Čerenkov Light in Extensive Air Showers and the Chemical Composition of Primary Cosmic Rays at 10^{16} eV*

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An array of nine atmospheric Čerenkov light (CL) detectors has been operated on Mt. Chacaltaya, Bolivia (altitude 5200 m) in conjunction with the Bolivian Air Shower Joint Experiment (BASJE). Data were obtained during the periods July to November 1966 and June to November 1967. CL detectors were located at radii of 15, 150, and 300 m from the center of the BASJE particle-detector array. Each CL detector consisted of nine 5-in.-diam photomultipliers with a total sensitive area of 880 cm^2 and an acceptance cone of 65° (full width at half-maximum) about the vertical. The minimum detectable CL pulse, in the presence of background starlight, was less than 10^4 photons/m^2. For showers in the size interval $10^6<N<10^8$ particles, the CL intensities $\rho\ (r,N)$ in the radial region $r=25$–300 m are fitted fairly well by the function $\rho\ (r,N)=kN^{0.7\pm0.1}\exp(-\alpha r+\beta r^2)$, where $\alpha=1.8\times10^{-2}$ m^{-1}, $\beta=1.3\times10^{-5}$ m^{-2}, and $k=155\pm80$ (visible photons) m^{-2}. The distribution of CL intensity (normalized to constant size and radius) indicates that the primary cosmic-ray beam at 10^{16} eV is probably mixed in chemical composition, much as it is at 10^{12} eV.

I. INTRODUCTION

The total flux of Čerenkov light (CL) associated with an extensive air shower (EAS)[1] is, to first order, proportional to the integrated track length of electrons above the observation plane.[2] For EAS of constant size, the track-length integral should depend in part upon the nature of the primary particle of the EAS (e.g., proton, Fe nucleus, γ ray, etc.).[3] This effect could be masked by fluctuations which arise from the statistical fluctuations in the depths of the first interactions of the primaries. These fluctuations are significantly minimized if observations are carried out at an atmospheric depth near the point of maximum development of the EAS.[4] At the atmospheric depth of 530 g cm^{-2} (altitude 5200 m), EAS of total energy 10^{15}–10^{17} eV are near their maximum development.[5]

The present experiment was designed to measure the characteristics of the CL in EAS at this altitude and, if possible, to derive information about the primary composition. The measurements were carried out in conjunction with the Bolivian Air Shower Joint Experiment (BASJE), which measured the size, core location, and arrival direction of each EAS with good precision. The CL measurements differ from those of an earlier study at mountain altitudes (3860 m)[6] in that they are nearer the depth of shower maximum of the detected EAS. Also, they make use of a larger array (diam 600 m) of more sensitive detectors. This makes possible observations of CL at greater distances from the core of the EAS, and also permits observations of infrequent high-energy EAS (up to 10^{17} eV).

Knowledge of the chemical composition of primary cosmic rays is important to an understanding of the origins of these particles. For instance, the steepening of the primary energy spectrum between 10^{14} and 10^{17} eV [5] has been attributed to a rigidity-dependent cutoff either during the acceleration or subsequent storage of the cosmic rays.[7] Such a cutoff would become effective for protons at lower energies than for heavy particles. The chemical composition of the primaries might thus be expected to become richer in heavy nuclei with increasing energy.

The composition of the cosmic-ray beam at energies near 10^{12} eV is well established from studies with nuclear emulsions flown at balloon altitudes. The composition is mixed and exhibits features which might be expected for cosmic rays accelerated and stored within the galaxy.[8] At higher energies the situation is not yet clear. There is some evidence from the Soviet satellite experiments Proton I and II that a rigidity cutoff sets in at around 10^{12} eV.[9] However, at 10^{15} eV there is rather convincing evidence from studies of the nuclear core of EAS that the composition remains roughly similar to that at $\sim10^{12}$ eV.[10,11] An analysis of CL

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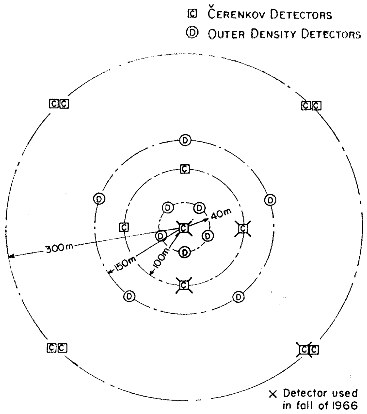

Fig. 1. Schematic map showing the locations of the outer detectors of the BASJE array and the locations of the CL detectors. The four CL detectors used during the 1966 operation are indicated.

fluctuations in EAS at altitude 3860 m also yields this result.[12]

At 10^{16} eV, studies of the nuclear-core structure and density spectrum of EAS suggest a composition of solely heavy nuclei.[10] This would appear to confirm the hypothesis of a rigidity cutoff as suggested by the primary energy spectrum. On the other hand, the zenith angle, energy dependence, and multiplicity of cosmic-ray muons are reported to indicate that the composition remains constant from 10^{15} to 10^{17} eV and is either mixed or possibly pure protons.[13] At $\sim 2\times 10^{17}$ eV, studies of the muon component in EAS with the BASJE and the University of Tokyo array indicate a composition of pure protons,[14] whereas muon results from the Haverah Park array suggest a composition which is mixed or rather heavy ($A_{\text{av}} \geq 10$) at this energy.[15] Above 10^{18} eV, where the primaries are almost certainly of metagalactic origin, muon results from the Volcano Ranch array indicate a pure composition.[16] Other data from the same experiment suggest that the primaries are protons.

EAS induced by heavy primary cosmic rays of mass number A should start higher in the atmosphere than showers initiated by protons, because of the geometrical increase in the interaction cross section for the heavier particles. Also, EAS induced by heavy nuclei will reach their point of maximum development closer to their point of first interaction than will proton-induced EAS of the same total energy because the energy is distributed over a greater number of secondary particles after the first interaction. Thus, at an observation level near the depth of maximum development of proton-induced EAS, one would observe more CL per observed-electron Q/N for the EAS induced by heavy nuclei than for the proton-induced EAS. For instance, the value of Q/N for an EAS induced by an iron nucleus of energy 10^{16} eV at an atmospheric depth of 530 g cm^{-2} can be shown to be enhanced by a factor of more than 2. The present experiment was planned to be sensitive to such differences.

Our measurements of CL in EAS were made during the periods July–November 1966 and June–November 1967. Preliminary results of the first season of operation have been presented elsewhere.[17] In the present paper we present the final results of the full experiment. The lateral distribution of the CL as a function of shower size and the nature of fluctuations in CL will be presented. The latter result suggests a mixed composition at 10^{16} eV.

II. EXPERIMENTAL ARRANGEMENT

The nine CL detectors used in this experiment were arranged to form an array nearly concentric with the BASJE array. The central detector had a sensitive area of 880 cm^2, and was placed 15 m northeast of the center of the BASJE. Four similar detectors were placed at radii of 100 m from the center. Four "double detectors," of twice the sensitive area, were placed at radii of 300 m from the center. Figure 1 shows the complete CL array and the outer detectors of the BASJE at the time of these measurements. During the first season (1966) four CL detectors were operational, and during the final season (1967) typically six CL detectors would be operational on a given evening.

The BASJE consists of 20 plastic scintillation detectors for the measurement of electron densities, 60 m^2 of shielded detectors for the detection of muons and nuclear active particles, and five fast-timing detectors.[18] The particle detector array was used to provide a trigger for the recording of atmospheric CL flashes, and to provide the size, core location, and arrival direction of each EAS.

Figure 2 is a cutaway drawing of a single CL detector. Each such detector consisted of (a) nine 5-in. RCA 8055 photomultipliers with S-11 photocathodes directed upward in a blackened aluminum housing, (b) a remotely controlled lid, (c) a remotely controlled hydrogen corona-discharge light flasher ($\sim 10^6$ photons in 5×10^{-9} sec) for calibration during the nighttime hours, and (d) electronics for the analysis of the fast pulses prior to their transmission over the long cables. Each detector in the outer ring consisted of two such

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sets of nine photomultipliers and a common set of electronics.

The nine photomultipliers of each detector were roughly matched for cathode sensitivity and maximum linear dynamic range. Each of the photomultipliers could produce an output pulse proportional to the input light pulse over a range of more than 2000 in light intensity. The nine photomultiplier anodes were capacitively coupled to each other and to a 51-Ω output cable. This resulted in a net time constant of 40 nsec.

The blackened aluminum housing served to define the angular sensitivity of the CL detector. One could increase or decrease the acceptance angle of the detector by raising or lowering the photomultipliers in the housing. We chose an acceptance angle of 65° full width at half-maximum. Calculations based upon the work of Zatsepin[19] indicate that ~90% of the incident CL pulse from EAS with zenith angles as great as 30° and core distances as great as 400 m from a given detector would be within this field of view. Also, scattered light from directions close to the horizon was eliminated. The bottom part of the aluminum housing served as a weatherproof, temperature-controlled compartment for the detector electronics.

The photomultiplier pulses were pulse-height analyzed at the detector site to avoid the nonlinearities introduced by the transmission of fast pulses through several hundred meters of coaxial cable. The pulses first passed a normally closed gate which served to prevent pileup of background pulses induced by light from the night sky. The gate was opened for 100 nsec by a discriminator whose adjustable level was set to yield ~1200 background counts per second. The probability that a background pulse would be included in an EAS record was about 0.05. The pulses were then analyzed by a logarithmic amplifier[20] whose output, a pulse of length between 8 and 180 μsec, was proportional to the logarithm of the input pulse height. This output pulse was transmitted by coaxial cable to the BASJE data-recording system. Pulses which were coincident with a trigger pulse from the BASJE particle detectors were recorded along with the data from the BASJE array. The readout period, i.e., the deadtime, for each event was 19.6 sec. The dynamic range in CL intensity for the entire detection system exceeded 1000.

An absolute sensitivity of the detectors (in terms of Čerenkov photons per unit area) was obtained from measurements of the pulse height produced by minimum-ionizing particles traversing 13.5 cm of Lucite. The number of photons incident upon the photocathode was taken from the expression given by Jelley[21] and the light-collection efficiency was taken to be 70%. The

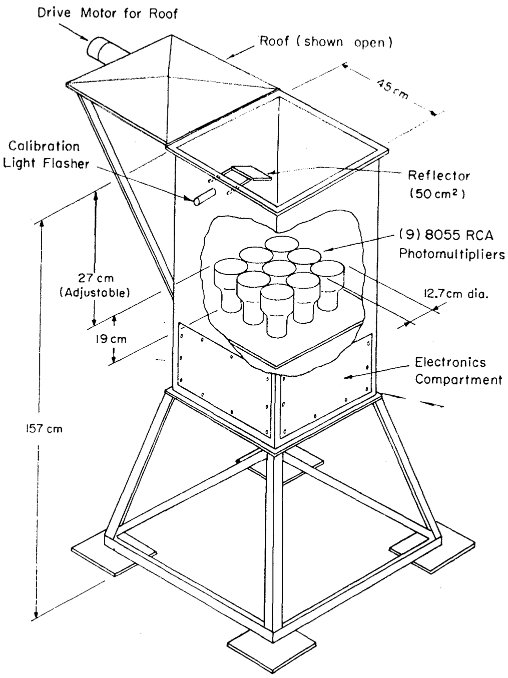

FIG. 2. Cutaway drawing of an individual CL detector.

uncertainty in this efficiency renders the absolute calibration uncertain by about 50%. The minimum detectable CL pulse in the presence of background starlight was found to be approximately 10^4 photons/m^2 in each of the five inner detectors, and about 30% less in each of the four outer-ring double detectors.

The stability of each detector was monitored hourly during the experimental runs by means of the remotely controlled light flashers. These flashers were periodically calibrated against a standard photomultiplier tube to provide the relative gains of the detectors. In addition the relative gains were measured with a single portable light flasher. The long-term gain stability of the system was excellent. Variations were less than ~10%. A thermal sensitivity in the gate circuit housed in each detector led to short-term variations in gain of typically 20% and occasionally more in a given night. However, the temperature of the circuits was monitored and corrections could be applied. About 15% of the data was rejected because of extreme temperature fluctuations. The hourly calibrations with the flasher tubes confirmed that all the corrected data were obtained when the gain of each detector was known to better than 10%.

Three other features of the experiment were the following:

(1) The CL pulse produced in the glass of the photomultiplier tubes by local shower electrons was measured. The photomultipliers were covered with an opaque cloth. The local electron density was obtained from nearby scintillation detectors. Thus, during obser-

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TABLE I. The percentage of the recorded EAS which yielded a CL pulse as a function of shower size and the distance of the detector from the shower axis. The number in parentheses is the total number of EAS observed in the interval. Note that a single EAS may contribute to several radial intervals.

	Radial interval (m)									
$\log_{10}$ size	0–25	25–50	50–75	75–100	100–150	150–200	200–250	250–300	300–350	>350
5.5–6.5	100(34)	100(3)	100(1)	54(11)	67(21)	–(0)	0(3)	0(20)	0(22)	0(2)
6.5–7.5	100(19)	100(38)	89(62)	80(101)	81(171)	86(104)	74(78)	57(54)	24(75)	9(108)
7.5–8.5	100(2)	100(2)	100(4)	100(9)	93(14)	67(9)	80(10)	70(10)	29(7)	54(13)
8.5–9.5	–(0)	–(0)	–(0)	–(0)	100(1)	100(6)	100(1)	100(2)	100(7)	75(4)

vations of atmospheric CL from EAS, the electron density at any CL detector could be obtained from the BASJE data, and the proper correction could be applied to the CL-detector pulse height. The magnitude of this correction was rarely more than 10% of the associated atmospheric CL pulse.

(2) Measurements of CL from EAS with two detectors placed side by side indicated that the precision (standard deviation) of individual measurements was ~17% after all corrections were applied.

(3) Data were obtained during periods when the altitude of clouds was known to be about 500m above the experimental station. No CL signal was obtained from detectors located more than ~50 m from the axis of an EAS. Thus, most of the CL observed on clear nights must be produced at greater altitudes, as expected.

The transparency of the atmosphere was monitored continuously during the measurements. Sequential 30-min photographic exposures of the sky served to monitor the optical transparency of the atmosphere during the operation of the experiment. Examination of the star trails enabled us to distinguish those periods when atmospheric transparency was reduced by dust, haze, or clouds.

III. DATA COLLECTION

The experiment was in operation for 51 nights during July to November, 1966 and June to November 1967. We report the results of 277 clear, moonless nighttime hours of operation. Data-collection periods commenced either one hour after sunset or one-half hour after moonset and continued until one-half hour before moonrise or one hour before sunrise. Runs were terminated early in the event of cloudy skies.

Approximately 5000 EAS associated with a BASJE trigger condition sensitive to EAS in the size range $10^6 < N < 10^9$ were recorded during these periods. The trigger condition was changed slightly for the 1967 period to permit the observation of EAS with sizes on the order of $10^{5.5}$. The core location, arrival direction, size, and zenith angle of the EAS were determined by computer analysis of the data obtained from the particle detectors.

We eliminated from consideration those showers whose core locations were outside the detector array and also those where the variance of the particle data from the best-fit Nishimura-Kamata-Greisen (NKG) lateral distribution[3] exceeded a specified limit. This insured that the uncertainty of the size determination was less than about 25%. We further restricted our attention to the 779 EAS whose arrival directions were within 30° of the zenith, to minimize corrections for the field of view.

The effectiveness of the CL detectors to EAS of various sizes at various distances from the shower axis is indicated in Table I. CL from small showers is observed only near the shower axis where the CL flux exceeds the detection threshold. CL from large showers is observed more readily at greater distances from the shower axis.

The CL pulse at each detector was corrected for the Čerenkov light produced by the shower electrons in the glass envelope of the photomultipliers and for the angular response of the detector. We assumed that the incident CL beam is a plane wave parallel to the arrival direction of the EAS. We thus obtained values of the CL intensity at up to nine different radii in the shower plane for each EAS.

IV. RESULTS

The average lateral distribution of the CL intensity, normalized to shower size, $\rho(r)/N$, for three shower-size intervals of one decade each is given in Fig. 3. The fluctuations in the data which make up each point arise from uncertainties in N as well as in $\rho(r)$. The error bars in Fig. 3 represent

$$\sigma = \{\sum[(\rho/N)_i - \langle\rho/N\rangle_{\text{av}}]^2/n(n-1)\}^{1/2},$$

the standard deviation of the average of n measurements of the photon density per shower electron. Figure 3 includes data points for radial-size intervals where the measurement efficiency was as low as 50% (Table I). When the CL flux for a given measurement was below the detection threshold, i.e., no CL pulse was observed, we adopted the threshold density for the calculation of the datum point in Fig. 3. However, we then recalculated the average flux under the assumption of zero CL density for these measurements, and then extended accordingly the lower error limit of the datum point in Fig. 3.

It is apparent that the average CL intensity per shower electron is greater for small EAS than for large. We find that the data between 25 and 300 m from the shower axis are fit fairly well by the following expression for ρ_{av}, the average intensity of visible Čerenkov photons:

$$\rho_{av} = kN^{0.7\pm0.1}\exp(-\alpha r+\beta r^2)\,, \qquad (1)$$

where $k=155\pm80$ photons/m², $\alpha=1.8\times10^{-2}\text{m}^{-1}$, $\beta=1.3\times10^{-5}\text{m}^{-2}$. The error in k reflects the uncertainty in the absolute calibration of the detector sensitivities. We have calculated the CL lateral distributions to be expected at our altitude for EAS induced by protons with energy 10^{15} and 10^{17} eV. These calculations were carried out according to the theory of Zatsepin.[19] The results are presented as solid lines in Fig. 3. The absolute intensities are in approximate agreement with the data when we take into account the 50% uncertainty in our absolute calibrations. The shape of the data is also in fair agreement except that, for the largest size interval, a pure exponential function would give a better fit.

The data for individual CL events were compared to the average lateral distributions. In no case did the shape of the measured lateral distribution deviate significantly from the average. On the other hand, the fluctuations in the total CL intensity exceeded those expected from the known measurement uncertainties. The data for three individual events (Fig. 4) illustrate the range of normalized intensities encountered.

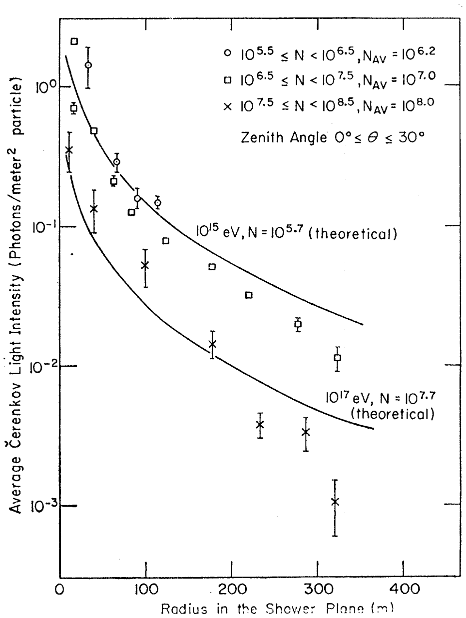

FIG. 3. Average lateral distribution of the CL intensity per shower particle $\rho(r)/N$ for three intervals of shower size. The error limits for the size interval $10^{6.5}\le N<10^{7.5}$ are smaller than the graphical symbols for radii between 75 and 250 m. The solid curves are calculations of the expected CL lateral distribution for EAS induced by primary protons (see text). The angular response of the CL detectors was taken into account in the calculation.

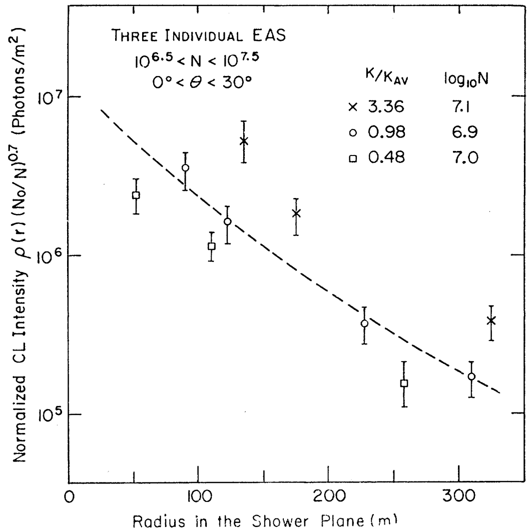

FIG. 4. Lateral distribution of the CL intensity for 3 EAS adjusted to the constant size $N_0=10^{7.0}$. These EAS illustrate the range of fluctuations in CL intensity. The dashed line is the average lateral distribution for this size [Eq. (1)]. The CL intensity in each EAS is characterized by the parameter K [Eq. (2)] relative to the average, K_{av}, for the 233 EAS presented in Fig. 5.

An estimate of the track-length integral Q was obtained for each of the 233 EAS with size $10^{6.5}<N<10^{7.5}$ and with one or more data points in the radial interval 75 $m<r<200$ m. A one-parameter fit of the function

$$\rho(r,N)=KN^{0.7}\exp(-\alpha' r+\beta' r^2) \qquad (2)$$

to these data points yielded the best-fit value of K for each EAS. The fixed coefficients

$$\alpha'=3.3\times10^{-2}\,\text{m}^{-1},$$
$$\beta'=7.1\times10^{-5}\,\text{m}^{-2}$$

were obtained from a best fit to the average lateral distribution data for these restricted radial and size intervals. The total CL flux in the 75–200 m radial interval is very nearly proportional to the track-length integral, according to the theory of Zatsepin and Chudakov.[22] Thus, we adopted

$$Q\propto\int_{75\text{ m}}^{200\text{ m}}\rho(r,N)dr\propto KN^{0.7} \qquad (3)$$

for the track-length integral. Approximately 50% of the CL emitted by these EAS falls within this radial interval. At lesser radii, the CL is emitted low in the atmosphere and therefore is relatively independent of the high-altitude effects of differing types of primaries. At greater radii, the detection efficiency begins to differ appreciably from 100% (Table I). The resultant

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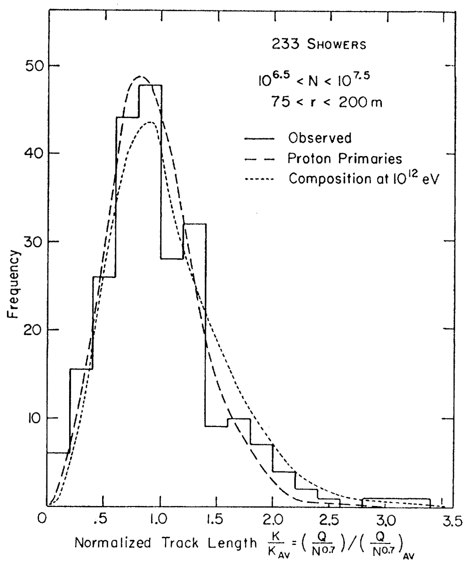

FIG. 5. Frequency distribution of the normalized track length, $K \propto Q/N^{0.7}$, as derived from 233 EAS in the size interval $10^{6.5} < N < 10^{7.5}$ with zenith angle of the arrival direction less than 30° [see Eq. (2)]. The distribution is given in units of the average value of K because of the relatively large uncertainty in the absolute sensitivity of the detectors. Theoretical distributions of $Q/N^{0.7}$ are also shown. They were calculated by the Monte Carlo technique for a pure-proton primary-cosmic-ray beam and for the cosmic-ray composition observed at $\sim 10^{12}$ eV. One thousand simulated events were calculated for each assumed composition. (See Table II.)

distribution of $Q/N^{0.7}$, the track-length integral adjusted to constant size, is given in Fig. 5. The range of sizes was restricted in this analysis in order to minimize the effect of uncertainty in the size dependence, $N^{0.7}$.

We have compared the track-length distribution (Fig. 5) with Monte Carlo distributions for three different models (see Table II) of the primary chemical composition: (1) pure protons, (2) a mixed composition similar to that observed at energies on the order of 10^{12} eV,[8] and (3) an "augmented" composition enriched by a factor of about 3 in heavy nuclei. A one-dimensional Monte Carlo simulation of the EAS, described in the Appendix, yielded the distribution of the track-length integral normalized to $N^{0.7}$. It took into account fluctuations in the inelasticity of the nuclear interactions, fluctuations in the nuclear-interaction free path, and random errors of observation in

TABLE II. Models of the primary-cosmic-ray composition, for fixed energy per nucleus, used in the Monte Carlo calculations. Five types of nuclei, mixed in the proportions shown, were used to approximate the desired composition.

Model	Atomic weight 1	4	14	30	51
Proton	100%	0	0	0	0
Mixed ($\sim 10^{12}$ eV)	45	28	12	5	10
Augmented	14	14	21	27	24

the determinations of the intensity of the CL flash and the size of the EAS. The calculation was similar to that reported by LaPointe *et al.*[23] About 1000 EAS were generated for each model. Figure 5 shows two of the theoretical distributions.

The distribution calculated for the mixed low-energy composition has the over-all shape of the CL data and may be considered to be consistent with it (χ^2 probability is 0.10). On the other hand, the pure-proton model is clearly deficient in events with large $Q/N^{0.7}$ [$P(\chi^2) = 5 \times 10^{-3}$]. The augmented composition yields a distribution which is even narrower and therefore even less consistent with the data at large $Q/N^{0.7}$. A primary beam of pure heavies can also be excluded because it would yield a distribution narrower yet. Note that these conclusions depend upon the reliability of our experimental and theoretical results at large $Q/N^{0.7}$ (see Fig. 5).

We have examined in detail the seven real EAS with the largest values of $Q/N^{0.7}$. The particle data are well fitted by the NKG distribution with age parameters s in the range 0.70–0.96. In no case is the rms deviation of the calculated particle data from the observed data greater than two standard deviations. The CL data also correspond quite closely to the shape of the average lateral distribution. No individual datum point lies more than 2.2 standard deviations from the best-fit curve with the average shape, Eq. (2). The largest rms deviation of the several CL data points from the best-fit curve is 1.8 standard deviations. Four of the seven EAS, including the largest, are fitted to within one standard deviation.

Our theoretical models of shower development are unlikely to underestimate fluctuations leading to large $Q/N^{0.7}$. First, the experimental uncertainties introduced into the calculation are probably overestimated and, secondly, the source of the greatest fluctuations in EAS, i.e., the depths of the interactions of the primary particle, were properly taken into account. Moreover, our model of fluctuations has been shown[4] to predict quite well the observed details of shower structure at 530 g cm^{-2}. In addition, we have simulated over 8000 EAS with proton primaries with all interaction parameters free to vary. The chosen nuclear-interaction mean-free-path ranged from 60 to 90 g cm^{-2}. For 1000 of these events, the shower size was allowed to fluctuate with a standard deviation of 50% rather than 25%. Not a single event was produced with an expected CL intensity greater than or equal to three times the average value. In contrast, we observed two such events in 233 EAS.

The EAS at high $Q/N^{0.7}$ could be understood if $\sim$10% of a primary beam of pure protons interacts in the atmosphere with an inelasticity of 1.0. We are not aware of experimental evidence at 10^{16} eV which would

[23] M. La Pointe, K. Kamata, J. Gaebler, I. Escobar, V. Domingo, K. Suga, K. Murakami, Y. Toyoda, and S. Shibata, Can. J. Phys. **46**, S69 (1968).

exclude this possibility. However, at 2×10^{15} eV, the data on the nuclear-active component of EAS from BASJE [24] clearly exclude this extreme model. Not one EAS in over 100 was found to have the extremely small energy content of nuclear-active particles expected from such a model.

V. CONCLUSIONS

We have derived the following conclusions from this experiment:

(a) The flux of Čerenkov photons at the observation level of 530 g cm^{-2} was found to vary approximately as $kN^{0.7}\exp(-1.8\times10^{-2}r+1.3\times10^{-5}r^2)$, where r, the distance from the shower axis, is in meters, N is the shower size, and $k=155\pm80$ photons/m^2 [see Eq. (1) and Fig. 3]. This dependence is in satisfactory agreement with that obtained from calculations based upon the theory of Zatsepin[19] for these sizes, $10^{5.5}<N<10^{8.5}$.

(b) The shape of the lateral-distribution function for each individual shower obeyed this dependence within the measurement uncertainty of $\sim15\%$ in CL intensity at each detector. Thus, no evidence for extreme fluctuations in shape was obtained. This is expected, since the Čerenkov flux at 530 g cm^{-2} is derived from the entire electron track length of the shower and thus should represent an average over the fluctuations in shower development.

(c) The Čerenkov light flux, integrated over the observation plane, was found to exhibit greater fluctuations from shower to shower than would be expected for a pure chemical composition of cosmic-ray primaries at 10^{16} eV. Thus the data apparently are inconsistent with a primary beam of solely protons or solely heavy nuclei. The fluctuations are also greater than would be expected for a primary composition materially enriched in heavy nuclei (augmented model, Table II). However, the data are consistent with the mixed composition observed at lower energies (10^{12} eV) or with a pure-proton primary beam of which about 10% interacts with inelasticity ~1.0 in the first interaction. There is good evidence against the latter hypothesis at lower energy, 10^{15} eV.[24] These conclusions depend upon the proper interpretation of about five events with particularly large Cerenkov-light content. Reexamination of the records of the continuous and careful calibrations of the detectors during the experiment, and extensive calculations with Monte Carlo methods, have failed to provide any other reasonable interpretation of these events.

The data thus indicate with some assurance that the composition at 10^{16} eV is mixed much as it is at 10^{15} eV[11] or at 10^{12} eV,[8] and that a rigidity-dependent cutoff has not yet become important at 10^{16} eV. Such a cutoff has been deduced from studies of the nuclear core of showers at sea level.[10] However, recent muon studies[15] give results which are consistent with those presented here.

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APPENDIX

The one-dimensional Monte Carlo simulation of EAS was carried out as follows. We used electron development curves representing the average cascade expected from a single initiating nuclear interaction as calculated by Tanahashi.[25] The atmospheric depths of the successive interactions of the primary particle of an EAS were randomly chosen from a Poisson distribution with the mean free path 80 g cm^{-2}. The inelasticity was randomly chosen from a uniform rectangular distribution which varied from 0.25 to 0.75. For each shower, the development curves arising from the interactions at amospheric depths down to 530 g cm^{-2} were then summed to yield the shower size at 530 g cm^{-2} and the integrated track length above 530 g cm^{-2}. These two quantities were then allowed to fluctuate independently with Gaussian probability distributions to simulate the measurement errors. A standard deviation of 25% was adopted for the shower size, and 17% for the track-length integral. The latter is the error determined for a measurement of CL intensity by a single detector (see Sec. II). This is an overestimate of the experimental error for those EAS where more than one CL detector would have sampled the CL flux. EAS with primaries of atomic weight A were generated under the assumption of complete breakup in the first interaction.

[24] H. Hasegawa, M. Noma, K. Suga, and Y. Toyoda, in *Proceedings of the Ninth International Conference on Cosmic Rays, London, 1965* (The Institute of Physics and the Physical Society, London, 1966), Vol. 2, p. 642.

[25] G. Tanahashi, J. Phys. Soc. Japan **20**, 883 (1965).