as large energy losses by a few particles rather than small losses by many.

The upper limit determined from the cloud chamber data of Bayley and Crane[23] by inspection and by Fermi and *K-U* extrapolations are given below for comparison.

Inspection...............	12.0 ± 0.6 Mev,
Fermi Plot...............	12.4 ± 0.6,
K-U Plot................	14.5 ± 0.7,
Above value..............	13.3 ± 0.5.

[23] D. S. Bayley and H. R. Crane, Phys. Rev. **52**, 604 (1937).

ACKNOWLEDGMENTS

The suggestions and help of Messrs. W. E. Ramsey and M. A. Pomerantz contributed a great deal to the success of the investigation. The author is also indebted to Dr. W. F. G. Swann for his constant interest and frequent advice. Mr. Austin Nester constructed all counters used and Mr. S. H. Forbes assisted in the computations. Thanks are also due to Dr. E. L. Hudspeth and Mr. C. P. Swann for their assistance in the operation of the Bartol Van de Graaff generator.

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Shower Production by Penetrating Particles at 14,000 Feet

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Showers produced by penetrating particles were studied at 14,000 feet by simultaneous observations with G.M. counters, a cloud chamber, and an ionization chamber in a combined array. At least two-thirds of the observed showers generated by penetrating particles that struck a five-inch lead absorber consisted of a mixture of energetic electrons and particles heavier than electrons. The frequency of these events at high altitude relative to sea level shows that the initiating particles are not ordinary mesons. The presence of heavier particles in the electron shower indicates that the showers result from nuclear interactions in which the nucleus is disrupted rather than from a simple radiation process. Details of the events and their relation to some other cosmic-ray phenomena are discussed.

1. INTRODUCTION

THE production of high energy showers by penetrating particles has been observed with ionization chambers,[1] with cloud chambers,[2] and with counter arrangements.[2]

The observations described in this paper were undertaken in order to study the nature of the showers that have been observed at high altitude under lead shields thick enough to exclude electron or photon initiated showers.[1] For this purpose, the lead was divided into a thick lead shield that was placed above a cloud chamber and a series of lead plates that were placed inside the cloud chamber. A coincident signal from G.M. counters and an ionization chamber controlled the expansion of the cloud chamber. With suitable geometry, this procedure makes possible a detailed study in the cloud chamber of the event responsible for the burst in the ion chamber.[3] Thus it was hoped that the results would provide general information about high energy showers and conclusive evidence as to the nature of the showers studied by Bridge, Rossi and Williams with shielded ionization chambers at high altitudes.[1]

Since the terminology used to describe events

* Now at University of Michigan, Ann Arbor, Michigan. Some of the cloud chamber equipment was constructed during the tenure of a John Simon Guggenheim Memorial Fellowship.

[1] H. Bridge, B. Rossi, and R. Williams, Phys. Rev. **72**, 257 (1947).

[2] See W. B. Fretter, Phys. Rev. **73**, 41 (1948) for cloud-chamber observations and references to previous work.

[3] A brief report of the results was included in a letter by H. Bridge, W. Hazen, and B. Rossi, Phys. Rev. **73**, 179 (1948).

of the type discussed in this paper is by no means standardized, it seems advisable to define terms as they will be used in what follows.

Burst: any event that produces an ionization pulse in an ion chamber.

Nuclear Disintegration: production of secondary particles by a nuclear collision with emission of particles heavier than electrons.

Star: a nuclear disintegration in which only nuclear particles with energies of the order of nuclear binding energies are emitted. These particles have an essentially isotropic angular distribution.

Electronic Shower: a shower of electrons and photons that develops by the ordinary multiplication process.

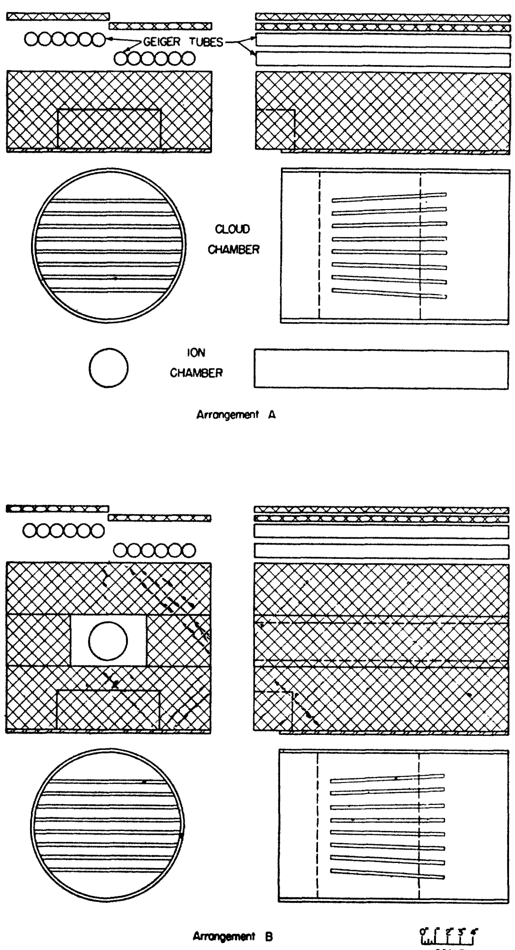


FIG. 1. Experimental arrangements for the two parts of the experiment. The cross-hatched material is lead. The scale is in inches.

Penetrating Shower: a shower consisting primarily of penetrating particles.

Mixed Particle Shower or Mixed Shower: a shower that obviously contains heavy particles as well as energetic electronic radiation.

Air Shower: a shower which has developed at least partly in the air before striking the detecting instrument.

2. APPARATUS AND RESULTS

Apparatus

The two arrangements used in the course of the experiments are shown in Fig. 1. The ionization chamber was filled with purified argon to seven atmos. pressure. The use of electron collection at the wire gave information about the type of ionizing event occurring in the chamber.[4] The cloud chamber contained eight $\frac{1}{4}$-inch lead plates and was filled with argon at about 65 cm pressure. The cloud-chamber photographs were stereoscopic. Signals from the G.M. counters and the ionization chamber were applied to a coincidence stage the output of which triggered the cloud chamber expansion. No pulse was obtained from the coincidence stage unless the pulse from the ionization chamber exceeded a minimum value. In most of the measurements, this value was equivalent to the average pulse produced by 15 fast electrons traversing the ionization chamber perpendicular to the axis. Hence the cloud chamber was insensitive to showers which contained a small number of fast particles. The ion chamber pulses were delayed in time and photographed on an oscilloscope whose sweep was also triggered by the coincidence signal. Air showers were identified by the multiplicity of discharges in the G.M. counter tray and by the appearance of the shower in the cloud chamber.

Reprojection of the stereoscopic views of the cloud chamber allowed an accurate reconstruction of observable penetrating particle tracks, an accurate determination of the position of a shower origin when it was in the cloud chamber, and a moderately good determination of the direction of the shower axis.

The observable depth of the cloud chamber (shown by the dotted lines in Fig. 1) was about

[4] H. Bridge, Phys. Rev. **72**, 172A (1947); R. Sherr and R. Peterson, Rev. Sci. Inst. **18**, 567 (1947).

eight inches, whereas the lengths of the G.M. tubes and of the ion chamber were about twenty inches. Consequently, the cloud chamber was expanded in many cases as a result of an event that was not seen in the observation region. However, as can be seen from Fig. 1, the geometry was such that any single ionizing particle which discharged a G.M. tube and which was seen in the observable volume of the cloud chamber must have penetrated all of the lead absorber above the cloud chamber. This implies that electrons are excluded as agents responsible for the observed events. Of course, an air shower at a large angle with the vertical can trigger the apparatus and appear in part in the observable volume, but such events are readily identified.

Results Obtained with Arrangement A

Arrangement A (Fig. 1) was intended to be selective for events in which a shower originated in the cloud chamber. Analysis of the records reveals that 20–25 percent of the 700–800 cloud-chamber pictures showed evidence of electron showers and/or groups of penetrating particles. Pictures in which penetrating particles appeared without electrons constituted about 5 percent of the 20–25 percent group. The expressed uncertainty in the figures derives from the difficulty in defining useful pictures (i.e., in determining from the picture alone whether or not the cloud chamber was operating in a satisfactory way), and in applying a criterion for a lower limit to the number of particles which should be required in a photograph to classify the picture as a shower.

Analysis of the 20–25 percent group indicates that about one-half (described under I below) showed particles whose initiators must have been incident on the five-inch lead block, while the other half (described under II below) showed particles that came from the sides, front, or back of the five-inch lead block and entered the cloud chamber at an angle with the vertical such that the initiating rays traversed little or no lead before striking the plates in the cloud chamber.

The large number of pictures which did not show showers (75–80 percent) can be attributed to the following factors:

(a) Accidental coincidences between the ion chamber and the G.M. counters account for 10 percent of the coincidence signals and hence 10 percent of the cloud-chamber expansions were caused by spurious coincidences.

TABLE I. Events of Class I, Arrangement *A*.

Number of pictures: 68				
Shower origin—(a) in the cloud chamber				25
(b) above the cloud chamber				42
(c) below the cloud chamber				1
Shower Components Observed	*Origin*			*Total*
	a	*b*	*c*	
Penetrating particles only	1	8	1	10
Electron cascade radiation only	6	4	0	10
Mixed particle shower	18	30	0	48
Mixed shower with energetic heavy particles				34
Mixed Showers				
Electrons and fast heavy particles from a common origin				11
Electrons and slow heavy particles from a common origin				12
Electrons and either fast or slow heavy particles from a common origin				16
Associated stars or slow heavy particles				
(1) along the path of the shower				13
(2) other parts of chamber				4

(b) The pulse shape records of the ion chamber signals showed that in 15 percent of the expansions the ion-chamber pulse was caused by a small number of heavily ionizing particles. These cases were presumably the result of a star produced near the ion-chamber wall by a charged particle which had discharged a G.M. tube and penetrated the lead above the cloud chamber.

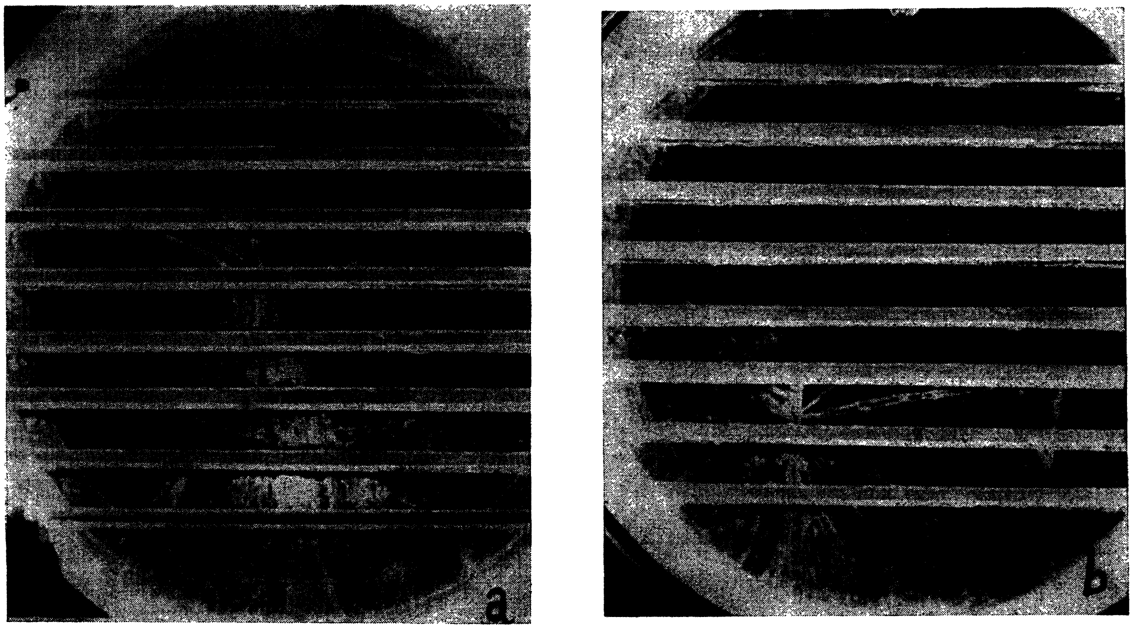
(c) This leaves 75 percent of the pictures which should have been caused by showers. Of this 75 percent only between $\frac{1}{2}$ and $\frac{1}{3}$ would be seen in the cloud chamber because, as pointed out above, not all triggering events passed through the observation region. Thus between 37 and 25 percent of the pictures should have shown showers. The observed fraction of 20–25 percent is not considered to be in disagreement with the above.

Details of the two classes of events (I and II) in which radiation appeared in the cloud chamber in arrangement *A* are given below.

I. *Electron showers and/or groups of penetrating particles in which the initiating particles were incident on the five-inch absorbers*

Illustrations of the events are given in Figs. 2 and 3.

In two short runs where a detailed correlation was made with ion chamber pulses using ar-



(a) (b)

Fig. 2. (a) Mixed shower originating in the cloud chamber. There are many penetrating particles and an electronic shower component with an energy of the order of one Bev. An originating particle track is visible on the negative. (b) Mixed shower produced by a non-ionizing particle. The G.M. tube was probably triggered by an accompanying air shower particle. It is impossible to tell how many of the shower particles are penetrating but there are either a number of penetrating particles or else a number of widely divergent low energy electrons from the shower origin. At least one of the particles is an energetic electron since there is cascade multiplication in the bottom lead plate.

rangement *A*, the following information was obtained. There were six cases in which the cloud chamber showed that electron showers from initiating particles incident on the five-inch lead block struck the ion chamber. In all six events the shape of the ion-chamber pulse indicated uniform volume ionization. In one case the ion-chamber pulse indicated a mixture of volume and concentrated ionization. Five of the six events resulted in the discharge of no more than two G.M. counters.

II. *Electrons from the Sides, Front, or Back of the Five-Inch Absorber*

As stated earlier, these events occurred with about the same frequency as the events of Class I. In contrast to the events of I, only a very small fraction of these side showers gave any evidence of fast or slow heavy particles associated with the electronic radiation. A correlated ion-chamber, G.M. counter, cloud-chamber record yielded eleven events with the cloud chamber showing side showers of Class II which clearly struck the ion chamber. In all eleven cases the ion-chamber record indicated volume ionization and in only one instance were fewer than 3 G.M. counters discharged.

Results Obtained with Arrangement B

In Arrangement B, Fig. 1, the five-inch lead filter between the ion chamber and cloud chamber was designed to remove the electron component of a burst that struck the ion chamber before the shower products reached the cloud chamber. The ion chamber was well shielded from electron air showers, in contrast to *A*. The geometry was such that we should expect the number of showers observed in the cloud chamber relative to the number of showers detected by the ion chamber to be less in arrangement *B* than in *A*.

The statistics from the 490 photographs with Arrangement *B* are given in Table II.

3. DISCUSSION

1. Initiating Particles

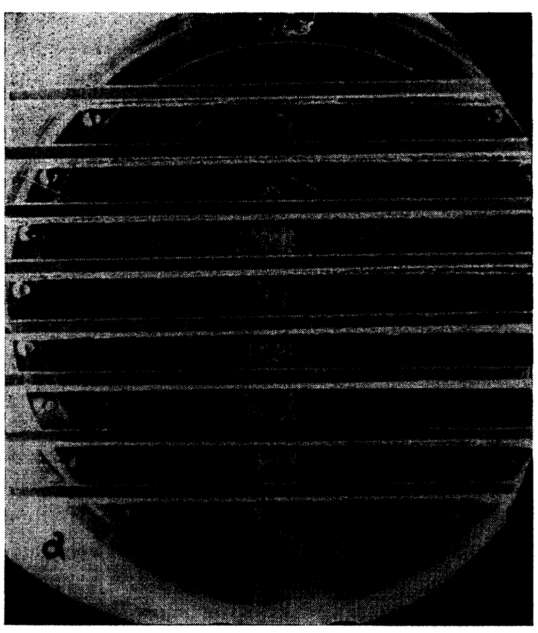
Arrangement A, Class I: In the cases where the cloud-chamber pictures showed bursts in which the initiating particles were incident on the five-inch absorber, there was seldom a multiple discharge of the G.M. tray above the lead absorber. Therefore, initiating particles were not ordinarily parts of dense electron air showers, either extensive or local. However, one cannot rule out the possibility that the initiating particles were frequently parts of low density air showers.

The initiating particles were certainly not electrons since an electron capable of producing an electron cascade of the observed size under six inches of lead would have to have an energy of the order of 10^{12} ev. It does not seem possible that such electrons occur with the observed frequency of the mixed showers, or that they could account for the heavier particles observed in the showers. The energy of the initiating particles for arrangement *A* Class *I* must have been 1 to 5 Bev in most cases since this energy release was observed in the electron cascades associated with the showers. Because of the method of detection this should also apply to observations with arrangement *B* (i.e., an electron shower in this energy range would be required to affect the ionization chamber).

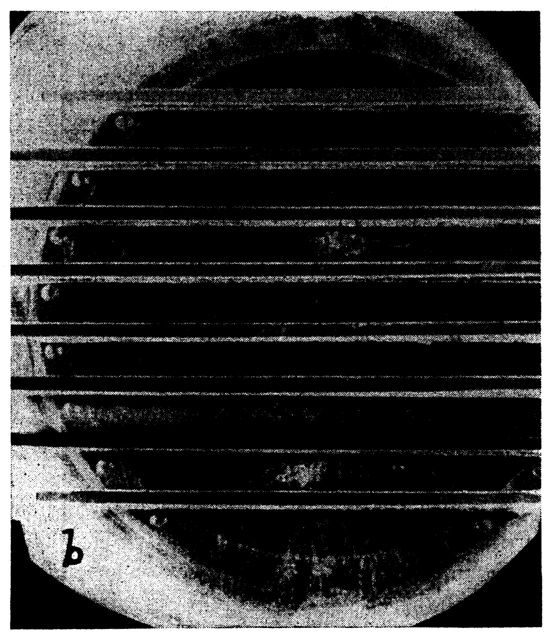
In the pictures obtained with arrangement *A* where mixed showers were produced above the cloud chamber, it was difficult to decide in some cases whether the penetrating particle component of the mixed shower could have originated at the same point in the five-inch lead block as the electronic radiation or whether the penetrating particles accompanied the particle that produced the electron shower in the five-inch block.

In ten cases of the 42 in this category (Table I), the penetrating particles seem certainly to be parts of air showers rather than products of the shower from the five-inch block, since the penetrating particles were widely separated in position and were far from having a common origin in the vicinity of the apparatus.

Arrangement A, Class II: In the cases where the cloud-chamber pictures showed electronic radiation entering the chamber from the side, front, or back, multiple discharges of the G.M. tray (3 or more tubes), were recorded in ten out



(a)



(b)

FIG. 3. (a) Mixed shower originating above the cloud chamber. There appear to be several penetrating particles and two separate electron cascade shower cores. A star is seen to originate in the path of the left shower core in the seventh plate. (b) Penetrating particle shower originating above the cloud chamber. Eight penetrating particles enter the cloud chamber and either a neutron or one of the penetrating particles produces another disintegration of six or more penetrating particles in the third plate. There also appear to be some small electron cascades at the bottom.

TABLE II. Statistics for arrangement *B*.

Two or more penetrating particles from above	21 photographs
Electronic radiation from above (very small showers)	2 photographs
Electronic radiation from side	11 photographs
Few low energy electrons	6 photographs
Mixed showers (all but one from side)	11 photographs

of the eleven cases that were correlated. Therefore, the majority of these events were probably initiated by air showers. There were very few cases of penetrating particles associated with the electron cascades or of heavy particles produced locally by the shower.

Arrangement B: The data from arrangement *B* give additional evidence for occasional association of the shower-producing penetrating particles with low density air showers that contained penetrating particles (see Table II), since there were ten events in which mixed radiation entered the cloud chamber from the side while the ion chamber responded to an associated shower. The data thus show that about one-fourth of the shower-producing penetrating particles are accompanied by other particles within the observed area of roughly 1000 cm^2.

2. Position of the Shower Origin

The origin of a shower was usually within the three inches of lead nearest the ion chamber. This observation is consistent with the following arguments. If we assume the ion-chamber pulse to be caused by electron showers alone, 15 or more particles that traversed the chamber perpendicularly to its axis would give the minimum required pulse. Thus the average 10^9 ev shower could produce the required pulse only in the immediate vicinity of its maximum at one inch of lead below the shower origin. Therefore, one would expect the origin of such a shower to be in the central plates of the cloud chamber. On the other hand, a shower of 5 Bev energy with an origin in the range $\frac{1}{2}$–$2\frac{1}{2}$ inches of lead above the ion chamber could give the required minimum pulse.

3. Composition of the Mixed Showers

The showers were similar to those recently described by Fretter.[2] Heavily ionizing particles (a), penetrating particles (including a few identifiable mesons) (b), and electron cascade radiation (c), were directly visible; the emission of neutrons (d) is inferred from the presence of time associated stars and single slow heavy particles in parts of the cloud chamber removed from the burst origin.

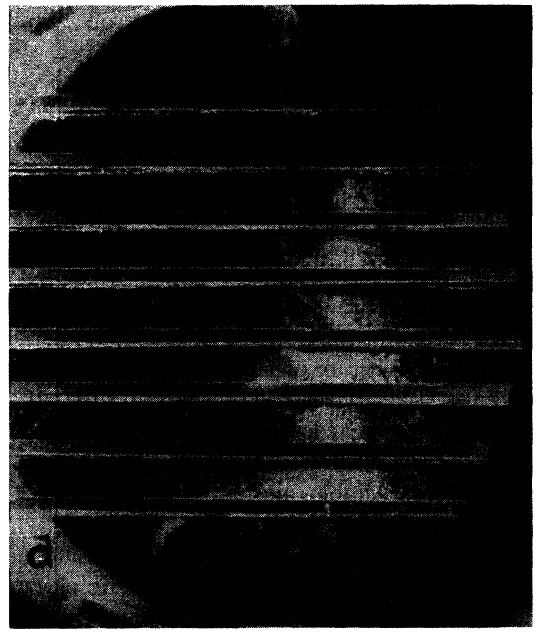
(a) Heavily ionizing particles were emitted from the shower centers with an essentially isotropic angular distribution. The heavy ionization indicates low energies, perhaps of the order of a few Mev and certainly less than 50 Mev for particles that do not penetrate one plate. There were 21 heavily ionizing particles emitted from the 25 mixed shower origins that occurred in the cloud chamber. Thus the average number of *observed* heavily ionizing particles was about one per shower.

(b) The penetrating particles observed in arrangement *A* had a wider angular divergence than the electronic radiation and in one case a meson was even projected upward with an energy of 40–50 Mev. The lower limits that can be assigned to the energies of the penetrating particles, however, are not high, since the lead absorber in the chamber totaled only two inches and many showers did not originate in the top plates. For protons, the lower limit would be only 200 Mev and for mesons, 100 Mev, even when the origin of the shower was in the top plate. The events observed in arrangement *B*, however, probably represent mixed showers produced near the ion chamber, and thus the penetrating particles which were observed in the cloud chamber with this arrangement must have traversed more than five inches of lead. Therefore they must have had energies of more than 200 Mev if mesons or greater than 350 Mev if protons. The frequency of occurrence of these high energy penetrating particles can be estimated from a comparison of the data for arrangements *A* and *B*. The yield of photographs showing penetrating particles from above was at least four percent in arrangement *B*, whereas the yield of photographs showing showers by penetrating particles (Class I) was ten percent in arrangement *A*. Upon taking into account a factor of about $\frac{2}{3}$ for the difference in efficiencies of the cloud chamber as a detector in the two cases, we can conclude that more than half of the showers produced by the penetrating particles contained penetrating particles with a range greater than five inches of lead.

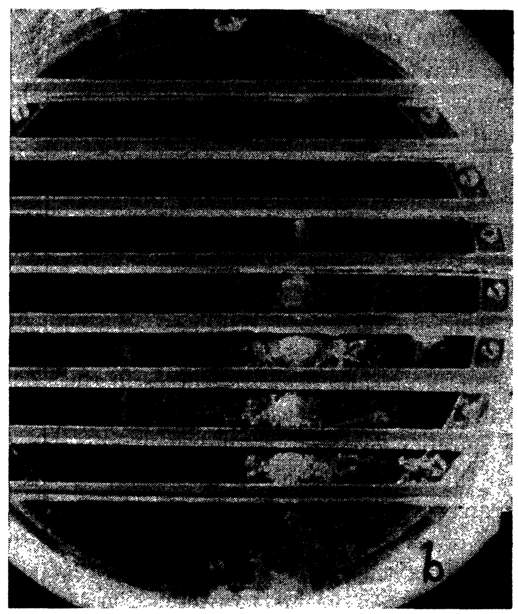
The number of penetrating particles per shower is difficult to estimate, particularly in arrangement *A* where the electron component would mask penetrating particles travelling in the same direction. However, the pictures of arrangement *B* indicate that, on the average, each shower contained one penetrating particle which penetrated five inches of lead.

(c) The electron cascade radiation usually exhibited energies in the range 1–5 Bev. These estimates were based on the size of the shower at its maximum and/or the longitudinal development of the electron shower. Since few electrons appeared in the cloud chamber in arrangement *B*, the "range" of the electronic shower component was less than five inches, as expected. Occasionally, a few low-energy electrons were distributed throughout the upper part of the cloud chamber in *B*, which indicated that the incident radiation had produced showers whose low-energy γ-ray residue reached the cloud chamber.

The electron shower component appeared to have a common origin with the penetrating particles in cases where the origin was clearly defined. There is some evidence for multiplicity at the origin which is based on the observation of an unusually wide lateral spread and/or separate shower cores in many of the mixed shower pictures. A direct comparison with showers that seem certainly to be electron or photon initiated leads one to believe that nearly all of the mixed showers are difficult to interpret in terms of a single-particle origin for the electron component. As a reference for electron or photon initiated showers, we select those which are frequently observed in pictures of Class II. These occur at a large zenith angle and hence the initiator misses the lead absorber above the cloud chamber. The electron cascade then originates in the first radiation length and never includes heavy particles. Showers that originate at all depths of lead with approximately equal probability occur much less frequently and, in addition, are usually mixed particle showers. Thus, there is considerable assurance that we actually can select single electron or photon initiated events for use in the observation of the



(a)



(b)

FIG. 4. (a) One of the cases of an electron shower with an extraordinary lateral spread, and, apparently, more than one shower core. The shower also has a slow heavy particle at the origin and a star in the fifth plate. (b) What is believed to be an ordinary single electron shower. The initiating particle struck the edge of the third plate while travelling down and back 45 degrees from the vertical, thus missing the 5 inch absorber as well as the first and second cloud-chamber plates.

development of a "normal" electron shower without in any way invoking preconceived ideas of the appearance of a "normal" shower as a selection criterion.

Examples of mixed showers where the cascade component is difficult to interpret except in terms of more than one energetic electron or photon at the origin are shown in Figs. 2a, 3a, and 4a. A shower initiated by a single electron is shown in Fig. 4b. The apparently unusual lateral spread of some of the showers may be due to a large admixture of penetrating particles, but the cases of separated cores seem difficult to interpret except as events in which the electron cascades were initiated by more than one ray with an appreciable angular separation at the shower origin.

The relative frequency of occurrence of showers with and without an energetic electron component is impossible to estimate from the present results, since the detecting system was highly selective for showers with a large number of particles.

(d) The occurrence of associated stars and slow heavy particles along the course of the showers and in the other parts of the cloud chamber is most reasonably explained by assuming that neutrons are also emitted in the initial disintegration. Some of the events might well be proton induced but there were two cases in which the star occurred outside the main shower core in a region where the nature of the initiating particle might be ascertained; it was non-ionizing in both cases. There were 15–20 associated stars or slow heavy particles in the photographs of mixed showers. A rough estimate of the number of protons and neutrons emitted from the shower centers can be made by assuming an average path for these particles of 25 g/cm^2 of lead in the cloud chamber and assuming an absorption coefficient of the order $(100\ g/cm^2)^{-1}$ corresponding to production of an observable star by energetic protons or neutrons. The result is an average of about one energetic neutron or proton per shower.

Since most of the associated slow particles occurred along the path of the shower or in its immediate vicinity, it is unlikely that they were produced by neutrons from the air. It is also unlikely that they were produced by photons since stars and slow particles occur infrequently in the electron cascades of air showers.

The lateral distribution of the associated slow particles shows that the producing neutrons have a rather wide angular distribution, in contrast to the angular spread of the energetic electronic component of the showers. This is additional evidence that the associated stars and slow heavy particles are not produced by photons.

4. CONCLUSIONS

The showers in Class I that we have observed frequently contained slow heavy particles and fast heavy particles, including occasional identifiable mesons in addition to the electronic radiation that was almost always present. From this we conclude that showers of this type result from nuclear interactions in which electrons and heavier particles are produced. The presence of these heavy particles proves that the electron component of the shower does not arise from simple radiation processes of mesons or any other particle.

5. BURSTS OBSERVED WITH SHIELDED IONIZATION CHAMBERS

Extensive measurements of the burst rates in shielded ionization chambers have been made, both at sea level and at higher elevations, and the fraction of bursts not caused by extensive air showers has been attributed to electromagnetic interactions of mesons.[5] The above conclusion about the nature of showers observed under lead at high altitude is not in agreement with this interpretation and the present results show that a large number of the bursts observed in ionization chambers must be the result of nuclear interactions in which electrons and heavier particles are produced. This applies strictly to showers in which the electron component develops at most to a maximum of 100–200 particles which corresponds to the minimum burst size in most previous ionization chamber measurements.

Even at sea level there is evidence that showers of the mixed particle type may contribute to the observed burst rate. The recent work of Fretter[2] gives evidence that the mixed shower intensity

[5] R. E. Lapp, Phys. Rev. 69, 321 (1946).

is roughly comparable to that of showers containing only electrons and believed to be meson induced. Of 52 showers containing electronic radiation, Fretter observed 30 with a heavy particle component and 22 without, all of which were initiated by penetrating particles in the lead plates of the cloud chamber. Since most of the showers were not very large, those containing penetrating particles would be able to set off the counter control located outside the cloud chamber more often than those that did not. Thus the cloud chamber was biased in favor of these events. However, Fretter points out that a considerable fraction of the mixed showers originated in the last two plates; in these cases the discrimination would be negligible. Thus it appears likely that, even at sea level, the mixed shower contribution to ion chamber bursts may not be negligible.

6. NUCLEAR DISINTEGRATION IN GENERAL

The nuclear disintegrations previously studied by one of us at 10,000 feet[6] showed a rapid increase of intensity with altitude[7] as do the "bursts" we have been discussing above. It was concluded at that time that the ionizing penetrating particles which were observed to produce many of the high energy disintegrations were not mesons because of the rapid altitude variation observed by Anderson.[7] Thus it seems likely that the nuclear disintegrations previously studied[8] and the mixed showers of the present discussion are results of the same type of interaction. The difference evidently is merely one of energy expended in the disintegration.

Thus, the existing evidence indicates that we can make the following tentative summary of the nuclear disintegrations at 10,000–14,000 feet resulting primarily when the strongly altitude-dependent penetrating particles (protons and neutrons?) make nuclear collisions in lead. The disintegrations (stars) where total energies of 50–200 Mev appear in the disintegration products seem to result in the ejection of heavy nuclear particles (protons, α-rays, etc.) and occasional mesons for the higher energy events. The initiating particles are predominantly neutrons but occasionally protons. It is not clear whether or not the initiating particle always loses most of its energy.

When the total energy of the disintegration products is 200–1000 Mev, slow and fast heavy particles, occasional identifiable mesons, and a few electrons are emitted. The initiating particles are about equally divided between neutrons and protons.

When the total energy is greater than 1000 Mev, slow and fast nuclear particles, occasional identifiable mesons, and energetic electronic radiation appear. In the present observations events initiated by ionizing penetrating particles (protons) were selected, but sea level observations without such selection indicate neutron initiation as well.[2]

From the present results one cannot say whether there are a large number of events in this high energy region in which a relatively small number ($\sim$10–20) of high energy penetrating particles are produced without being accompanied by high energy electrons. As has already been pointed out the detecting arrangement was insensitive to such events. Thus the observations seem to be consistent with an increase in the number of constituents with increase in energy released in the disintegration. However, in the case of electrons there may be different origins for low and high energies; the low energy electrons may have their origin in nuclear excitations whereas those of higher energy may originate in the decay of short lived mesons.[9] Hence it is not clear whether the appearance of high energy electrons as we go to high energy showers represents a threshold or a transition effect.

7. INITIAL MULTIPLICITY OF MIXED SHOWER COMPONENTS

There are varying degrees of quality in the evidence for initial multiplicity for the various shower components. It is certain that fast and slow penetrating particles occur multiply; there are a few examples of more than one identifiable meson per disintegration in the literature;[10]

[6] W. E. Hazen, Phys. Rev. **65**, 67 (1944).
[7] C. D. Anderson and S. H. Neddermeyer, Phys. Rev. **50**, 263 (1936).
[8] See also W. M. Powell, Phys. Rev. **69**, 385 (1946).
[9] H. Lewis, J. R. Oppenheimer, and S. Wouthuysen, Phys. Rev. **73**, 127 (1948).
[10] For example, see E. Hayward, Phys. Rev. **72**, 937 (1947).

there is some indication of initial multiplicity of the electron component in the present observations.

The initial angular divergence of penetrating particles appeared to be greater than that of the electron shower particles (assuming that the latter do have a multiple origin). If a sizeable fraction of the penetrating component is composed of mesons, the above observation is in conflict with the neutron meson hypothesis for the origin of the electronic component.[9] However, the apparent difference in angular divergence may not be real since the "range" of an electron of energy 50–100 Mev (which is typical of the energies of the penetrating particles occurring at large angle assuming they are mesons) is so short that it would not even be identified in many cases. It was not possible to compare angular divergences at high energies since the penetrating particles would be concealed by the cascade radiation; it is interesting to note, however, that there were no cases of narrow bundles of penetrating particles observed even under the favorable conditions of arrangement *B*.

8. APPLICATION TO INTERPRETATION OF EVENTS IN THE ATMOSPHERE

The marked altitude dependence of the showers produced by penetrating particles leads one to believe that the showers may be a characteristic of the primary particles or at least that the showers play an important role in determining the relationship among the various cosmic-ray components. If we apply the ideas deriving from observations of interactions in lead to the case of the atmosphere, the following tentative picture suggests itself, at least for initiating energies of perhaps 1–10 Bev. The collision of primary protons, or secondary protons and neutrons, with air nuclei results in multiple production of mesons and, directly or through a short-lived intermediary, in the production of electrons or photons of about the same energy as the mesons. In addition, neutrons and protons are emitted. As already pointed out by Bridge, Rossi and Williams,[1] the production of high energy photons or electrons by nuclear interactions may explain that part of the electron component which does not arise from the decay or other secondary processes of ordinary mesons.[11]

The degradation in energy of the penetrating particles evidently proceeds by more than one large step. The cloud-chamber evidence for this is twofold: first, the present observations and the sea-level observations[2] both showed events in which a penetrating particle that produced a high energy shower in the cloud chamber was accompanied by other penetrating particles (the latter indicating a precursory shower in the air); second, sea level observations[2, 12] have produced examples of successive showers in the apparatus itself.

The protons and neutrons produce additional nuclear disintegrations but, because of the low density of electrons in the air shower at the level of observation, these disintegrations will appear to be unassociated with an electronic air shower component. In addition, the low energy disintegrations will occur at large lateral distances from the shower axis, because of the large average value of the initial angular divergence of the low energy neutrons and protons. Thus, as observed,[6, 8] we expect the frequent occurrence of stars and low energy nuclear disintegrations that appear to be unassociated with air showers.

Ionization loss causes a rapid attenuation of the proton intensity for energies less than about 500 Mev and hence neutrons will predominate as the star-producing agent at low energies. The transition from production of disintegrations with nearly equal frequency by protons and by neutrons to production predominantly by neutrons does indeed occur at star energies of a few hundred Mev.[6]

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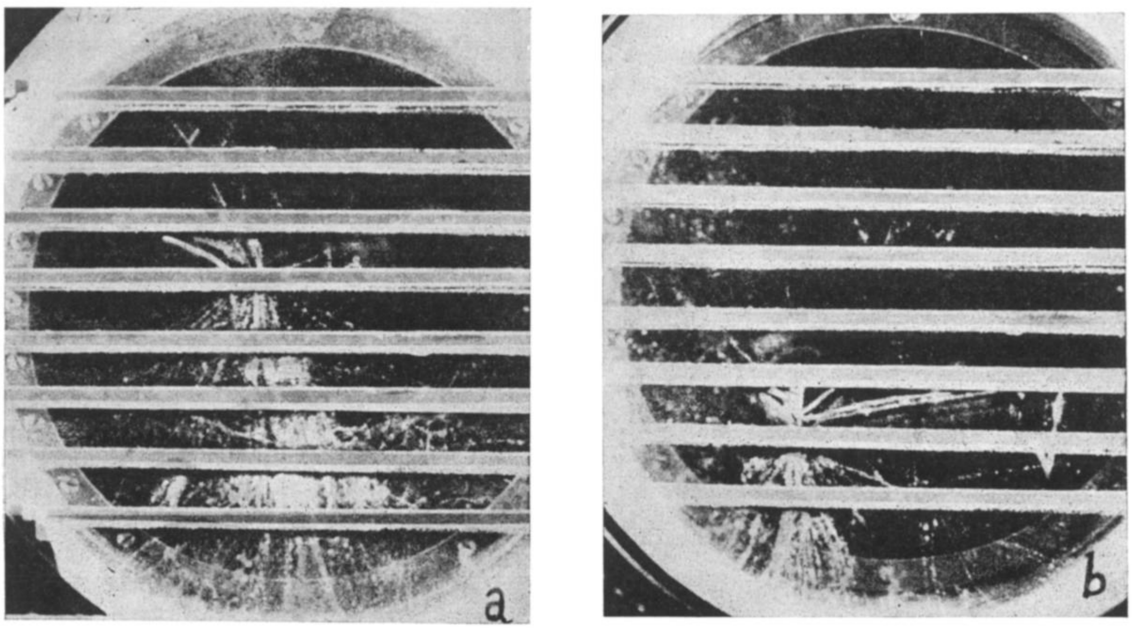
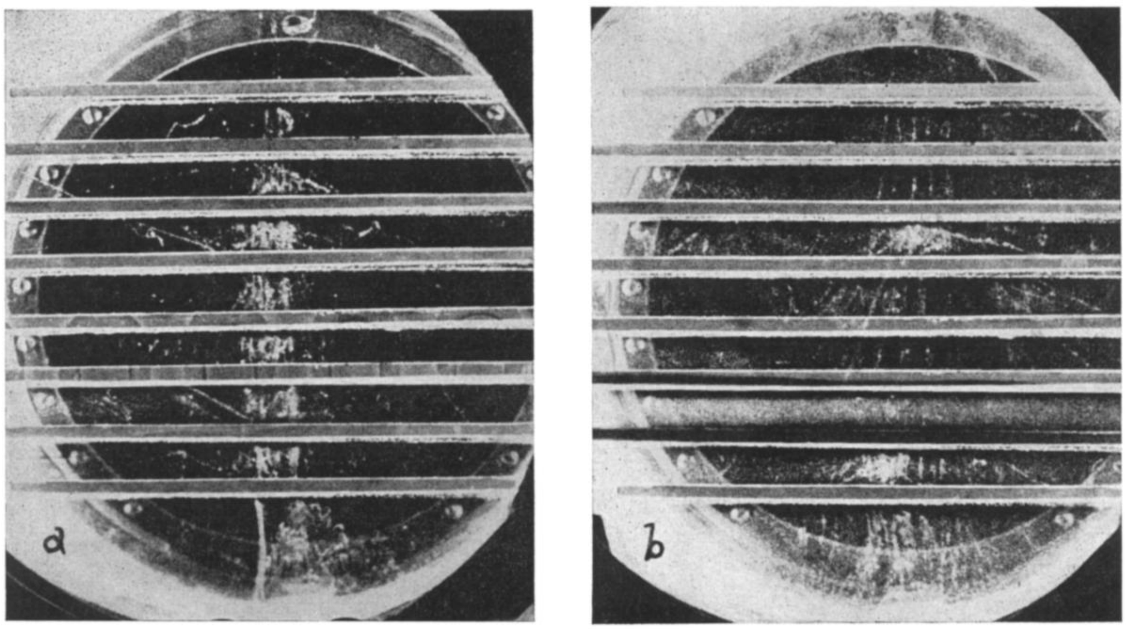


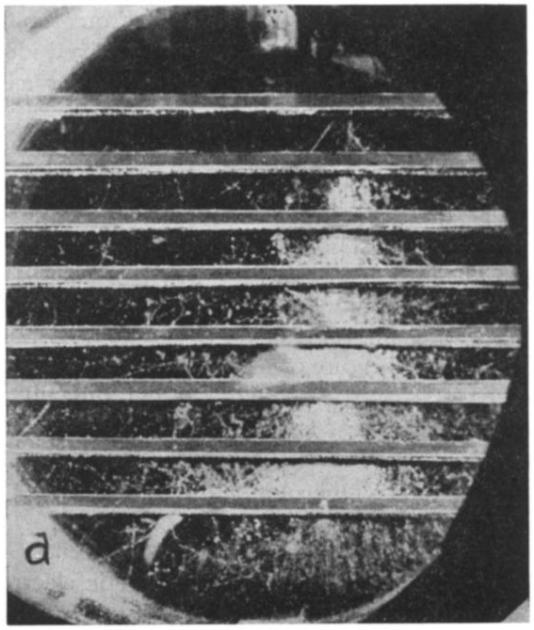
(a) (b)

FIG. 2. (a) Mixed shower originating in the cloud chamber. There are many penetrating particles and an electronic shower component with an energy of the order of one Bev. An originating particle track is visible on the negative. (b) Mixed shower produced by a non-ionizing particle. The G.M. tube was probably triggered by an accompanying air shower particle. It is impossible to tell how many of the shower particles are penetrating but there are either a number of penetrating particles or else a number of widely divergent low energy electrons from the shower origin. At least one of the particles is an energetic electron since there is cascade multiplication in the bottom lead plate.

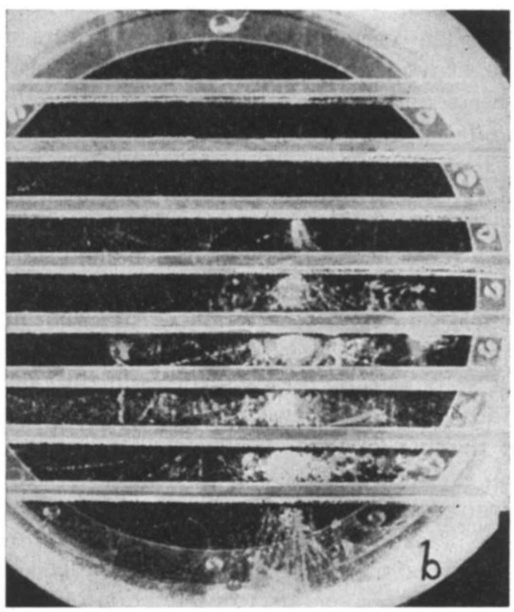


(a) (b)

FIG. 3. (a) Mixed shower originating above the cloud chamber. There appear to be several penetrating particles and two separate electron cascade shower cores. A star is seen to originate in the path of the left shower core in the seventh plate. (b) Penetrating particle shower originating above the cloud chamber. Eight penetrating particles enter the cloud chamber and either a neutron or one of the penetrating particles produces another disintegration of six or more penetrating particles in the third plate. There also appear to be some small electron cascades at the bottom.



(a)



(b)

FIG. 4. (a) One of the cases of an electron shower with an extraordinary lateral spread, and, apparently, more than one shower core. The shower also has a slow heavy particle at the origin and a star in the fifth plate. (b) What is believed to be an ordinary single electron shower. The initiating particle struck the edge of the third plate while travelling down and back 45 degrees from the vertical, thus missing the 5 inch absorber as well as the first and second cloud-chamber plates.