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Cascade Showers and Nuclear Disintegrations at 10,000 Feet

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A large cloud chamber containing eight lead plates was operated without counter control at 10,000 feet. In 8500 photographs, 1090 cascade showers and 58 nuclear disintegrations were observed. The differential energy spectrum for the shower-producing rays, which was obtained from the relative frequency of occurrence for showers of a given size, is proportional to $E^{-1.7}$ for $E=2\times10^8$ ev and to $E^{-3.0}$ for $E=10^9$ ev. The shower-producing rays with $E>2\times10^8$ ev constituted 6.5 percent of the radiation observed in the cloud chamber; one-third of the shower-producing rays were photons. Approximately one-third of the observed nuclear disintegrations contained particles that penetrated at least 0.7 cm of lead and four contained particles that penetrated at least 2.8 cm of lead. Most of the disintegration particles were protons or mesotrons. The initiating particles were neutrons and protons, with the former predominant for the lower energy disintegrations. There appears to be no sharp line of distinction between low energy and high energy disintegrations. No correlation was observed between the disintegrations and the cascade showers.

VARIOUS types of cloud-chamber experiments have been performed in order to analyze the cosmic radiation at altitudes of ten to fifteen thousand feet.[1] In the present experiment the details of the interaction of cosmic rays with lead were studied at an altitude of 10,000 ft. A large cylindrical cloud chamber (30 by 30 cm) was operated at Tioga Pass, Yosemite National Park, without counter control. The chamber contained eight lead plates each consisting of a 0.6-cm lead plate and two reflecting steel sheets plated with chromium. The equivalent lead thickness, calculated on the basis of densities, was 0.7 cm, and since the steel constituted such a small fraction of the absorber, it is assumed in all subsequent calculations that the plates were simply 0.7-cm lead sheets. Since there was sufficient illumination to obtain images of individual drops, diffuse tracks could be photographed, and these are included in the statistics in some cases. The chamber was filled with air and the saturated vapor from a 1 : 3 liquid mixture of water and ethyl alcohol to a total pressure of $\sim$70 cm when compressed and $\sim$60 cm when expanded. Other details of the apparatus have been given previously.[2]

The lead plates made possible the classification of the ionizing particles in two groups: particles of electronic mass, and particles of many times electronic mass (mesotrons and protons). Furthermore, the details of the interaction of each type of particle with lead could be observed. Essentially all of the photons initiated cascade showers in the lead and thus could be detected,

[1] Several of these experiments will be mentioned later in the paper.

[2] W. E. Hazen, Phys. Rev. **64**, 7 (1943).

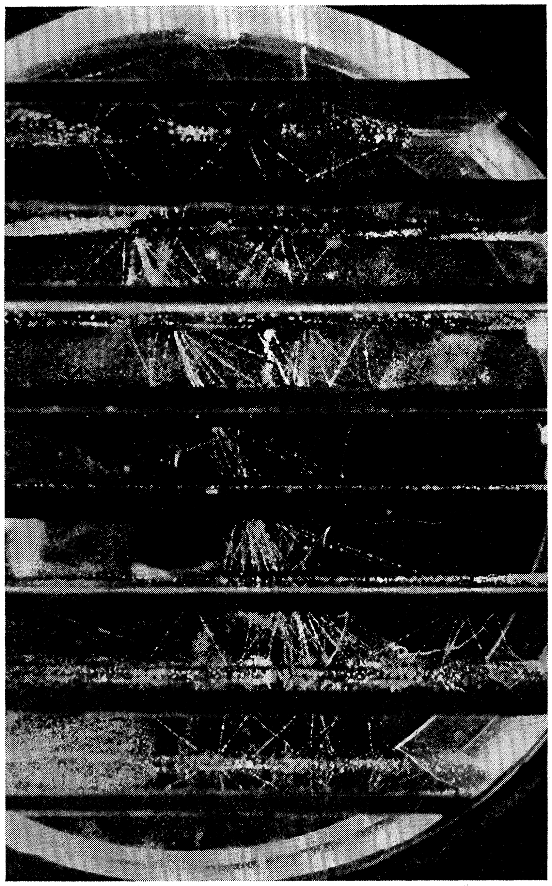

FIG. 1. Three time-associated showers were photographed in this expansion. The initiating particles are probably part of an air shower. There are 30 particles in the largest shower at its maximum, which occurs under the sixth lead plate (4.2 cm of lead). The energy of the particle that initiated this shower was 1.5×10^9 ev and the predicted position of the maximum is 4.5 cm of lead. Reflected images of the tracks can be seen in the plate surfaces, most clearly in the top and bottom plates.

whereas only a small fraction of the non-ionizing particles interacted with the lead. The analysis of the data pertaining to the production of collision electrons by the heavier particles has already been given.[2]

CASCADE SHOWERS

If an electron or photon has an energy greater than 10^8 ev, it is very unlikely to pass through a series of 0.7-cm lead plates without producing an observable cascade shower. In the cases where the initiation of the shower is observed, it is possible to distinguish between electrons and photons as the originating rays; where the maximum of the shower is observed, the energy of the originating ray can be estimated.

In the 8500 useful photographs, 1090 cascade showers with maxima of four or more particles were observed; 731 were classified as giving rise to sharp tracks, the rest as giving rise to diffuse tracks. Examples of the photographs are reproduced in Fig. 1. In the same series of photographs, 8678 sharp tracks from penetrating particles were observed. A size-frequency block diagram for the showers is given in Fig. 2. The relative number of four-particle showers is too low because many showers of this size originated in one plate and stopped in the next plate. This situation makes the chance of observation less than that for the larger showers, which nearly always passed through several plates.

The energy values shown along the scale of abscissae were obtained from the number of particles at the shower maximum by the use of Eq. (2.104) of Rossi and Greisen.[3] The number of particles at the shower maximum is not appreciably different for showers initiated by electrons and those initiated by photons of the same energy. When plotted with logarithmic scales the data are only reasonably well represented by a straight line (wth a slope of -2.4); see Fig. 3. If a simple power law is used to describe portions of the differential energy spectrum, the exponent

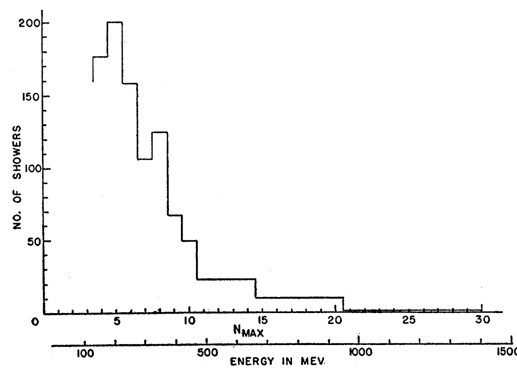

FIG. 2. Frequency of occurrence of cascade showers in lead as a function of the size of the shower. The size of the shower is expressed in terms of the number of particles at the maximum of the shower. The energy scale is obtained from shower theory [Eq. (2.104) of Rossi and Greisen, reference 3].

[3] B. Rossi and K. Greisen, Rev. Mod. Phys. **13**, 240 (1941).

varies from -1.7 for the lowest energies (2×10^8 ev) to -3.0 for the highest energies (10^9 ev).

The intensity of the shower-producing particles relative to the penetrating particles was obtained by considering sharp tracks only (the uncertainty in the equivalence of the total times of observation is thereby reduced). Since the total number of sharp tracks caused by showers with maxima greater than four particles was 605, while in the same series of photographs there were 8678 sharp penetrating tracks, the relative number of high energy electrons and photons ($E>2\times10^8$) is seven percent at 10,000 ft. From the cases where it was believed that the beginning of the shower was observed, the ratio of photons to electrons was found to be 1 : 2.5.

Auger[4] has compared the absorption of cosmic rays in lead and in aluminum, at about the same altitude as in the present experiment. Since Auger used a counter telescope with the absorber placed between the counters, the number of photons that would have been recorded is negligible. He obtained a ratio of 8 : 54 or 15 percent for the number of shower-producing particles with $E>10^8$ ev compared with the number of penetrating particles. If the spectrum from the present data is extrapolated to an energy of 10^8 ev, the value for the relative number of shower-producing rays (photons and electrons) with $E>10^8$ would not be much greater than 15 percent, even if the largest reasonable slope for the lower end of the spectrum is used in the extrapolation. A comparison of the results from the two experiments would thus lead one to the conclusion that the number of photons is negligible; however, the experimental uncertainties are fairly large in both cases and the result of the comparison cannot be considered as in conflict with the above-mentioned value of 1 : 2.5 for the ratio of photons to electrons. Most

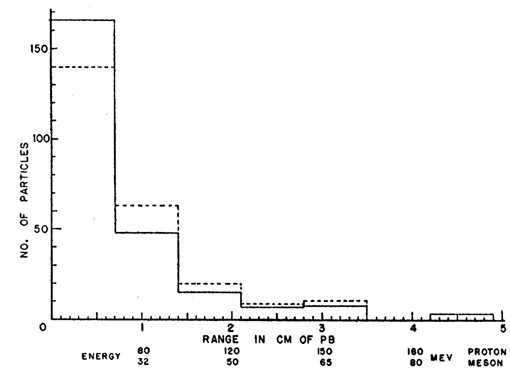

FIG. 4. The observed number of star particles as a function of their range in lead. The auxiliary scales of abscissae give the energies for protons and mesotrons. The dotted lines indicate the results of the correction for the finite size of the lead plates.

of the shower-producing rays originate as electrons,[5] and hence one would expect to observe more electrons than photons in a region where the rays are still being produced.

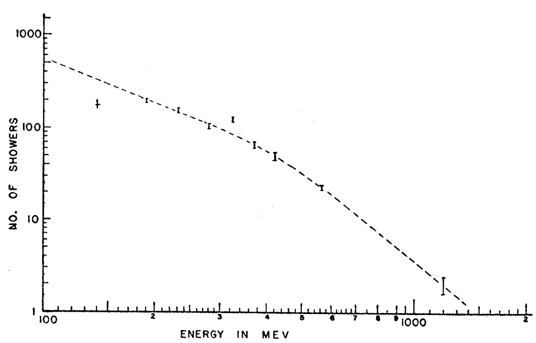

FIG. 3. The energy spectrum for photons and electrons (shower-producing rays). The ordinates represent the number of rays in an energy band of width 45 Mev. The experimental point with the smallest abscissa, which is represented by +, is relatively too low because showers of this size seldom penetrate more than one lead plate and therefore are less likely to be observed than larger showers; the other experimental observations are represented by lines whose lengths indicate the probable errors.

STAR SHOWERS OR NUCLEAR DISINTEGRATION

A few stars have been observed in the course of many cloud-chamber experiments and in one recent investigation 156 stars were observed.[6] In the present experiments a total of 58 stars consisting of two or more particles has been found in the photographs. The large area and close spacing of the lead plates resulted in a reasonably large chance that a particle would find several lead plates in its path if its range was several centimeters of lead. The interaction of a particle with the lead plates provides information concerning the nature of the particle.

Thirty-one of the stars consisted entirely of

[4] P. V. Auger, Phys. Rev. **61**, 684 (1942).

[5] K. Greisen, Phys. Rev. **63**, 323 (1943).

[6] W. M. Powell, Phys. Rev. **61**, 670 (1942).

the particles with range less than one lead plate (0.7 cm) and greater than 2.5 cm of air. Included in these thirty-one stars are the two which originated in the gas rather than in one of the lead plates. The rest of the stars contained particles with range of one or more lead plates, in addition to particles with range less than one lead plate. The average number of observed particles per star in the former group was 3.3, and in the latter group 5.5.

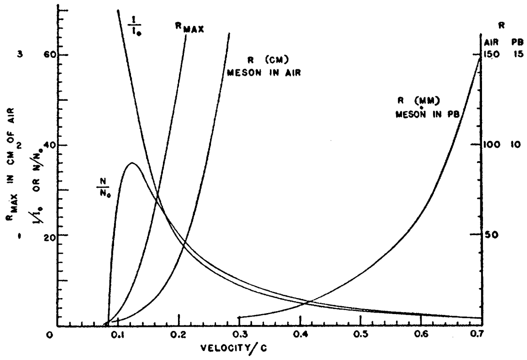

FIG. 5. Curves for δ-ray frequency, ionization, maximum range of δ-rays, and residual range of mesotrons or protons as a function of the velocity of the primary particle. N/N_0 and I/I_0 are, respectively, the frequency of δ-ray production and the ionization, both of them relative to the value of these quantities for a primary particle with velocity $\simeq c$. R_{max} is the maximum possible range for a δ-ray. R is the residual range of the primary particle. For an α-particle, N/N_0 and I/I_0 are four times as large as indicated, R_{max} is unchanged, and R is the same as for a proton.

A block diagram showing the observed frequency-range distribution for particles originating in nuclear disintegrations is given in Fig. 4. The relative numbers of short-range particles are too high since the solid angle subtended by a plate decreases as we proceed away from the origin of the star; the dotted lines of Fig. 4 indicate the results of the corrections for this effect. The original range distribution of the star particles is distorted by their passage through the lead plate in which they originated. The observed distribution is approximately the same as the original distribution for particles of range greater than one lead plate, but the observed distribution gives no idea of the original distribution for particles with range less than one lead plate. The *total* number of particles in the latter group can be estimated from the fact that 2/58 of the stars originated in the air between plates whereas the stopping power of the air relative to the plates in g/cm^2 was only 2/5800. We therefore conclude that there were roughly 100 stars (containing only short-range particles) that were not observed for each one that was observed; Powell[6] calculated a value of 50 for one-cm lead plates, which would reduce to 35 for 0.7-cm lead plates, in contrast to the value of 100 found in the present experiment. However, his calculation was made by dividing the lead thickness by the average range of the star particles; if Powell's data are analyzed in terms of stopping power of the gas relative to that of the lead, we again obtain a value of 100 for the number of unobserved stars per observed star. The discrepancy is attributable partly to experimental uncertainty and partly to the assumption that the frequency of star production is proportional to the nuclear mass. Thus we conclude that the true range distribution of star particles includes 35 to 100 times the observed number for particles with range less than one centimeter of lead; most of these unobserved short-range particles have ranges much less than one millimeter of lead.

In many cases the nature of the particles can be inferred from their ionization, change in ionization, scattering, or production of δ-rays. The first three methods have been discussed many times, but quantitative information for the latter method has not been found in the literature. Since low energy transfers predominate, the interaction due to spin is negligible and the collision probability for heavy particles[7] with electrons is proportional to

$$(1/\beta^2)(1-\beta^2E/E_{\max})dE/E^2, \tag{1}$$

where E is the energy of the ejected electron, β the velocity of the primary particle in units of c, and $E_{\max}$ is the maximum energy that can be transferred to the electron. For the type of collisions considered here, $E_{\max}$ is given by Eq. (1.5a) of Rossi and Greisen[3] with sufficient accuracy,

$$E_{\max}=2m_0c^2\beta^2/(1-\beta^2), \tag{2}$$

where m_0c^2 is the rest energy of the electron. The expression for the number of δ-rays per unit path with energy between $E_{\min}$ and $E_{\max}$ found by

[7] H. J. Bhabha, Proc. Roy. Soc. **164**, 257 (1938).

integrating (1) and expressing $E_{\max}$ in terms of β from Eq. (2) is

$$N=\frac{\text{const.}}{\beta^2}\left[\frac{2m_0c^2}{E_{\min}}-\frac{1-\beta^2}{\beta^2}-(1-\beta^2)\ln\frac{2m_0c^2\cdot\beta^2}{E_{\min}(1-\beta^2)}\right]. \quad (3)$$

In the present experiment δ-rays with ranges as short as one mm could be observed, and this fact leads to a value of 7 kev for $E_{\min}$.[8] If we define N_0 as the value of N for $\beta\simeq 1$, then N/N_0 represents the frequency of occurrence of δ-rays relative to the minimum frequency of occurrence (primary particle with $\beta\simeq 1$). A plot of N/N_0 as a function of β is given in Fig. 5. The ionization, the maximum possible range for a δ-ray, and the residual range of the primary are also plotted in Fig. 5. The value for N_0 obtained by Hornbeck and Howell[9] is 0.011 per cm of air at 76 cm and 15°C for $E_{\min}=12$ kev. For $E_{\min}=7$ kev the value for N_0 would be $0.011\times 12/7$ or 0.019 per cm, since we see from Eq. (3) that N_0 (the value of N for $\beta\simeq 1$) varies inversely with $E_{\min}$.

Of the 166 tracks of particles with range less than 0.7 cm of lead, 70 showed ionization corresponding to singly-charged particles with velocity greater than 0.75 c; such particles could be either electrons or mesotrons. The remaining 96 short-range particles ionized at least several times more strongly and therefore could not be electrons. Three of these particles were probably α-particles because of the large number of δ-rays occurring along their paths. Each of them had four or more δ-rays with range at least one mm in a track length of $\sim$2.5 cm. Thus N/N_0 is $\sim$85, which is a highly unlikely value for a proton or mesotron (Fig. 5). The rest of the particles were probably not α-particles since an α-particle with range <0.5 cm of lead would produce at least one δ-ray per cm. Shapiro[10] has found that 90 percent of the star particles registered by photographic emulsions are protons, and the remainder probably are α-particles. Since such particles lie near the short-range group under discussion, there is good agreement with the present results in respect to the small number of α-particles.

Among the particles with range greater than 0.7 cm of lead, there were twelve that might have been electrons, as judged from scattering and ionization; three of these twelve also multiplied and this indicates that the three were probably electrons. However, the identity of the twelve is not certain even in the case of the latter group of three. Three of the long-range particles might be interpreted as α-particles, but they might also be protons. The remaining 65 long-range particles were either protons or mesotrons. It is difficult to estimate how many of these long-range star particles are mesotrons rather than protons. Nielsen and Powell[11] photographed the tracks of slow particles at 14,000 ft. with a technique that left virtually no uncertainty in the identification of mesotrons. They found that only about one percent of the heavy tracks observed at high altitudes was due to mesotrons. However, this does not necessarily indicate that most of the star particles are not

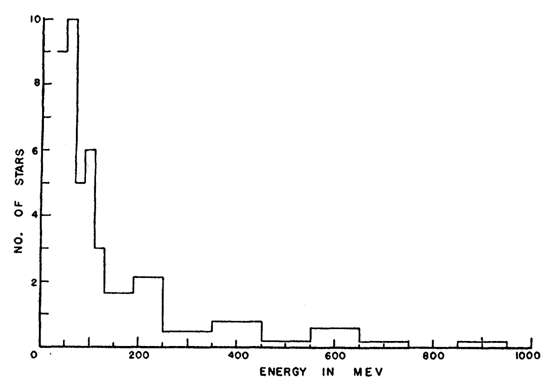

FIG. 6. Frequency of occurrence of stars in an energy band of width 20 Mev as a function of the total observed energy. The energy, which is calculated on the assumption that all the particles are protons, would be approximately one-half as great if the particles are mesotrons.

mesotrons. In the first place, the range of a slow proton is ten times that of a mesotron moving with the same velocity, and hence the observations of Nielsen and Powell indicate that the relative frequency of formation might be ten percent. In the second place, a large fraction of the slow particles occurs singly; that is, such

[8] G. Fr. von Droste, Zeits. f. Physik **84**, 17 (1933).
[9] G. Hornbeck and I. Howell, Proc. Am. Phil. Soc. **84**, 33 (1941).
[10] M. M. Shapiro, Phys. Rev. **61**, 115 (1942).
[11] C. E. Nielsen and W. M. Powell, Phys. Rev. **63**, 384 (1943).

particles did not originate as part of what we have termed a star shower (although the distinction may be based on energy alone). It is difficult to estimate the number of single slow particles from the present series of photographs because contamination α-particles traversed the full distance between the plates even when the path was inclined 45 degrees from the vertical. A lower limit, which may be several times too small, is 400 single particles that certainly were not α-particles. Anderson and Neddermeyer[12] observed on Pikes Peak about twenty times as many single heavily-ionizing particles as stars. Consequently, it is quite likely that Nielsen and Powell observed very few star particles, and their results do not necessarily indicate that most of the star particles are not mesotrons. Anderson and Neddermeyer[12] identified two particles in one star (Fig. 10, reference 12) as probably protons; one particle in each of two stars (Figs. 12 and 13) is definitely a mesotron; and four other particles in one star (Fig. 12) are either mesotrons or electrons. Crussard and Leprince-Ringuet[13] photographed a star (Fig. 3, reference 13) containing two particles that are certainly protons. There are two other cases that have been reported in which the multiple production of identifiable heavy particles has been observed.[14,15] The particles have been identified as mesotrons in both cases. In several other reports penetrating particles produced in multiples have been interpreted as mesotrons without any real justification for such an interpretation.

Only one of the thirty-one stars containing merely short-range particles was observed to have been caused by an ionizing ray, but in several cases such a ray could not have been observed. A time-coincident cascade shower accompanied one of the stars; in this case a non-ionizing ray gave rise to the star. Eight of the stars containing long-range particles were initiated by ionizing rays and thirteen by non-ionizing rays. In two photographs time-coincident cascade showers were also present. In one of these cases the star was initiated by a penetrating ionizing particle, which also appeared to initiate the shower through the medium of a knock-on electron; in the other case the nature of the ray that initiated the star could not be ascertained.

Twenty of the stars consisting of short-range particles contained only particles that were projected downward whereas the other eleven contained both upward and downward projected particles, the number of upward and downward projected particles being about equal in the latter case. On the other hand, only six of the stars containing long-range particles included upward projected particles, and the total number of such particles was only eight.

The energies of the particles can be estimated from their range limits in lead[3] (see Fig. 4). The most energetic particles had energies greater than 100 Mev if they were mesotrons or 200 Mev, if they were protons. A block diagram of the frequency *versus* total energy actually observed in the star is given in Fig. 6. The energies were calculated by assuming that all the star particles were protons. Examples of the photographs of stars are reproduced in Fig. 7.

In the above analysis, heavily-ionizing particles that occurred singly and originated in the lead plates have been omitted because, in the first place, it was impossible in many cases to distinguish between α-particles from radioactive sources and heavily-ionizing particles ejected by cosmic rays, and, in the second place, it is not known that the single particles result from the same type of event.

SINGLE HEAVILY-IONIZING PARTICLES

As mentioned in the preceding section, there were observed at least 400 heavily-ionizing particles that were projected from the lead plates and that could not have been contamination α-particles. Most of these particles evidently were projected from lead nuclei by neutrons, i.e., the incident ray was non-ionizing and the event was not associated with a cascade shower. Eight of the heavily-ionizing particles were projected from the lead by penetrating particles, which lost only a portion of their energies in the process and then continued through the remaining lead plates.

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[12] C. D. Anderson and S. H. Neddermeyer, Phys. Rev. **50**, 263 (1936).

[13] J. Crussard and L. Leprince-Ringuet, J. de phys. et rad. **8**, 213 (1937).

[14] G. Herzog and W. H. Bostick, Phys. Rev. **59**, 122 (1941).

[15] D. J. Hughes, Phys. Rev. **60**, 414 (1941).

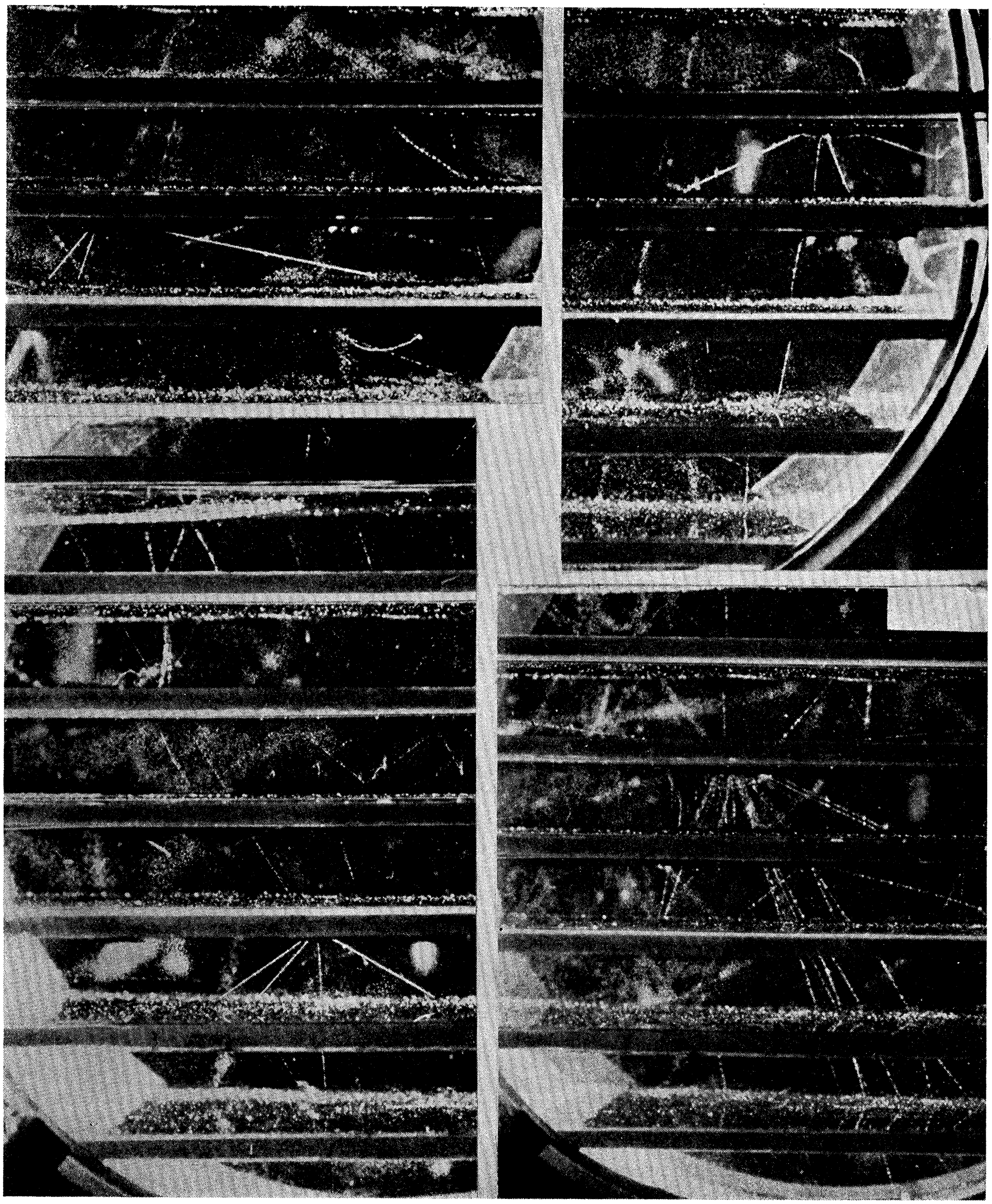


FIG. 7. Examples of nuclear disintegrations or star showers. *Upper left:* the most frequent type of star. The particles have short range and heavy ionization. *Upper right:* a star containing long- and short-range particles, probably initiated by a neutron. *Lower left:* a similar star initiated by a charged penetrating ray. *Lower right:* a star containing several long-range particles. The track doubling in one section results from a residual clearing field. The right long-range particle produces secondaries, but it is probably not an electron.

In some cases heavily-ionizing particles, which originated outside the chamber or in the glass cylinder, passed nearly horizontally through the chamber, and twenty or more centimeters of track length could be observed. In several cases eight or ten δ-rays occurred, a number that corresponds to about twenty-five times the number for $\beta \simeq 1$. These particles could not have been mesotrons since the range of such a mesotron would be only twenty centimeters (Fig. 5). They might be protons or α-particles.

A number of penetrating particles were observed that terminated their ranges in the lead plates but originated outside the chamber. In the last 4000 of the pictures, 5 inches of paraffin were placed above a portion of the chamber in order to determine whether the particles were protons projected from hydrogenous material by neutrons, as suggested by Powell.[6] A more detailed analysis of the photographs will be required before any conclusion can be drawn.

CONCLUSIONS CONCERNING NUCLEAR DISINTEGRATIONS

(1) The initiating particles are very seldom, if ever, electrons or photons. If they were electrons or photons with sufficient energy to produce the observed disintegrations, they would produce cascade showers in the lead plates above the star origin or they would be accompanied by other electrons or photons. In previous cloud-chamber experiments that seem to indicate a correlation between stars and cascade showers the cloud chamber was tripped by counters, in some cases with counter arrangements that selected multiple events only. For example, Anderson and Neddermeyer[12] observed cascade showers in more than one-third of their photographs taken at Pikes Peak. Hence their observation of 30 cases of time-coincident showers in 113 photographs with heavily-ionizing particles does not indicate association between the two types of events. The other published results also indicate no more association between cascade showers and stars or heavily-ionizing particles than would be expected of independent events. In the present work expansions were not counter controlled, and hence there was much less distortion in the relative frequencies of occurrence of the various events. Since eight percent of the photographs showed cascade showers of four or more particles, one would expect four or five of the 58 photographs of nuclear disintegrations to contain cascade showers; the observed number was three. Powell[6] also noted little if any association between showers and stars. On the other hand, Auger[16] observed a real correlation between heavily-ionizing particles and extensive (Auger) showers. However, this does not necessarily indicate production of penetrating rays by the soft component since it is known that penetrating rays are also present in Auger showers.

(2) The stars are probably produced by neutrons and protons. Since the non-ionizing rays that initiate stars are not photons, we are left with neutrons as the reasonable alternative choice. The ionizing rays that initiate showers are neither electrons nor α-particles, but in this case there are two further alternatives: protons or mesotrons. However, the frequency of occurrence of stars increases several times more rapidly than the intensity of the penetrating particles as we go to higher altitudes from sea level.[12] Since most of the penetrating particles are mesotrons, it would be possible for the relative number of protons to increase several times in going from sea level to 14,000 feet, whereas the relative number of mesotrons could not. Hence it seems most likely that the star-initiating ionizing particles are protons.

(3) There may be no sharp line of distinction between low energy stars with particles projected in all directions and high energy stars with long-range particles projected in the general direction of the incident particle. Rather there appears to be a gradual change from one type to the other with increasing energy of the initiating particle. Examples of all types of intermediate cases were photographed (Fig. 7). The single heavily-ionizing particles originating in the lead plates are perhaps merely the limiting case for low energies.

(4) The initiating particles are predominately neutrons for the lower energy stars and about equally divided between ionizing and non-ionizing particles (protons and neutrons) for the higher energy stars. Nearly all of the single

[16] P. Auger, R. Maze, P. Ehrenfest, and A. Freon, J. de phys. et rad. **10**, 39 (1939).

heavily-ionizing particles were produced by neutrons.

(5) The star particles are mostly mesotrons and protons. In the present work very few electrons or α-particles were observed in the high energy stars and less than half of the short-range particles could have been electrons. Examples have been quoted from other papers that gave proof of the presence of both mesotrons and protons.

Two other conclusions, which are related to reported results from other investigations, should be mentioned. (1) It seems rather presumptuous to assume that an observation of the multiple production of long-range particles with either counters or a cloud chamber is necessarily an observation of the production of mesotrons, in cases where there is no evidence that the particles are not protons. (2) Detailed analyses of stars observed in photographic emulsions that make use of conservation of momentum or of energy are likely to be meaningless with present techniques since particles with minimum ionization occur in a few of the stars and are not observed in photographic emulsions.

The observed characteristics of stars are satisfactorily described in terms of the semiquantitative theory of nuclear collisions as discussed by Heitler.[17] He not only suggests that all of the transferred energy of the incident particle might be dissipated in "heating" the entire nucleus, with subsequent emission of many particles, but he also suggests the possibility that the particles near the edge of the nucleus receive the energy and escape before sharing their energy with the rest of the nucleus. Heitler's estimates give 2×10^7 ev for the maximum energy of the emitted particles in the former process, when the energy of the incident particle is 2×10^9 ev. In the present as well as in previous work energies at least five or ten times larger than 2×10^7 ev have been observed for star particles. This result might indicate that the initiating particles had energies $\sim 10^{11}$ ev or else that the latter of the processes suggested by Heitler was occurring.

There appears to be a gradual transition from the low energy uncollimated type of star produced mostly by neutrons to the high energy collimated type initiated by neutrons and protons. It may be that stars of the latter type constitute examples of the production of mesotrons by protons such as is indicated by the experiments of Schein, Jesse, and Wollan.[18] If this is so, it seems likely that protons are also produced in the same events.

Hamilton, Heitler, and Peng[19] have suggested a cascade process for the mutiple production of mesotrons. None of the present photographs gives evidence for such a process.

The author welcomes this opportunity to express again his gratitude to Superintendent Frank A. Kittredge and other members of the staff of Yosemite National Park for their helpfulness.

[17] W. Heitler, Phys. Rev. **54**, 873 (1938).

[18] M. Schein, W. P. Jesse, and E. O. Wollan, Phys. Rev. **59**, 615 (1941).

[19] J. Hamilton, W. Heitler, and H. W. Peng, Phys. Rev. **64**, 78 (1943).

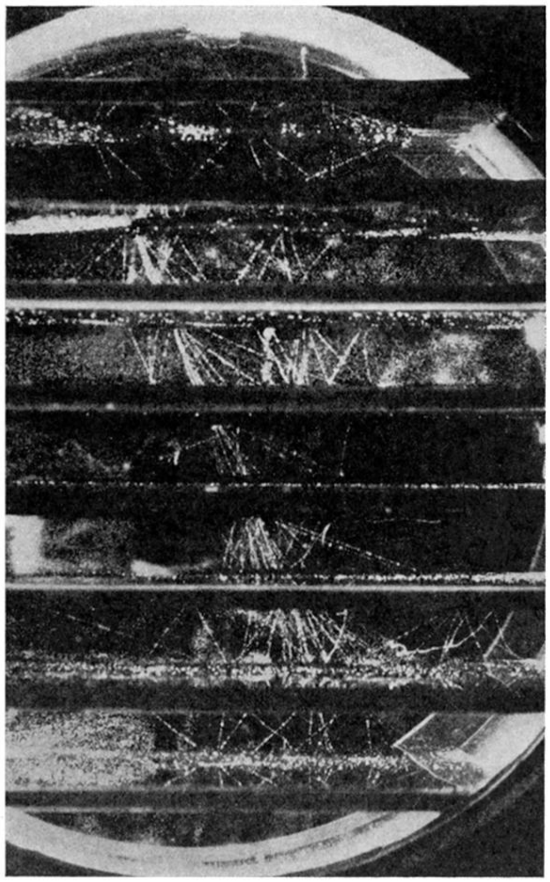
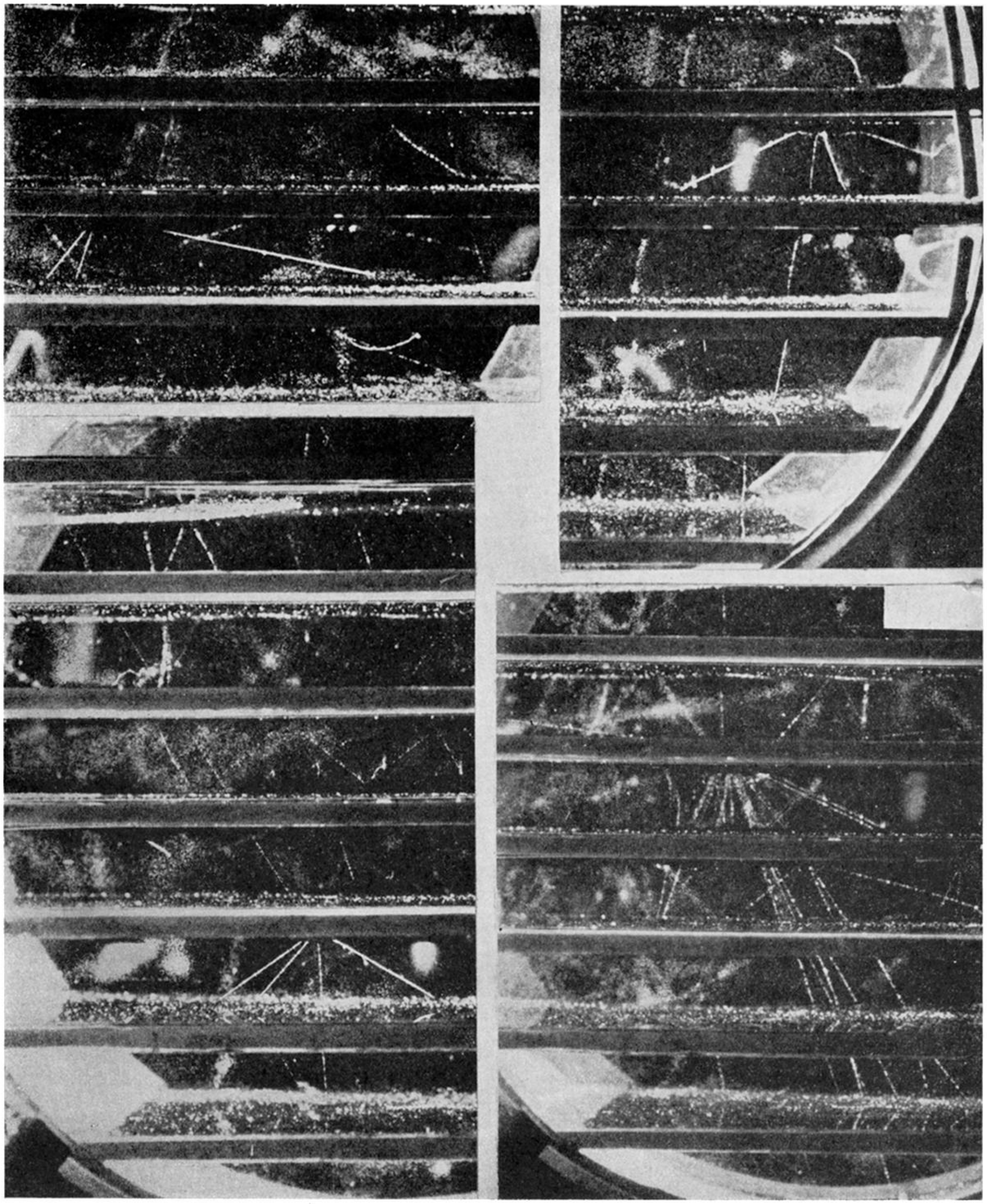


FIG. 1. Three time-associated showers were photographed in this expansion. The initiating particles are probably part of an air shower. There are 30 particles in the largest shower at its maximum, which occurs under the sixth lead plate (4.2 cm of lead). The energy of the particle that initiated this shower was 1.5×10^9 ev and the predicted position of the maximum is 4.5 cm of lead. Reflected images of the tracks can be seen in the plate surfaces, most clearly in the top and bottom plates.



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