The Production of Cosmic-Ray Showers in Lead

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(Received November 4, 1937)

Photographs were taken of cosmic-ray showers arising in lead plates of various thickness placed in turn inside a Geiger counter controlled cloud chamber. These showers are classified according to the number of particles in the shower and according to the manner of production, whether by an ionizing particle or by nonionizing radiation. The average size of showers was found to increase with the plate thickness. Studies of the frequencies of showers of different sizes as a function of plate thickness show that electron-produced and photon-produced showers occur in approximately equal numbers and are of the same character. These facts give support to the theories of Carlson and Oppenheimer and of Bhabha and Heitler. They consider the shower to be the result of repeated subdivision of incident radiation through pair production by gamma-rays and through radiative losses of high energy electrons giving rise to other gamma-rays. Eight percent of the electrons striking lead plates near seven millimeters thick gave rise to showers. About an equal number of showers from gamma-rays were present.

INTRODUCTION

A NUMBER of cloud chamber photographs[1] have been published showing large cosmic-ray showers in which electrons and γ-rays passing through lead plates have given rise to secondary particles. Many such showers are so complex that the great bulk of the tracks cannot be traced to a definite source. Others contain one or more shower centers produced either by ionizing or nonionizing radiation, or by a mixture of the two. With several thin lead plates in the cloud chamber, the progress of the shower can be followed in its passage through matter, and from these experiments it appears that no single event constitutes the origin of a large shower. Rather, a cascade of electrons and γ-rays gradually increases in size as it strikes each successive layer of lead. The large complex showers observed are simply late stages of showers originating in the walls or atmosphere surrounding the cloud chamber. Additional evidence for the multiplicative nature of shower formation is found in measurements of shower frequency as a function of absorber thickness. Both ionization chamber[2] and Geiger counter[3] methods show that the thickness of lead which gives the greatest frequency of showers of a given size increases with the size of the shower considered. Such a shift of optimum thickness with shower size is a consequence of multiplication, whatever the process by which secondaries may be emitted.

The presence of nonionizing radiation and the absorption of shower-producing radiation according to a Z^2 mass-absorption law,[4] as for the degradation of γ-rays by pair production, indicates that pair production is an important factor in shower formation. The primary electron loses a large fraction of its energy in creating a quantum of radiation. The resulting radiation forms electron pairs, and these electrons like the primary electron create more γ-radiation. The process continues until the energy is dissipated through ionization losses of many secondaries. Calculations[5] formulated on this basis lead to plausible explanations for most shower phenomena where only electrons and γ-rays are involved. Showers containing heavily ionizing particles appear to come from a disintegrative process and are not treated in the theory.

Rough calculations as shown by Carlson and Oppenheimer give the relation $n=2^t$ for the number of shower electrons to be expected at a depth t, the unit in t being 0.5 cm for lead, 1.7 cm

[1] C. D. Anderson and S. H. Nedermeyer, Phys. Rev. **50**, 263 (1936); E. C. Stevenson and J. C. Street, Phys. Rev. **49**, 425 (1936); P. Auger and P. Ehrenfest, Jr., J. de phys. et rad. **8**, 204 (1937); J. Crussard and L. Leprince-Ringuet, J. de phys. et rad. **8**, 213 (1937).

[2] R. T. Young, Jr., Phys. Rev. **52**, 559 (1937); J. K. Boggild, *Über die Sekundaren Wirkungen der Hohenstrahlung* (Kopenhagen, 1937).

[3] D. K. Froman and J. C. Stearns, Phys. Rev. **52**, 382 (1937).

[4] J. E. Morgan and W. M. Nielsen, Phys. Rev. **50**, 882 (1936); **52**, 568 (1937).

[5] J. F. Carlson and J. R. Oppenheimer, Phys. Rev. **51**, 220 (1937); H. J. Bhabha and W. Heitler, Proc. Roy. Soc. **A159**, 432 (1937).

for iron, 40 cm for water. Choice of t in these units makes the description of the shower identical for all substances. The expression above is obtained on the assumptions that the probabilities of radiation and of pair production are equal and independent of energy, and that none of the particles is stopped. Actually the probability of pair production is less than that of radiation, and both probabilities are inversely proportional to the energy. Hence small showers will occur with a maximum frequency for absorber thickness somewhat greater than the rough estimate, and large showers, because of the increased probabilities of conversion as the energy decreases, will become most frequent at a thickness smaller than estimated. In the present series of observations this rough approximation is about as good as the data. Therefore more precise solutions of the multiplication equations will not be used since such solutions are not in the most convenient form for experimental comparison. What is desired is a check for the optimum thickness of lead for showers of only a few electrons, because in the thin lead plates where these will be most plentiful there is small chance that electrons will be stopped, and agreement between theory and experiment should be best.

Since shower frequencies measured by means of Geiger counters arranged in multiple are likely to indicate too few small showers, counters are not suited to the experiments. As the simplest case consider the counting of two-particle showers. Three counters placed at the corners of a triangle with the apex just beneath a block of absorber, require at least two particles to excite all three counters simultaneously. All large showers produce counts, but there is a good chance that many small showers, especially those of two electrons, miss one of the two lower counters. Consequently, the data obtained represent an average for a shower containing substantially more than two electrons. Likewise, arrangements of counters that require higher orders of coincidence register but few of the showers containing just the minimum number of electrons. In order to check the radiation pair production theory it is desirable to obtain more accurate information concerning individual small showers than can be gotten from Geiger counters or from ionization chambers. Although operation of a cloud chamber requires considerable time to accumulate sufficient counts, the completeness of the data obtained seems to justify the effort. A record is made of every shower, and selection of those fulfilling certain requirements becomes possible.

Apparatus

A cloud chamber[6] of the moving diaphragm type 30 cm in diameter and 10 cm deep was employed in a vertical position. The shower source consisted of a lead plate suspended across the center of the chamber by means of two brass bands in contact with the glass cylindrical wall. Several different plates 8×22 cm^2 in area and of thicknesses from 0.15 to 1.6 cm were used. Another lead plate 0.63 cm thick, 7×15 cm^2 in area, was fastened to these same bands at the top inside of the chamber during part of the experiments, and replaced by an aluminum plate 0.2 cm thick for the remainder. Cemented to the upper plate with paraffin was a small glass dish containing a mixture of two parts ethyl alcohol and one part water. Previous work had shown the necessity of keeping excess liquid at the top of the chamber if expansions as close as one minute apart were to show tracks. Argon, being a monatomic gas, was chosen to fill the chamber because it requires a smaller expansion ratio than most other gases to give the same adiabatic cooling, and, since it has a fairly high atomic number, electron tracks produced in it are less diffuse than at the same age in a gas like nitrogen. When assembled with a lead plate just put in place, the chamber was flushed with tank argon until less than 10 percent air remained, and filled to a pressure of about 1.8 atmospheres. According to the exact amount of air left, between 8.0 and 8.5 percent volume expansion gave the clearest tracks. With this small expansion there is very little distortion and consequent lack of resolving power produced by gas slipping past the edges of the lead plates.

Although the most reliable data would be obtained from expansions of the cloud chamber taken at random, the number of successful pictures, that is, pictures in which a cosmic-ray track of any sort could be seen, amounts to about

[6] R. B. Brode, H. G. MacPherson, and M. A. Starr, Phys. Rev. **50**, 581 (1936).

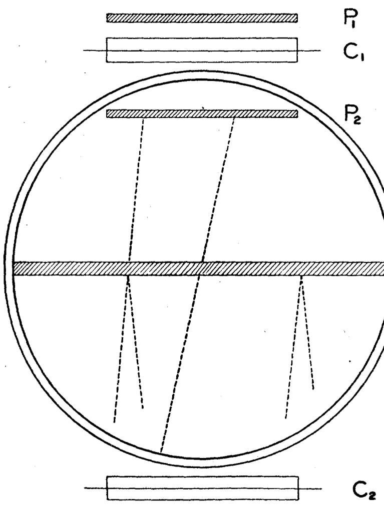

FIG. 1. C_1 and C_2 are Geiger counters; P_3 the shower source; P_1, 0.36 cm lead; P_3, 0.36 cm lead.

three percent of all the pictures. In order to speed the process of taking usable pictures, expansions of the chamber were controlled from a coincidence counter set. Two Geiger counters connected in parallel were placed at the top of the chamber and similar counters at the bottom, so as to cover a fairly large area. Each counter was two cm in diameter and fifteen cm long, and the two overlapped to present an area of about 3.5×15 cm^2 to the vertical. This was slightly less than the illuminated section of the chamber, through which a beam of light about five cm broad was projected by means of cylindrical lenses. The counting rate of either pair of counters alone was 120 per minute. In vertical coincidence with the two pairs separated by forty cm the rate was about 60 per hour.

Objection may be raised to the use of counters, but the same arguments do not apply to double coincidence as to triple. Every shower passing through the chamber can be recorded, because only one particle is required to pass through the lower counter. There are two other faults, however, which tend to select data. One is that those showers in which some particle does not have an energy great enough to penetrate the glass wall of the chamber and the walls of the second Geiger counter will not be counted. This energy, as estimated from calculations of Bethe,[7] is about five million volts, a value below the average energy of secondaries in showers. Thus, in general, we can expect very few showers to terminate inside the chamber and thereby escape detection. A more serious fault is that showers produced by γ-rays will not register unless accompanied by an ionizing particle passing through the upper counter. An attempt was made to find the magnitude of this selection by measuring shower frequencies with and without

[7] H. Bethe, *Handbuch der Physik*, Vol. 24/1, (1933), p. 522.

TABLE I. *General summary of tracks observed.*

Plate Thickness	Number of Pictures	Penetrating Electrons	Absorbed Electrons	Total Tracks Above Plate	Total Tracks Below Plate	Ratio Below/Above	Number of Electron Showers	Total Tracks	Average in Electron Shower	Number of Photon Showers	Total Tracks	Average in Photon Shower	Unresolved Showers	Tracks Above	Tracks Below	Measure of Incident Radiation
1.0 cm of lead above																
0.15	1163	971	113	1247	1182	1.05	43	98	2.3	39	82	2.1	13	55	86	1014
0.4	1650	1128	185	1633	2055	1.26	102	275	2.7	83	193	2.3	35	218	459	1230
0.65	1603	1032	213	1466	1847	1.26	94	262	2.8	89	215	2.4	32	127	307	1126
0.9	1680	1154	300	1647	1999	1.21	93	285	3.1	87	221	2.6	27	100	339	1247
1.65	1788	1255	328	1476	1847	1.25	73	281	4.0	54	192	3.6	31	105	430	1328
No lead above																
0.65	1263	960	114	1172	1341	1.15	89	254	2.9	42	95	2.3	4	9	32	1049
0.9	1302	930	104	1144	1526	1.33	92	322	3.5	34	99	2.9	7	18	75	1026
1.65	1368	1013	142	1271	1716	1.35	91	426	4.7	50	197	3.9	9	25	90	1104

additional lead plates present above the plates in which the observed showers originated. This point will be discussed in more detail below.

Five different lead plates were placed in turn at the center of the cloud chamber, and a set of pictures taken for each. The apparatus was entirely automatic, taking a picture for the first coincidence after each resetting. The time of reset could be controlled by a resistance in series with a motor which wound the film and operated relays to put everything in readiness for the next expansion. This time was set at forty-five seconds in order to allow the chamber to reach temperature equilibrium and to reduce turbulent motion of the gas. In addition to the central plate there was a total of one cm of lead arranged as shown in Fig. 1.

The experiments were carried out at an elevation of about 100 m under a thin sheet iron roof so that the incident radiation is essentially the normal sea-level cosmic radiation. Because no magnetic field was available to produce an energy spectrum, the results are to be interpreted as the average behavior of cosmic radiation, with no differentiation as to initial energy of the rays. Since showers of different sizes may be produced by incident rays of different energies, this lack of information is a handicap, but it is to be expected that the distribution of energy for each run with a given plate is about the same within statistical errors. As over a thousand pictures were taken for every thickness of lead, the incident rays are assumed to be identical at all times.

Classification of Tracks

Comparison of results for the various plates requires a systematic classification of the tracks photographed and a measure of the incident radiation. Only those electrons have been tabulated which excited the counters or at least were coincident in time with counter excitation. Also the condition was imposed that the track be included within the solid angle subtended by the counters. Stereoscopic photographs aided in locating tracks. Tracks of different ages can be identified by two means. Positive and negative ions in the track are separated by the clearing field and in a short time give the track a double appearance. An equally good estimate of age is made from the width and density of the track. These methods fail when background fog is present. For this reason the cloud chamber was

Table II. *Numbers of showers.*

Particles per shower	2	3	4	5	6	7	8	9	10	Others
Electron										
1 cm Pb above										
0.15	35	5	2	1						
0.40	63	20	12	3	2	2				
0.65	59	19	6	5	1	2	1		1	
0.90	63	12	4	5	2	2	1		2	11, 17
1.65	47	9	3	1	2	1	4	1	1	11, 13, 25, 32
Zero cm Pb above										
0.65	54	20	6	2	3	1	1	1	1	
0.90	52	15	10	6	6	3			2	13, 13
1.65	41	16	4	3	5	7	1	2	3	11, 11, 11, 13, 13, 14, 15, 20, 22
Photon										
1 cm Pb above										
0.15	37		2							
0.40	67	8	6	1	1					
0.65	66	13	2	5	1	1	1			
0.90	64	9	9	2	1	2				
1.65	34	8	1	3	2	3				14, 14, 20
Zero cm Pb above										
0.65	36	4	1			1				
0.90	22	3	4	2	1	2		1		11
1.65	33	5	3		1	2	1		1	12, 12, 12, 30

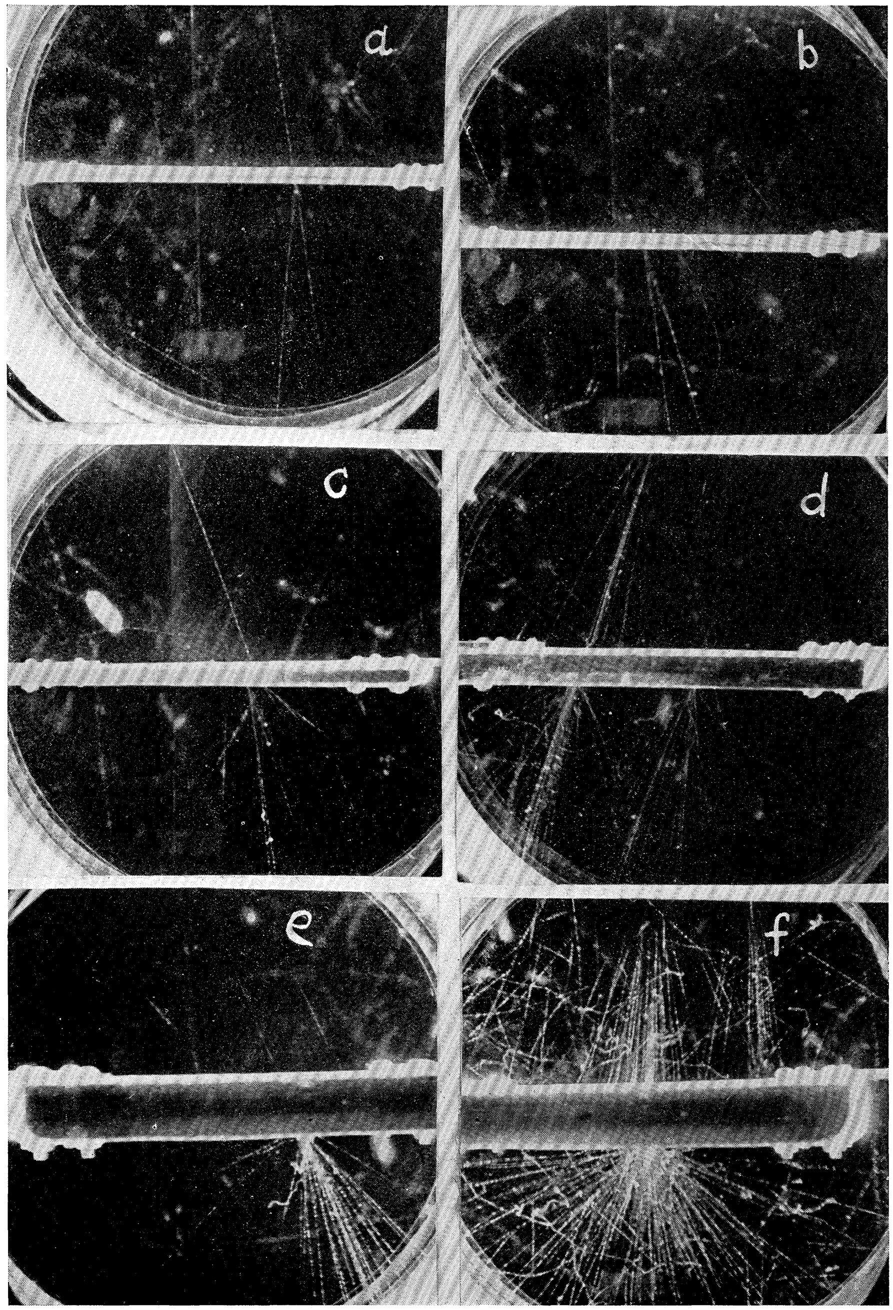

FIG. 2. *a*, Two-particle shower from an incident electron. The fuzzy vertical line is a wire used in stereoscopic measurements. *b*, Two-particle shower from an incident gamma-ray. The fuzziness and displacement of tracks in this and other photographs are caused by turbulent motion of the gas during expansion. *c*, Six electrons are produced by the incident electron, and four electrons by a gamma-ray. *d*, An unresolved shower showing absorption of deflected electrons. *e*, A few pictures were taken with a 3 cm plate. This is one of the larger showers; two-particle showers are most plentiful even for this plate. *f*, An exceptionally good example of the apparent origin of a shower in the last few millimeters of the absorber. Practically all the incident electrons stop in the plate.

thoroughly cleaned each time it was taken apart to introduce a new lead plate, and the expansion was checked visually at the beginning of every run of some forty pictures. Altogether, only a few tracks of doubtful age were photographed. Application of these two conditions to the selection of tracks assures us of obtaining consistent incident radiation, and of counting phenomena produced under comparable conditions.

A large percentage of the photographs show that a single particle has been responsible for the expansion, and has passed through the central lead plate unaffected. These particles are listed in Table I as penetrating electrons. Other particles striking the plate each produce a shower of two or more electrons, of which it is extremely probable that at least one will be contained in the solid angle covered by the lower counter, and thus complete the coincidence necessary to set off the expansion. The total number of tracks in electron-produced showers and the average per shower are listed, also the same numbers for photon-produced showers. A detailed list of showers produced by single incident electrons and γ-rays is given in Table II. Another type of shower occurred whenever a shower from the lead at the top of the chamber was increased in size by passage through the central plate. Most of these have been classified in Table I as unresolved because it is impossible to assign the electrons below the plate to a shower produced by some one particular incident electron or γ-ray. The relatively small number of unresolved showers obtained when the upper lead plates are removed is due to the fact that small angle showers are not present above the central plate to the same extent as with the lead in place. Typical examples of showers are shown in Fig. 2. Particles reaching the end of their range in the plate are called absorbed electrons.

The average number of tracks in showers is shown in Fig. 3 for the various arrangements of lead. In agreement with the theory proposed by Carlson and Oppenheimer, the average increases with the thickness of lead through which the radiation has passed. In every case the average for electron-produced showers is greater than for the corresponding photon-produced showers. This may or may not be significant. When the distribution of showers according to size is taken into consideration, it might be interpreted as meaning that the average electron has more energy than the average photon. Such increase in average size with increasing thickness of lead points to a process which does not take place at one assigned point. Out of a total of eighty-two showers originating in the thinnest plate, only one had as many as five electrons. Nine had three or four. All the rest were pairs. In comparison, with approximately twice as much incident radiation, the thickest plate gave rise to twenty showers containing more than ten tracks. The largest of these had thirty-two. There were forty-three showers of from five to ten electrons each. The fact that the thin plate gives no large showers while the thicker plates do, is fairly conclusive evidence for the verification of a multiplicative process of shower formation.

Discussion

In the multiplicative theory, an electron does not lose so large a fraction of its energy by radiation as to change its penetrating power to any great extent. Electrons and γ-rays will move along more or less in the direction of the initial radiation. Consequently wherever there is a γ-ray there is a good chance of finding an electron nearby. The centimeter of lead at the top of the chamber is sufficient to filter out most of the air γ-rays and replace them with lead γ-rays. Hence photon showers observed in the lower half of the chamber must for the most part have come from a γ-ray radiated in the lead by the same electron which excited the upper counter. On such argu-

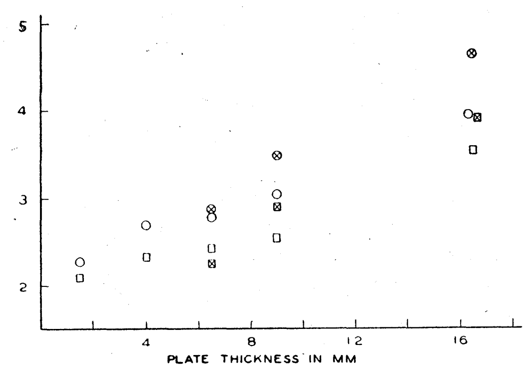

Fig. 3. Average number of electrons in showers. Circles for electron produced showers; squares for photon-produced showers. Open figures for showers with 1 cm lead above chamber; crossed figures, without lead above.

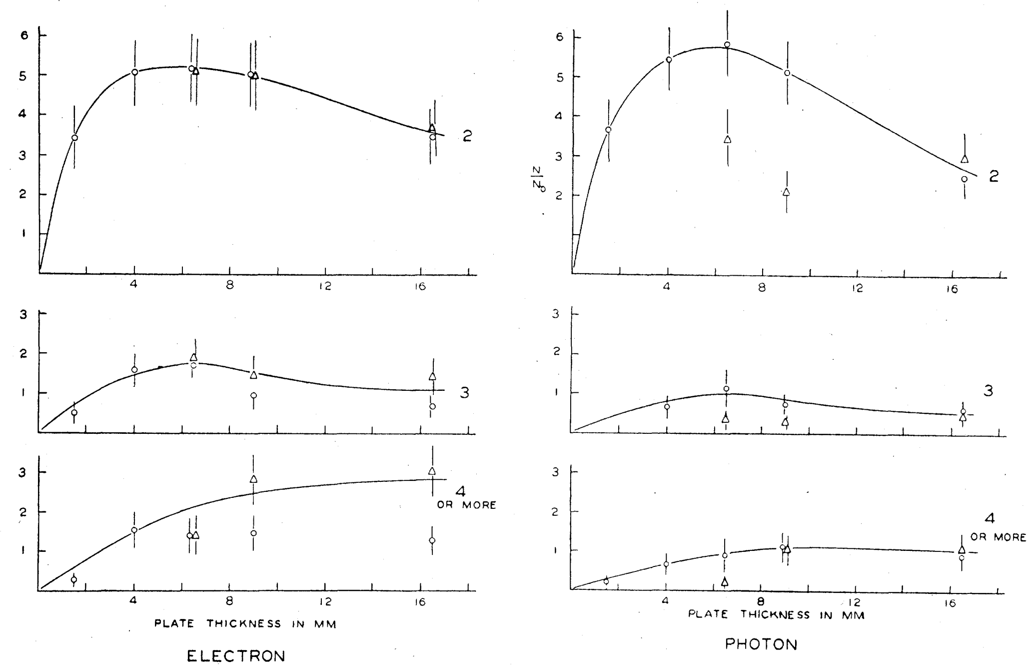

FIG. 4. Frequencies of showers of 2, 3, and 4 or more electrons plotted as percent of the incident radiation against absorber thickness. These are the showers that could be traced to a single entering electron or to a gamma-ray. Circles are for showers observed with one cm lead above the shower source: triangles without lead above.

ments it appears that a correct count of the number of showers from photon encounters is obtained from pictures taken with the upper lead present. Photographs taken at random by Anderson and others do not show more showers produced by photons than observed here. Old tracks also give a check in that they are effectively random, and they do not indicate large numbers of unrecorded photon showers. During the second part of the experiment, in which the upper lead plates were removed, relatively fewer showers from photons occurred in the photographs. This reduction is to be expected, since the source is spread over a long vertical path in air, unit t for air being about 300 m. If the process giving rise to photons takes place at some distance from the cloud chamber, there is a possibility that no electron will pass through the chamber along with a photon, because electrons and their secondary photons may go off at slightly divergent angles. Although transition effects will occur between air and lead, absorption of cosmic radiation in lead will not increase to any great extent the proportion of γ-rays. The difference in numbers of photon showers observed with and without lead above the chamber is attributed to a difference in counting efficiency rather than to an actual difference in numbers of γ-rays present.

Since the ionization produced by an electron of cosmic-ray energy is practically independent of energy, the total number of electron tracks counted in a given volume is a measure of the total ionization in that volume. By counting all tracks below and above the central plate, we derive a ratio of ionization in these two volumes. According to ionization chamber measurements, up to two cm of lead has very little effect. The ratio first rises a little and then falls slowly with increasing absorber thickness. In Table I are the results of adding all recorded tracks. It is seen that the ratio is much larger than the expected value. The discrepancy very likely is caused by the selective action of the Geiger counters. Many electrons of only a few million volts energy, which would be effective in an ionization chamber, are absorbed in the central plate and cannot reach the lower counter. Therefore, they are not photographed. About the only tracks unrecorded below the plate are in photon showers.

Lack of these low energy electrons in the statistics is not a serious loss, because they have too small an energy to create showers and hence are of little interest in the problem. As the most appropriate measure of the incident radiation it was decided to take only those electrons which penetrated the plate plus those which produced showers. In this way incident electrons of fairly high energy are selected without the use of a magnetic field. Single electrons unable to pass through the system do not appear in the photographs, but in unresolved showers there are usually several electrons stopped by the center lead plate, which come off at rather large angles to the main bundle of particles. It is not at all surprising that the outermost portions of the shower are absorbed, since only secondaries of low energy have a chance of being deflected in nuclear fields. This absorption frequently gives large showers the appearance of coming from the bottom millimeter of absorber, as though all particles radiated from a single point. In discarding unresolved showers and low energy electrons, we obtain a slightly distorted measure of incident radiation because of the difference in stopping power of the various lead plates. An electron loses roughly 50 to 100 Mev by ionization in passing through the thicker plates, and on the average, those photographed will have this much more energy than those striking the thinner plates. It is exactly such selection, however, which gives electrons equivalent energy distributions below the different plates, and makes possible the comparison of the numbers of showers observed. There is no accurate method of determining the number of γ-rays present. We must simply assume that their number is proportional to the number of electrons.

In Table I are given the measures of incident radiation as described above. The frequencies of showers of two, three and four or more electrons in terms of this measure are plotted against plate thickness in Fig. 4. Electron showers of two particles occur at the same rate with and without the presence of the upper lead plates. Larger showers occur more frequently when a small shower strikes the central plate, and cannot be resolved as easily as two-particle showers. With the removal of the top lead there are fewer such groups of tracks to confuse interpretation, and practically all large showers can be identified as being produced by single electrons, or γ-rays. Taking into consideration the shifting of about half of the larger showers into the unresolved class when lead is placed above, we are led to the conclusion that the number of showers produced by electrons is not noticeably affected by the passage of cosmic radiation through one centimeter of lead. As already mentioned, absence of lead above the chamber reduces the efficiency of recording showers produced by photons by say one-half. When use is made of this factor, we see that showers from γ-rays occur with the same frequency as those from electrons. Theory predicts 1.5 times as many γ-rays as electrons, and about the same preponderance of showers from γ-rays over showers from electrons. Since the recording of photon showers is dependent on the presence of an electron in the upper counter and not on the number of electrons in the shower, photographs taken under the conditions of the experiment may indicate too few showers from γ-rays, but the relative frequencies should be correct. Therefore, although the absolute magnitude of measured frequencies may be in error, the similarity of photon and electron excitation curves for showers of two particles indicates that the mechanism of shower production does not depend upon the manner in which energy is supplied. In good agreement with the theory, the optimum thickness of lead for producing these showers is about six millimeters. Larger showers occur in too small numbers to give very reliable curves. Even these, however, are similar in that the maximum number of showers occurs at a greater thickness of lead than for two-particle showers.

Similarity of electron and photon excitation of showers and the good agreement of optimum thickness with calculations, indicate that showers are formed by a succession of radiation and pair production transformations. Since the theory is based on an extension from medium to high energies of the formulae for the interaction of high speed electrons and γ-rays with matter, it appears that the formulae are valid throughout the cosmic-ray energy spectrum. If this is true, we are at a loss to explain why less than ten percent of the electrons passing through a six millimeter lead plate produce showers. At sea level this thickness is the most efficient in producing showers; the number falls off to about five percent for thicker plates. A statistical treatment of the problem by Furry[8] predicts that over twenty percent of the electrons passing through five mm of lead will give showers, forty percent at one cm, etc. Since we have reason to accept the calculated probabilities of radiation and pair production, we are left with about half or two-thirds of the incident radiation behaving in an anomolous manner. This is more than can be explained by statistical fluctuations. We may assume either that electrons and quanta of extremely high energy do not react readily with nuclei, or that the radiation is composed in large part of particles which ionize like electrons, but which do not radiate quanta. Measurements of energy loss in heavy metals as found by Nedermeyer and Anderson[9] seem to indicate the presence of such nonradiating particles. Photographs taken by Street and Stevenson[10] indicate that these penetrating particles are not protons because they do not ionize heavily enough at the end of their range. In order to account for their great penetrating power and their low ionization, the existence of a new particle with electronic charge and the mass of 100 to 200 electrons has been proposed. Further experiments by Fussell[11] and experiments in progress at Berkeley on the specific ionization of cosmic-ray particles may shed more light on the question of the existence of such a particle.

The author wishes to express his gratitude to Professor Robert B. Brode under whose helpful guidance these experiments were carried out, and to Professor J. R. Oppenheimer for his continued interest in the problem.

[8] W. H. Furry, Phys. Rev. **52**, 569 (1937).
[9] S. H. Nedermeyer and C. D. Anderson, Phys. Rev. **51**, 884 (1937).
[10] J. C. Street and E. C. Stevenson, Phys. Rev. **51**, 1005 (1937).
[11] L. Fussell, Jr., Phys. Rev. **51**, 1005 (1937).

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The Latitude Effect in Cosmic Radiation at High Altitudes

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(Received November 2, 1937)

Measurements of cosmic-ray intensities in the equatorial and temperate regions are reported, and the instrument described. The apparatus consists of a single Geiger counter, the impulses of which are transmitted by radio to a ground station. The results are compared with high altitude electroscope measurements and are found to agree satisfactorily. Flights up to 70,000 feet were obtained in Peru. The results indicate that the intensity of cosmic radiation in the upper atmosphere in Peru is about half that at Washington. The component which produces about one-half the maximum total intensity of ionization at high altitudes over Washington is cut out by the earth's magnetic field and does not reach the top of the atmosphere in Peru. The energy of this component lies between 3 and 12×10^9 ev. Analysis of the data shows agreement with the Carlson-Oppenheimer curves. The ionization at high altitudes is shown to be in large part due to secondaries.

Introduction

The latitude effect in cosmic radiation has been one of our chief aids in determining the energy spectrum of the incoming radiation. It has long been realized that one of the most important parts of this study has been that of the latitude effect at high altitudes. Hitherto high altitude work has necessitated the use of recording equipment which depended upon recovery of the instrument after the balloon flight to obtain the record of the intensity. With the development of radio transmission of balloon-data, a new method, useful for this work, has made its appearance. It is clear that recovery of recording instruments presupposes an inhabited country and literate populace. Where the topog-

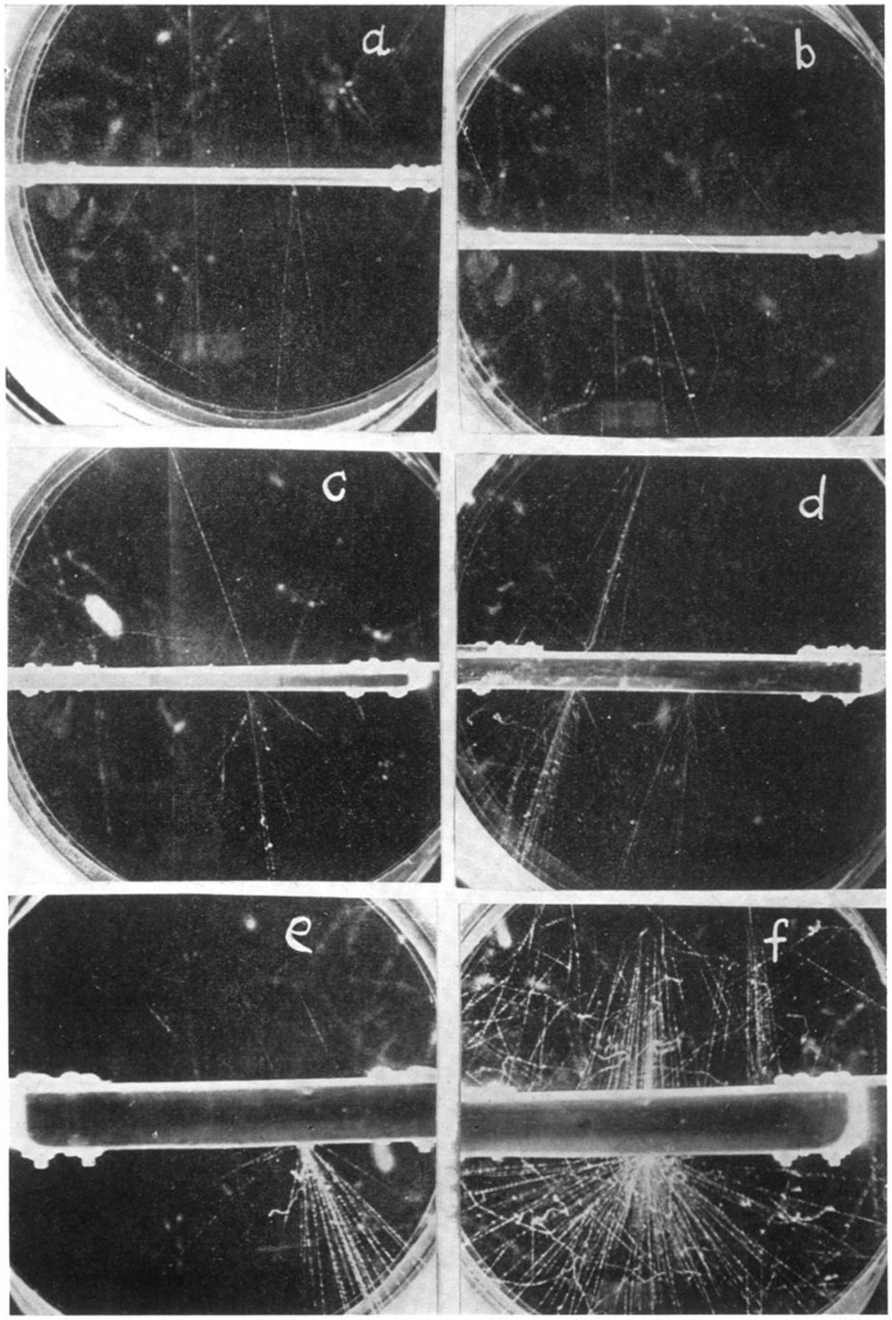

FIG. 2. *a*, Two-particle shower from an incident electron. The fuzzy vertical line is a wire used in stereoscopic measurements. *b*, Two-particle shower from an incident gamma-ray. The fuzziness and displacement of tracks in this and other photographs are caused by turbulent motion of the gas during expansion. *c*, Six electrons are produced by the incident electron, and four electrons by a gamma-ray. *d*, An unresolved shower showing absorption of deflected electrons. *e*, A few pictures were taken with a 3 cm plate. This is one of the larger showers; two-particle showers are most plentiful even for this plate. *f*, An exceptionally good example of the apparent origin of a shower in the last few millimeters of the absorber. Practically all the incident electrons stop in the plate.