{-0.6},$$

where R is distance from the core in m, R_M is 91.6 m at Akeno, and C is a normalization factor. η is a function of the arrival direction's zenith angle θ and is expressed by $\eta = 3.97 - 1.79(\sec\theta - 1)$. This function was determined previously for showers between 10^{18} and 10^{19} eV [15]. No energy dependence of η is observed in that energy range. It is found that the lateral distribution of this giant EAS can be well fitted to Eq. (1) up to 2.5 km from the core with η determined from the 10^{19} eV region.

As will be described later, we use the particle density at 600 m from the core $S_0(600)$ [subscript represents zenith angle] as an energy estimator. The $S_{23}(600)$ of this event at the zenith angle 23° is determined to be 892 m^{-2}. If we convert this density to the vertical $S_0(600)$ by using the attenuation length determined in the 10^{19} eV region [15], we find $S_0(600) = 1065$ m^{-2}. If this shower is at maximum shower development, the attenuation correction may be inappropriate. Therefore $S_0(600)$ should be between 892 and 1065 m^{-2}.

TABLE I. Details of the most energetic event.

Event number	#akn25400-0296
Date	3 December 1993
Incident time	12:32:47 UT
Zenith angle	22.9 deg
Error circle in arrival direction determination	1.0° radius
Determined $S_{23}(600)$	892 m^{-2}
Error in $S_{23}(600)$ determination	+21 and −6.6%
$S_0(600)$	892–1065 m^{-2}
Primary energy	$(1.7–2.6) \times 10^{20}$ eV
Right ascension	18.9 deg
Declination	21.1 deg
Galactic longitude	131 deg
Galactic latitude	−41 deg
Exposure for the event	5.0×10^{15} m^2 sec sr

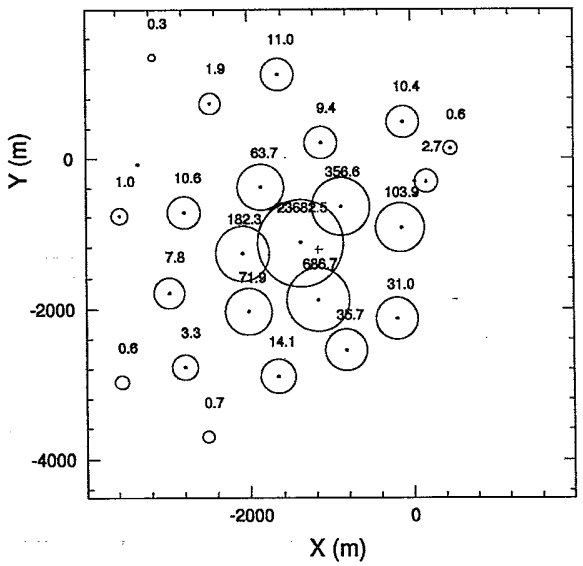

FIG. 1. Map of the density distribution of the giant EAS. The radius of each circle represents the logarithm of the density at each detector location. A cross shows the estimated position of the shower core.

The muon densities observed in each detector at different core distances are also plotted in Fig. 2. Each detector in this event consists of 11–18 proportional counters of 0.2–0.5 m^2 area. Within 1000 m from the core, most proportional counters exceeded their dynamic ranges, and hence the number of particles cannot be determined un-

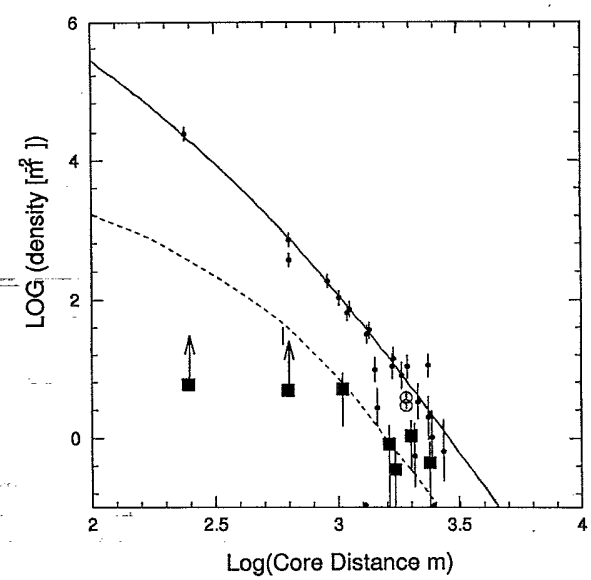

FIG. 2. The lateral distribution of charged particle (closed circles) and muons (shadowed squares). The large open circle is that measured by a detector for arrival time distribution. The expected lateral distribution of charged particles is shown by a solid line and that of muons by a dotted line.

ambiguously. Only lower limits are plotted with arrows for points within 1000 m from the core.

The lateral distribution of muons ($\geq$0.5 GeV) drawn by a dotted line in the figure is obtained by fitting the experimental points beyond 1000 m from the core to our recent function [16] determined at Akeno for energies between $10^{16.5}$ and $10^{19.5}$ eV.

The estimated $\rho_\mu(600)$ for this event is plotted by an open circle in Fig. 3. The filled circles in that figure are average values in each bin for the $\rho_\mu(600)$ vs $S(600)$ relation observed by the AGASA. The solid line is a fit for $0.8 < \log_{10}[S_0(600)] < 2.4$, and the dashed line is its extrapolation. A dotted bar at $\log_{10}[S(600)] = 2.95$ indicates an extrapolated uncertainty. It is found that $\rho_\mu(600)$ is consistent with the extrapolated line, and hence the muon component agrees with the expectation extrapolated from lower energies.

The distribution of arrival times for the incident particles over the scintillation detectors of 30 m^2 area have been measured at the east corner of the Akeno Branch [17] by adding the signals from all 15 scintillation detectors of 2 m^2 area each. Since the trigger pulse is issued at the center of the Akeno Branch and delivered to the east corner through an optical fiber, the trigger pulse is delayed from the time signal by an interval which depends on the core position and arrival direction. The time signal is recorded by a wave form recorder in an interval of 102 μsec before the trigger pulse. The arrival time distribution of this event started from 67 μsec before the trigger pulse, consistent with the expected delay time. The distance of the detector from the core is 1920 m, and the recorded signal shape is shown in Fig. 4. The time resolution for recording is 50 nsec, and the average pulse height for a muon traversing vertically on the scintillator is 11.8($\pm$20%) mV and FWHM is 92.4($\pm$15%) nsec.

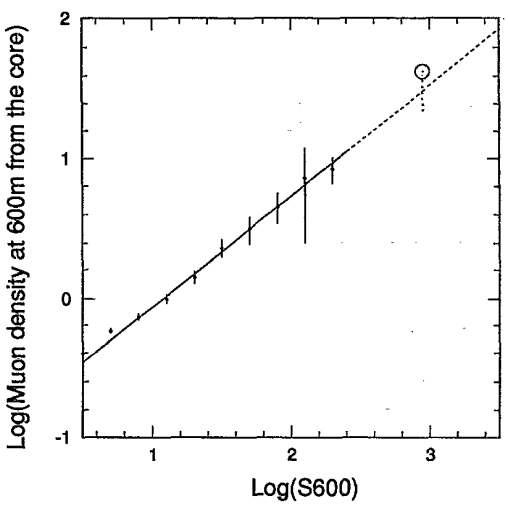

FIG. 3. $\rho_\mu(600)$ vs $S_0(600)$ relation. An open circle is the estimated value of the present event, and filled circles are average values for each bin determined by the AGASA experiment.

The observed number of particles in 30 m^2 are 87 and 115 particles within time intervals up to 3.5 and 8.1 μsec from the start, respectively. These densities, $2.9 \pm 0.3/m^2$ excluding delayed pulses and $3.8 \pm 0.36/m^2$ including delayed pulses, are plotted by open circles in Fig. 2. Both circles are in good agreement with measurements of other detectors in the Akeno Branch, but lie below the expected lateral distribution curve derived from lower energy showers. A curve in Fig. 4 is an expected empirical function from the lower energy showers between 10^{18} and 10^{19} eV. The pulse shape within 3.5 μsec is well fitted to the extrapolation of the standard pulse shape in the lower energy region. There are five signals after 3.5 μsec, the pulses corresponding to 12.2, 2.8, 2.8, 2.3, and 7.7 particles, respectively. The probabilities of these delayed pulses to be accidental can be determined experimentally by artificial triggering and are approximately 5.0×10^{-5}, 1.3×10^{-3}, 1.3×10^{-3}, 2.1×10^{-3}, and 1.4×10^{-4}. Therefore these particles are surely associated with the giant EAS. This kind of delayed pulse is observed frequently in large air showers at large core distances.

Hillas *et al.* [19] showed that local particle density at 600 m from the shower axis $S_0(600)$ is proportional to the primary energy and is a good energy estimator, since this value depends only weakly on the primary mass or fluctuations in the cascade development. The conversion relation from $S_0(600)$ to primary energy at Akeno level is evaluated by the Monte Carlo simulation up to 10^{19} eV by Dai *et al.* [20] to be $E = 2.0 \times 10^{17} S_0(600)$ eV.

Uncertainty in the energy determination arises from possible systematic error in the calibration of each detector, unusual detector response, the resolution of the detector, uncertainty in the LDF, statistical fluctuation in the number of observed particles in each detector, and fluctuation of $S_0(600)$ due to cascade development. The details of these uncertainties are discussed by Yoshida *et al.* [21]. The gain of each detector is continuously monitored and calibrated within $\pm$0.5% at the time of analysis.

In order to know the possible errors in the $S_{23}(600)$ determination for this giant EAS due to other factors men-

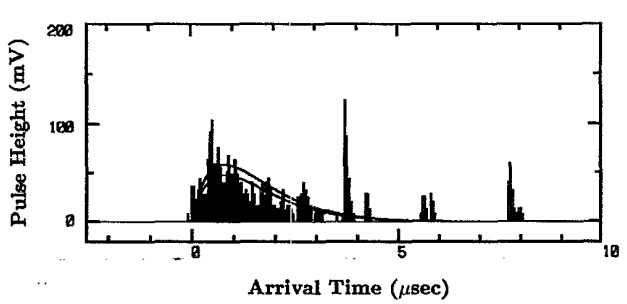

FIG. 4. The arrival time distribution of charged particles measured by a wave form recorder at 1920 m from the core. Solid curves are expected ones at this core distance determined by showers of 10^{19} eV energy [18]. The areas are normalized to the number of particles: 87 and 115.

tioned before, we simulated artificial showers including both fluctuation of shower development and detector response. Here the fluctuation of shower development is assumed to be similar to that in the 10^{19} eV energy region. Artificial showers are analyzed with the same method used for real showers. The resulting output $S_{23}(600)$ is on average underestimated, and its determination error is +21% and −6.6% at 68% C.L. These values can be applied to the $S_0(600)$ determination.

As was shown before, all observables, such as the lateral distribution and the arrival time spread of charged particles, and the lateral distribution of muons can be nicely fitted to those extrapolated from lower energy. Therefore we may use the above conversion relation up to the highest energies in the present analysis. Taking into account both ambiguity of the stage of shower development and possible errors in $S_0(600)$ determination, $S_0(600)$ is within the range $833-1289\ \mathrm{m}^{-2}$, and the primary energy is estimated to be $(1.7-2.6) \times 10^{20}$ eV.

The exposure for this event is $5.0 \times 10^{15}\ \mathrm{m}^2\ \mathrm{sec\ sr}$ and 1.1–2.7 events are expected for $E \geq 1.7 \times 10^{20}$ eV, if the primary energy spectrum determined below $10^{19.9}$ eV extends farther above 10^{20} eV without the GZK cutoff [21]. The energy estimated for this event is, however, a factor of 3 larger than the second-highest energy event, 6.7×10^{19} eV, and no events are observed between them, whereas 2.1–4.2 events would be expected.

Since the spread of arrival times of shower particles agrees with that observed at lower energies and the arrival direction is near vertical, the error in arrival direction determination estimated by the Monte Carlo simulation [14] can be applied to this event, and it gives an error circle of 1.0° radius.

The galactic latitude of this event is −41°, which suggests an extragalactic origin if the primary particle is a proton. We do not have any definite indication of the particle species; however, it should be noted that the $\rho_\mu(600)$ vs $S(600)$ relation shown in Fig. 3 is unchanged from that in the 10^{19} eV energy region, where most primaries are claimed to be protons by the Fly's Eye experiment [22].

The attenuation lengths for protons, nuclei, and gamma rays of energy 2×10^{20} eV are about 27 [13], 30 [10], and 37 [13] Mpc, respectively, in intergalactic space. Therefore, a search for the correlation with any active object is very important, in relation to the intergalactic magnetic field. The direction of the present event is on the edge of the Pisces cluster of galaxies [23]. There is, however, no known nearby active object (<30–50 Mpc) such as an active galactic nucleus within a few degrees circle around its arrival direction. Though the exposure is larger in the direction of the outer galaxy for experiments in the northern hemisphere, it is interesting that all three energetic events (Fly's Eye [7], Yakutsk [24], and AGASA) which clearly exceed 10^{20} eV come from within 50° of the antigalactic center. A detailed discussion of a search for sources of these high energy events beyond the expected 2.7 K cutoff energy has been made by Elbert and Sommers [25].

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