Extensive Penetrating Cosmic Ray-Showers*

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The density spectrum of the particles in Auger showers capable of penetrating twenty centimeters of lead has been measured at 3026-meters elevation, and found to be very nearly the same as the density spectrum of the soft component of the showers, the ratio of penetrating to soft particles apparently decreasing slowly with increasing shower density. This ratio has been measured, using the coincidences between four trays of Geiger counters, all shielded by twenty centimeters of lead, and found to be about 2.3 percent. As this value is considerably higher than the value found by other methods, some calculations on the structure of Auger showers are given, in an attempt to explain the discrepancy. It is found that any experiment using coincidences between unshielded trays, horizontally separated by a few meters, is biased strongly toward recording only the cores of the extensive showers. A cloud chamber, tripped by extensive shower counters, is used to study the structure of the extensive showers, and local production of penetrating particles in lead plates within the chamber is definitely established.

I. INTRODUCTION

SINCE the discovery[1] of the Auger cosmic-ray showers by Geiger tube coincidences, many experiments have been performed to clarify the structure and composition of these showers, and their variation with altitude and barometric pressure. Most experiments using Geiger tube coincidences have been shown[2,3] to give results agreeing with the hypothesis of the cascade origin of these showers,[4] by the bremsstrahlung and pair-production effects of high energy electrons. The existence in Auger showers of particles much more penetrating than electrons has been demonstrated by many observers,[5–10] these particles being presumably μ-mesons produced high in the air above the recording apparatus.[10] The "density spectrum," i.e., frequency of occurrence of the Auger showers as a function of average particle density (particles per unit surface area) in the showers, has been measured both directly with ionization chambers,[11] and indirectly, using coincidences between several trays of Geiger counters.[9,12,13] These experiments have established that the frequency $F(\sigma)$ of the Auger showers in which the particle density is greater than σ is given satisfactorily by the expression

$$F(\sigma)=K\sigma^{-\gamma}, \qquad (1)$$

in which K and γ are functions of the altitude above sea level, but vary only slowly with density over a large range of densities. The constant γ has been shown to be about 1.5.

It has been shown[8,9] that all Auger showers contain penetrating particles and that all extensive penetrating showers were accompanied by electron showers, but the density spectrum of the extensive penetrating showers had not been measured, nor had the relative densities of penetrating particles and electrons in Auger showers been established with certainty. Consequently experiments were carried out during the summer of 1948 at Tioga Pass (elevation 3026 meters) in Yosemite National Park on the density spectrum of the penetrating particles in Auger showers.

II. EXPERIMENTAL ARRANGEMENT

The geometrical arrangement of the experiment is shown in Fig. 1. The extensive showers were detected by means of four trays of Geiger counters A, B, C, D of equal but variable area. Threefold coincidences were recorded between trays A, B, and C, arranged in a straight line with a spacing of 4.8 meters, and also fourfold coincidences were recorded with a fourth tray D, situated on the perpendicular bisector of the line joining the threefold trays at a distance of 8.0 meters from this line. The coincidence circuits were housed in a thin-walled trailer, which also housed a large cloud

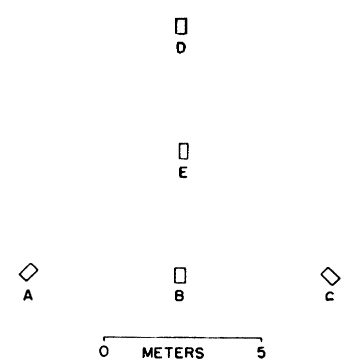

FIG. 1. Geometrical arrangement of apparatus.

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** Abraham Rosenberg Fellow of the University of California.
[1] Auger, Maze, and Grivet-Meyer, Comptes Rendus **206**, 1721 (1938).
[2] H. W. Lewis, Phys. Rev. **73**, 1341 (1948).
[3] G. Cocconi, Phys. Rev. **72**, 964 (1947).
[4] G. Moliere, *Cosmic Radiation*, edited by W. Heisenberg (Dover Publications, New York, 1946).
[5] Auger, Maze, Ehrenfest, Daudin, and Robley, Rev. Mod. Phys. **17**, 238 (1939).
[6] J. Daudin, Comptes Rendus **216**, 411 (1943).
[7] A. Rogozinski, Ann. de physique **20**, 391 (1945).
[8] Cocconi, Loverdo, and Tongiorgi, Phys. Rev. **70**, 852 (1946).
[9] J. E. Treat and K. Greisen, Phys. Rev. **74**, 414 (1948).
[10] Cocconi, Cocconi, and Greisen, Phys. Rev. **75**, 1063 (1949).
[11] R. W. Williams, Phys. Rev. **74**, 1689 (1948).
[12] Cocconi, Loverdo, and Tongiorgi, Phys. Rev. **70**, 841 (1946).
[13] J. Daudin and A. Loverdo, Journal de Physique **9**, 134 (1948).

chamber E, which was used during part of the experiment. The Geiger counter trays were shielded by means of rectangular lead bricks piled above the trays, the supports being short lengths of 2-inch×4-inch lumber. The trays were placed flat on the ground with no shielding underneath, and the shielding at the ends and sides of the trays was kept constant at 10 centimeters of lead, while the shielding above the trays was varied from 5 to 20 centimeters of lead, being the same over all four trays. Measurements were also taken with no shielding above or at the sides and ends of the trays.

The thickness of 20 centimeters of lead used to absorb the soft component of the showers was based on the results of absorption measurements obtained during the course of these experiments, as well as on the results of other observers,[14–16] all of which had indicated that the absorption curve started its "tail" at thicknesses of about 15 centimeters of lead. Cocconi and collaborators[8] had used 16 centimeters of lead in the only previous work of the kind described here and had found no significant change in coincidence rate between 16 and 24 centimeters of lead. Recent results, both experimental[10] and theoretical,[17] have shown that the effects of electrons in discharging counters under lead screens are not entirely eliminated for thicknesses of lead less than 20 centimeters. This penetration in lead, much greater than formerly believed, is due to the effects of the many low-energy photons in air showers which, although possessing insufficient energy for pair-production, can nevertheless set off counters by means of Compton electrons originating in the walls of the counters. Incidentally, as pointed out by Greisen,[17] this invalidates much of the previous work done on extensive penetrating showers, in which insufficient lead shielding was used to completely absorb the soft component.

The Geiger counters used in this experiment were of the all-metal type filled with an argon-alcohol mixture. They were all of 2-inches inside diameter and 14-inches effective length. The counter trays consisted of several of these counters connected in parallel inside a light wooden tray of $\frac{1}{4}$-inch plywood. Oilcloth sheets covered each tray to keep moisture off the counters.

Counting rates of the individual trays were taken daily with an electronic pulse counter. In this way failure of one Geiger tube in a tray could be immediately detected.

The coincidence circuit was patterned after that described by Howland, Schroeder, and Shipman,[18] with a few modifications. It consisted of an input cathode follower and amplifier, a differentiating circuit and an output cathode follower. The resolving time of the coincidence circuit, measured by chance coincidences between two counters with very high rates, was 14 microseconds. The maximum correction to the observed coincidence rate, caused by this long resolving time, was of the order of 15 percent, so no serious errors were thereby introduced.

TABLE I. Observational data (the probable errors are assigned only on the basis of statistics).

Area (cm^2)	Lead thickness (cm)	3fold rate ($hr.^{-1}$)	4fold rate ($hr.^{-1}$)
350		48.9 ±0.8	30.07 ±0.70
700	0	130 ±5	80.72 ±3.88
1050		234 ±3	144.6 ±2.1
350		6.14 ±0.33	
700	5		
1050		42.1 ±0.8	
350		0.55 ±0.08	
700	10		
1050		4.01 ±0.28	
350			
700	15		
1050		1.56 ±0.09	
350		0.193±0.015	0.114±0.013
700	20	0.588±0.033	0.360±0.031
1050		1.18 ±0.064	0.706±0.056

III. RESULTS AND CALCULATIONS

The data taken during the course of this experiment are shown in Table I. All counter trays had the same thickness of lead shielding and the same number of counters per tray, any variation in these last two quantities being made simultaneously in all four trays. All rates are corrected for accidental coincidences.

The absorption curve of the extensive showers in lead is shown in Fig. 2 where the threefold coincidence rate is plotted logarithmically against the lead thickness, the area of all trays being 1050 cm^2. The probable errors of all points lie within the small circles. This curve is in agreement with that given by Cocconi, Cocconi, and Greisen,[10] in that it shows a noticeable decrease in coincidence rate between 15 and 20 centimeters of lead, this decrease presumably being due to the absorption of the last of the soft component. Reynolds and Hardin[19] have obtained a similar curve by a somewhat different method, showing a slight initial rise in coincidence rate as the lead thickness is increased from zero to two centimeters, this rise being caused by the secondary multiplication of the shower electrons.

The theory underlying the determination of the density spectrum by variation of counter area was developed by Cocconi[12] and independently by Daudin.[20] It was shown by them that, assuming the density spectrum of the Auger showers to be given by Eq. (1),

[14] Auger, Maze, Ehrenfest, and Freon, J. de phys. et rad. **10**, 39 (1939).
[15] de Souza Santos, Pompeia, and Wataghin, Phys. Rev. **57**, 339 (1940) and **59**, 902 (1941).
[16] L. Janossy, Proc. Roy. Soc. **179**, 361 (1942).
[17] K. Greisen, Phys. Rev. **75**, 1071 (1949).
[18] Howland, Schroeder, and Shipman, Rev. Sci. Inst. **8**, 551 (1947).
[19] G. T. Reynolds and W. D. Hardin, Phys. Rev. **74**, 1549 (1948).
[20] J. Daudin, Ann. de physique **18**, 238 (1943).

the n fold coincidence rate between n trays of Geiger counters, all of area S, is given by

$$C(n, S)=\int_0^\infty K\sigma^{-(\gamma+1)}(1-e^{-\sigma S})^n d\sigma. \qquad (2)$$

It is tacitly assumed in the derivation of Eq. (2) that the shower density σ is the same over all counter trays. Because of the pronounced maximum of the integrand occurring at a shower density $\sigma \sim 1/S$, most of the contribution to the integral (2) comes from a comparatively narrow range of densities and hence the density-spectrum (1) need not be assumed valid much beyond this range of densities.

By varying the area S of all the counter trays the constant γ can be obtained from (2) by plotting logarithmically the coincidence rate *versus* the area S (see Fig. 3) and using

$$\gamma=\{d[\log C(n, S)]/d(\log S)\}. \qquad (3)$$

Using this equation, the value of γ obtained from the unshielded rates in Table I is 1.42 ± 0.02.

An independent determination of γ can be made by observing the ratio of fourfold to threefold coincidence rates. If the integral (2) be evaluated for $n=4$ and $n=3$, it can be shown that

$$\begin{aligned} C(4, S)&=KS^\gamma(-1-\gamma)![4^\gamma-4(3)^\gamma+6(2)^\gamma-4], \\ C(3, S)&=KS^\gamma(-1-\gamma)![-3^\gamma+3(2)^\gamma-3], \end{aligned} \qquad (4)$$

and from the ratio of these two rates, which is a function of γ alone, the value of γ may be obtained. From the observed ratio of fourfold to threefold unshielded coincidence rates in Table I, the computed value of γ is 1.58 ± 0.04, which is not at all in agreement with the value obtained by variation of counter area. Each of these values is in very good agreement, however, with the corresponding value obtained by Treat and Greisen,[9] who obtained, respectively, 1.40 and 1.55. A discussion of the discrepancy will be given in Section IV.

In Fig. 3 is shown a plot of the logarithm of the coincidence rate *versus* the logarithm of the counter area for the threefold and fourfold coincidence rates, both unshielded and under 20 centimeters of lead. The shielded coincidence rates have been multiplied by 100 in order that they might be shown on the same graph as the unshielded rates. The captions on the straight lines in Fig. 3 refer to threefold and fourfold coincidences, the "S" and "H" referring to "soft" (unshielded) and "hard" (shielded) showers. The values of γ as determined from the slopes of these curves are

$$\begin{aligned} (3S)\gamma&=2.425\pm0.019, \\ (4S)\gamma&=2.428\pm0.025, \\ (3H)\gamma&=2.65\ \pm0.09, \\ (4H)\gamma&=2.66\ \pm0.12. \end{aligned} \qquad (5)$$

In the determination of the density spectrum (1) for the extensive penetrating showers, it is evident from (5) that the exponents γ for the hard and soft showers apparently differ by about 0.23, which is well outside the statistical uncertainties. However, it must be remembered that the average (total) shower densities recorded with and without lead shielding differ by a factor of about forty-five because the average density of penetrating particles recorded under 20 centimeters of lead is identical to the *total* particle density recorded with no lead shielding, and the relative densities of hard and soft particles will be shown below to be about one in forty-five.

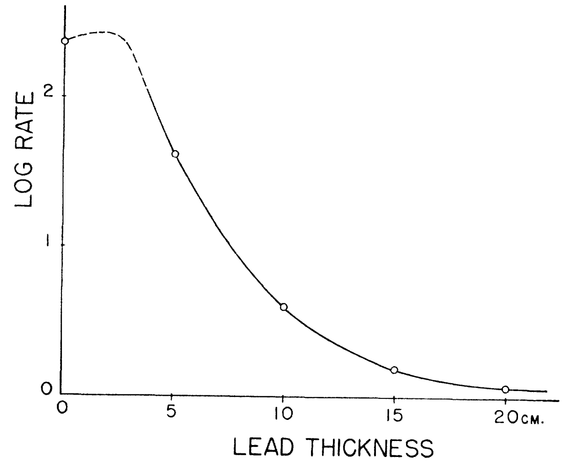

FIG. 2. Absorption in lead of extensive showers. The threefold coincidence rate between trays of area 1050 cm² is plotted as a function of the lead thickness above each tray.

The recent very exact measurements of Cocconi and Cocconi[21] on the variation of γ with shower density have established the empirical relation

$$\gamma=1.26-0.099\log_{10}S, \qquad (6)$$

where S, the area of the counter trays, is measured in square meters. For $S=700$ cm² (the middle of the range of values used in the present experiment) the value of γ as given by this equation is 1.37 (in good agreement with the value given in Eq. (5) above), while for $S=15.5$ cm² (which, because of the inverse relationship of counter area S to average shower density recorded, therefore corresponds to shower densities 45 times as large), $\gamma=1.54$. It is this last value of γ that must be compared to the value 1.65 ± 0.09 obtained for the extensive penetrating showers.

From these last two values of the density exponent γ, corresponding to penetrating and soft particles in showers of the same total density, it seems that the penetrating particles decrease slightly more rapidly than do the electrons with increasing shower density, i.e., the ratio of penetrating particles to electrons decreases slowly as the shower density increases, since

$$\text{penetrating particles/electrons} \sim \sigma^{-0.11\pm0.09}. \qquad (7)$$

The large probable error attached to the value of γ for

[21] G. Gocconi and V. Cocconi-Tongiorgi, Phys. Rev. 75, 1058 (1949).

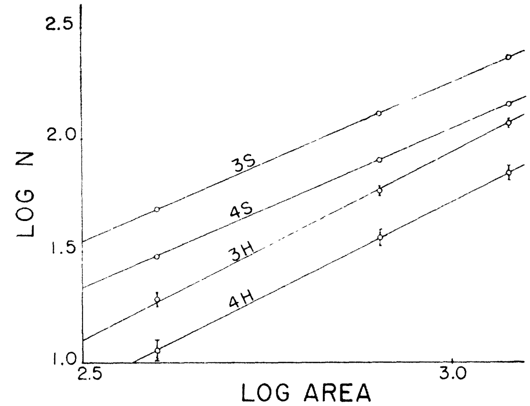

FIG. 3. Dependence of threefold and fourfold coincidence rates (N) on counter area, for unshielded counters ($3S$ and $4S$) and for counters shielded by 20 cm of lead ($3H$ and $4H$).

the penetrating showers precludes much confidence in the numerical value of the exponent in (7), but recent exact measurements of the ratio of penetrating to soft particles in extensive showers by Cocconi, Cocconi, and Greisen,[10] obtained by a somewhat different method, show that

$$\text{penetrating particles/electrons} \sim \sigma^{-0.13 \pm 0.02}. \quad (8)$$

It is shown in reference 10 that this relation is in accord with the provisions of the cascade theory if the assumption is made that the number of penetrating particles is proportional to the average energy of the initiating primary.

The evaluation of the relative densities of penetrating particles and electrons, which has been stated as being about one in forty-five, will now be given. The procedure will be as follows: the reduction in area of the unshielded counters necessary to produce the same coincidence rate as is obtained with the counters shielded by 20 centimeters of lead will first be found. The probability of a coincidence being recorded is a function only of the quantity σS, the average shower density times the area of the counter trays (see Eq. (2)). Therefore the new reduced area of the unshielded counters is to the area of the shielded counters as the ratio of penetrating particle density to total particle density.

We shall now calculate the area of the unshielded counters necessary to produce a threefold coincidence rate of 1.18 counts per hour, the value obtained with shielded trays of area 1050 cm². Denoting the unshielded coincidence rate by $C(3, S)$ and the surface area of the counter trays by S, we have from (3) and (6)

$$\gamma = \{d[\log C(3, S)]/d(\log S)\} = 1.26 - 0.099 \log_{10} S, \quad (9)$$

which can be immediately integrated to give

$$\log C(3, S) = 1.26 \log_{10} S - 0.0495(\log_{10} S)^2 + \text{constant}. \quad (10)$$

The constant term in (10) could be evaluated by substituting a particular set of values of $C(3, S)$ and S but in this case it is not necessary to do so. Let the subscript "1" refer to the values of $C(3, S)$ and S observed with unshielded trays of area 1050 cm² and let S_2 be the (unknown) surface area which produces the same coincidence rate $C(3, S_2) = 1.18$/hr. as do the shielded trays of area 1050 cm². Then we have

$$\begin{aligned} \log(234 \pm 3) &= 1.26 \log(0.105) - 0.0495(\log 0.105)^2 + \text{constant}, \\ \log(1.18 \pm 0.064) &= 1.26 \log S_2 - 0.0495(\log S_2)^2 + \text{constant}. \end{aligned} \quad (11)$$

By subtraction, the constant term can be eliminated and solution for S_2 gives

$$S_2 = 23.5 \text{ cm}^2, \quad \text{or} \quad S_1/S_2 = 45 \pm 1. \quad (12)$$

From what has been said above, the ratio of penetrating particle density to total shower density, which we shall call the "penetrating fraction" and denote by R, is then

$$R = 1/(45 \pm 2) = (2.25 \pm 0.12) \text{ percent}. \quad (13)$$

Essentially the same value is obtained by using the data at 700-cm² and 350-cm² tray area.

IV. DISCUSSION OF RESULTS AND COMPARISON WITH PREVIOUS RESULTS

A. Unshielded Data

The reasons for the discrepancy between the values of γ as obtained from the ratio of fourfold to threefold (unshielded) coincidence rates and from the variation of counter area will now be taken up in some detail, as considerable insight into the structure of Auger showers is thereby gained.

Treat and Greisen[9] had observed about the same difference in values of γ as obtained in the present experiment and listed several possible reasons for this effect. The variations in surface area of the counter trays were obtained by changing the number of cylindrical counters in parallel in each tray. The effective area of the counter trays for showers incident at angles to the vertical is therefore reduced relatively more for the larger areas. This makes the change in coincidence rate with counter area less pronounced than it actually is, or in effect, reduces the apparent value of γ. Cocconi and Cocconi-Tongiorgi,[21] in the most definitive study of the density spectrum of Auger showers to date, found no perceptible difference in coincidence rate when the counters in each tray were packed closely together and when they were separated by a distance equal to their diameter. They therefore concluded that the effect of inclined showers is negligible. This is in agreement with calculations of the present writers, who, by assuming that the frequency of Auger showers as a function of their zenith angle θ varies[22] as $\cos^8\theta$ have calculated[23] the change in the value of γ that would

[22] J. Daudin, J. de phys. et rad. **6**, 302 (1945).
[23] J. Ise, Jr., Ph.D. thesis, University of California.

be introduced by the inclined showers. It was found that, assuming a value of γ of 1.55, the *apparent* value of γ would be reduced only to 1.54. If the variation of shower frequency with zenith angle is taken as $\cos^4\theta$, the value of γ is still apparently reduced only to 1.53. Thus inclined showers cannot account for the difference in the values of γ obtained by the two methods.

Treat and Greisen also mentioned, as possible reasons for this discrepancy, the barometric effect of Auger showers,[24–26] which has been estimated as being 10 percent to 20 percent per centimeter change in barometric pressure. It is possible that this effect did introduce some error into the value of γ as measured by variation of counter area, but it is felt that such an error is small. The unshielded measurements extended over two periods of three days each, at the beginning and end of the summer, and the variations in counter area were made at intervals of about two hours, in order to intersperse the counting periods for a given counter area throughout as large a time interval as possible. The barometric effect would not be expected to introduce much error into the value of γ as determined from the ratio of fourfold to threefold coincidence rates, since these were measured simultaneously.

We believe that the true explanation of the discrepancy between the two values of γ is to be found in the geometrical structure of the Auger showers themselves. The analysis of the density spectrum of extensive showers rests upon the assumption that the average shower density σ is approximately constant over the area covered by the recording apparatus, so that the shower density is the same at all the counter trays. This assumption is by no means always correct, for, especially near the core of a shower, the density changes very rapidly with distance from the core. However, it can be shown that the calculated density spectrum is not affected by this variation in shower density from one counter tray to another, if the assumption is made that all showers are geometrically similar, and that the radial density distribution in a particular shower does not change along the downward path of the shower. This latter assumption is justified by Williams,[11] who quotes an analytic approximation, due to Bethe, for the particle density σ at a depth t below the top of the atmosphere and at a distance r from the shower axis, as

$$\sigma = N(t)(0.454/r)(1+4r)\exp(-4(r)^{\frac{1}{2}}) = N(t)f(r), \quad (14)$$

where $N(t)$ is the total number of electrons in the shower at depth t, and r is measured in units of the "characteristic scattering length," which at an altitude of 3050 meters is about 106 meters.

If it is now assumed that the differential frequency distribution of extensive showers according to the total

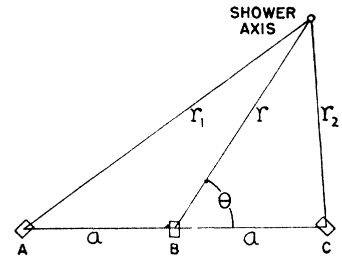

FIG. 4. Coordinates of shower axis with respect to the threefold coincidence trays A, B, C.

number of particles N in the shower, at a given elevation, is

$$F(N)dN = KN^{-(\gamma+1)}dN, \quad (15)$$

then the coincidence rate between three counter trays each of area S (which must be measured in units of the square of the characteristic scattering length) is

$$C(3, S) = \int_0^\infty KN^{-(\gamma+1)}dN \int d\Sigma \prod_i (1-e^{-NSf(r_i)}), \quad (16)$$

where r_i ($i=1, 2, 3$) are the distances of the three counter trays from the shower axis and the space integral over Σ must be extended over all relative positions of the counter trays and the shower axis, given by particular values of r_i. After this integration (16) may be written

$$C(3, S) = \int_0^\infty KN^{-(\gamma+1)}g(NS)dN$$
$$= S^\gamma \int_0^\infty KN^{-(\gamma+1)}g(N)dN, \quad (17)$$

and it is seen that, just as in the simpler analysis given in Section III, the coincidence rate varies as a power of the surface area of the counter trays. In this case the exponent γ refers not to a "density spectrum" but to the spectrum of the total number of particles in the shower. It is to be noted that, with this latter interpretation, the term "shower density" as applied to a particular shower is a meaningless term, since in any shower, regardless of the total number of particles, all shower densities are to be found, depending on the distance from the shower axis.[27] The integration indicated in Eq. (16) has been carried out numerically for the particular counter arrangement used in this experiment, i.e., three counter trays in a straight line, with a spacing a of 5 meters. If the central counter tray lies at a distance r from the shower axis, and the angle between the radius vector from the shower axis to the central tray and the line joining the three counter trays be denoted by θ (see Fig. 4), the threefold coincidence rate

[24] M. G. E. Cosyns, Nature **145**, 668 (1940).
[25] P. Auger and J. Daudin, Phys. Rev. **61**, 91 (1942).
[26] G. Cocconi, Phys. Rev. **72**, 964 (1947).

[27] In the derivation of Eq. (16) it has not been possible to take into account the variations in shower density over the individual counter trays. This neglect should not affect appreciably the results of these calculations.

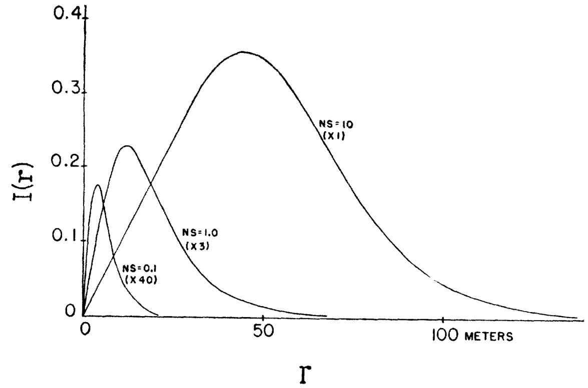

FIG. 5. Probability $I(r)$ of a threefold coincidence due to all showers striking at a distance r from the central counter tray (see Fig. 4), for various values of NS. (N=total number of particles in shower, S=counter area in units of 1.13×10^4 meter^2.)

is from (16)

$$C(3,S)=\int_0^\infty KN^{-(\gamma+1)}dN\int_0^\infty 2\pi r dr\int_0^{\pi/2}\frac{2}{\pi}(1-e^{-NSf(r)})\times(1-e^{-NSf(r_1)})(1-e^{-NSf(r_2)})d\theta,\quad(18)$$

where $r_{1,2}=(a^2+r^2\pm2ar\cos\theta)^{\frac{1}{2}}$ and

$a=5$ meters$=0.05$ in units of the characteristic scattering length.

The function

$$I(r)=r\int_0^{\pi/2}(1-e^{-NSf(r)})\times(1-e^{-NSf(r_1)})(1-e^{-NSf(r_2)})d\theta\quad(19)$$

is shown in Fig. 5 for $NS=0.1$, 1.0 and 10. This function represents the probability of a threefold coincidence due to all showers striking at a distance r from the central counter, for a particular value of the quantity NS. It will be noted that this function falls to zero for $r=0$, in spite of the obvious fact that a shower is more likely to cause a triple-coincidence if it hits right on the central counter tray than if it hits anywhere else. This apparent paradox is due to the fact that $I(r)$ is actually the product of two separate quantities, (a) the probability that a particular shower will cause a threefold coincidence if it hits at a distance r from the central counter tray, and (b) the number of such showers, which is clearly proportional to 2π-rdr. It is this last factor which brings the curves in Fig. 5 to zero at $r=0$. Perhaps a more meaningful quality would be $I(r)/r$, which therefore represents the probability (a) above, i.e., that probability that a particular shower will cause a threefold coincidence if it hits at a distance r from the central counter (averaged over all orientations θ). This is plotted in Fig. 6, for several values of the quantity NS. It will be seen that all these curves show a maximum probability of a coincidence when the shower strikes the central counter tray, i.e., at $r=0$.

In order that the curves in Fig. 5 might be shown on the same graph, the ordinates of the curve for $NS=1.0$ have been multiplied by 3 and the ordinates of the curve for $NS=0.1$ have been multiplied by 40. These curves show that for small showers for which $NS=0.1$ the maximum contribution to the threefold counting rate comes from showers whose cores strike within a few meters of the central counter tray, while for larger showers ($NS=10$) the maximum contribution is from showers whose cores strike perhaps 50 meters from the central tray.

A graph of the function,

$$R(N,S)=N^{-(\gamma+1)}\int_0^\infty I(r)dr=[dC(3,S)/dN],\quad(20)$$

versus the logarithm of NS is shown in Fig. 7 for $\gamma=1.5$. For any value of S, this curve shows the contribution to the coincidence rate of showers of various total numbers of electrons striking at all distances from the counter trays. Although the experimental value of the exponent γ obtained in this experiment is closer to 1.42 (see Eq. (5)), the value 1.5 has been chosen in this analysis in order to be able to compare the value of the constant K in Eq. (22) below with the value obtained previously by Blatt, as quoted by Williams.[11]

The sharp maximum in Fig. 7 at $NS=0.04$ thus shows that for a tray area of 100 cm^2 the maximum contribution to the coincidence rate is from showers in which the total number of electrons is

$$N=0.04/S=0.04/0.01\times(106)^{-2}=4.5\times10^4.\quad(21)$$

Furthermore, since the maximum in Fig. 7 occurs at $NS=0.04$, it can be seen from the curve in Fig. 5 that, regardless of the surface area of the counter trays, most of the showers recorded strike within ten meters of the central tray. This is an interesting result, since the *a priori* conclusion might well have been that smaller counter areas, which therefore select larger showers, would respond to showers whose axes were

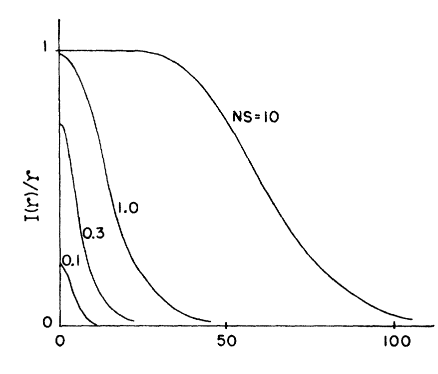

FIG. 6. Probability that a particular shower will cause a threefold coincidence if it hits at a distance r from the central counter of Fig. 4, for various values of NS.

farther from the central counter tray. Since the showers which produce threefold coincidences strike in the immediate vicinity of the central counter tray, it can be seen from the arrangement of the counter trays in Fig. 1 that on the average the fourth counter tray will be struck simultaneously with the other three trays less often than if it were nearer the central tray of the threefold set. This lowers the ratio of fourfold to threefold coincidence rates, and, as can be shown from Eqs. (4), leads to a value of γ calculated from this ratio which is too high. This explains the discrepancy between the values of γ calculated from the variation in counter area and from the ratio of fourfold to threefold coincidence rates. Cocconi and Cocconi[21] have used a more symmetrical counter geometry, with three counter trays at the vertices of an equilateral triangle and the fourth tray at the center of the triangle, and have found no significant difference in the values of γ obtained by the two methods. This is then an experimental verification of the conclusion given above, that the showers recorded almost always strike in the immediate vicinity of the recording counter trays.

With the assumption that the frequency of showers according to the total number of particles in the shower varies as given in Eq. (15) the constant K can be evaluated from Eq. (18), i.e., from the known coincidence rate at a particular value of counter area S, and from the measured area under the curve in Fig. 7, plotted on a linear scale. When this is done, the number of showers per square meter per hour with a total number of particles between N and $N+dN$ is found to be

$$F(N)dN=1.3\times10^{6}N^{-2.5}dN \text{ meter}^{-2}\text{ hr.}^{-1}. \quad (22)$$

The value quoted by Williams,[11] as obtained by Blatt from ionization chamber data is

$$F(N)dN=2.7\times10^{6}N^{-2.5}dN \text{ meter}^{-2}\text{ hr.}^{-1}. \quad (23)$$

Both these values depend on the assumption that Eq. (14) is valid for all showers, and Williams states that his value is uncertain by perhaps a factor of two. In view of this, the agreement seems very good.

B. Shielded Data

The form of the density spectrum for extensive penetrating showers obtained in this experiment agrees within the statistical uncertainties with the results of Cocconi, Cocconi and Greisen.[10] The value of the penetrating fraction R obtained in Eq. (13) is, however, almost twice as large as the value obtained in their work at very nearly the same altitude. The reason for this difference is not known but some suggestions will be discussed below.

If the penetrating fraction R is assumed to be constant throughout any shower, and the same for all showers, then its value may be obtained provided we know only the decrease in coincidence rate when a system of Geiger counter trays is shielded with at least

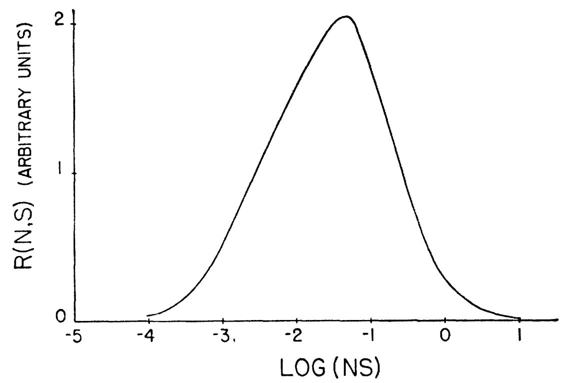

FIG. 7. Contribution to threefold coincidence rate of showers of various total numbers N of electrons striking at all distances from the central counter of Fig. 4.

20 centimeters of lead. In fact, if X is the factor by which the unshielded coincidence rate is diminished, it can be shown that

$$R=(1/X)^{1/\gamma}. \quad (24)$$

From the data in Table I, the value of X corresponding to a counter tray area of 700 cm^2 is 221. The value of γ which we must use in (24) will probably lie between 1.42 (the value obtained with no lead shielding) and 1.65 (the corresponding value under 20 centimeters of lead). Using these two extreme values of γ we find as extremal values of the penetrating fraction R, 3.9 percent and 2.2 percent, the latter of which is in good agreement with the value obtained in (13). The observed reduction factor in coincidence (221) is in very good agreement with that obtained by Cocconi, Loverdo and Tongiorgi[8] at 2200 meters elevation. It is true that these latter observers used only 16 centimeters of lead shielding, but they stated that no further change in coincidence rate occurred between 16 and 24 centimeters of lead. This last work was done using four trays of Geiger counters, all shielded.

We note further the work of Treat and Greisen.[9] They also carried out coincidence measurements between four shielded trays of Geiger counters, and obtained a value of the penetrating fraction of 3.4 percent at 3260 meters altitude. As pointed out by Cocconi, Cocconi, and Greisen,[10] Treat and Greisen had used insufficient lead shielding (14 centimeters), so that from the absorption curves in reference 10 about one third of their "penetrating particles" were really electrons and photons. With this correction, the value of the penetrating fraction becomes about 2.3 percent, in very good agreement with the value obtained in the present work at about the same altitude.

In the experiments of Cocconi and Greisen only one tray of Geiger counters was shielded, coincidences of this tray with three other unshielded trays being recorded simultaneously with threefold coincidences among these unshielded trays.

In the work of Cocconi, Loverdo, and Tongiorgi,[8] Treat and Greisen[9] and the present writers, on the other hand, all counter trays were shielded. From what has been said above concerning the localization of showers near the recording apparatus, it is seen that any experiment in which coincidences of several unshielded trays with one shielded tray are recorded will inevitably lead to a value of the penetrating fraction R which obtains at, or very near, the core of the showers. If the penetrating particles do not have the same extreme concentration toward the shower center shown by the soft component, then an experiment in which all the counter trays are shielded will not have this bias towards recording only showers which strike in the immediate vicinity. This would consequently lead to a larger value of the penetrating fraction than obtained with unshielded counters.

It is true that in the present experiment there was no lead shielding below the counter trays, and only ten centimeters at the ends and sides. It is possible that some coincidences were caused by electrons coming through the side shielding, even when the shielding thickness above the trays was 20 centimeters of lead. This would, as seen from Eq. (24), lead to a value of R which was too high. However, in view of the low frequency of inclined showers, and the small solid angle subtended by the sides and ends of the lead piles compared to that subtended by the top, it is felt that the great majority of the coincidences under 20 centimeters of lead was due to true penetrating particles.

V. CLOUD-CHAMBER OBSERVATIONS

A large cloud chamber containing 16 one-half inch lead plates was operated during most of the summer to obtain information on local penetrating showers.[28] The cloud chamber was triggered by a set of counters sensitive not only to penetrating showers but also to ordinary electron showers. Thus 2774 pictures of electron showers were obtained during the summer. That most of these showers were components of extensive air showers was evidenced by the simultaneous tripping of an extended counter tray of 1050 cm^2 area and frequently simultaneous tripping of one or more of the four shower trays described in the first part of this paper. These events were signaled by the flashing of neon lights mounted on the cloud chamber and photographed along with the event in the chamber.

In addition to these pictures thirty-four usable pictures were obtained with the cloud chamber triggered by threefold coincidences of the shielded extended counter trays, having areas of 350 cm^2 and 20 centimeters of lead shielding. These pictures have been analyzed for penetrating particles and penetrating showers which accompany the extensive air showers.

An attempt has been made in a series of 226 shower pictures taken with the first arrangement to count the number of electrons above the top lead plate. Poor lighting in this region of the chamber and sometimes very dense showers make the count rather inaccurate but an average of 17 particles per picture was obtained and this is probably right to a factor of two. The top wall of the chamber was $\frac{1}{2}$-inch brass, or 0.88 shower units; multiplication of a factor of two or so might be expected in the brass. Thus the average number of electrons incident on the chamber in these showers may have been 5 to 10. The illuminated area of the cloud chamber was 0.05 m^2 so it is seen that the average density of showers recorded by the particular counter area was very high.

In the 2774 pictures of electron showers obtained at 3027 meters elevation 482 parallel penetrating particles of the right age were observed. Using the above figures for average number of electrons, the percentage of penetrating particles comes out 1.7 percent to 3.5 percent, and in view of the inaccuracies involved must be considered in agreement with estimates made using counter data.

In addition to the penetrating particles, most of which penetrated many lead plates without noticeable interaction, some penetrating showers were observed in the midst of the electron showers. 64 of these "accompanied" penetrating showers were observed. In 28 the initiating particle could not be identified, in 3 the initiating particle was neutral, and in the other 33 the initiating particle was a charged penetrating particle. If we assume that the latter were secondary protons or π-mesons and compare the number observed to the number of ordinary penetrating particles, we see that the secondary protons or π-mesons may compose 5 to 10 percent of the penetrating component. In consideration of this figure it must be remembered that the detection of penetrating showers in the cloud chamber does not depend on very high energy or highly multiple events and that if large amounts of lead are used as in counter experiments[29] (which give a smaller nuclear component), only the very high energy nuclear components are detected. It is also probable that a fairly large fraction of the initiating particles are neutrons.

When the cloud chamber was triggered with three shielded extended counter trays as described above, six pictures showed extensive showers with a penetrating particle in the midst, twelve showed extensive showers without penetrating particles, and eight showed extensive showers in which the existence of penetrating particles is not certain. The uncertainty derives from the fact that in very dense showers, penetrating tracks might not be visible if present, and some of the pictures show penetrating tracks which may not be time-coincident with the shower. Some of the Auger showers are of very high density, one photographic negative being almost completely blackened with tracks of ionizing particles.

In four of the photographs there are either no electrons at all, or a few very weak tracks above the

[28] W. B. Fretter, Phys. Rev. 76, 511 (1949).

[29] J. Tinlot and B. Gregory, Phys. Rev. 75, 519 (1949).

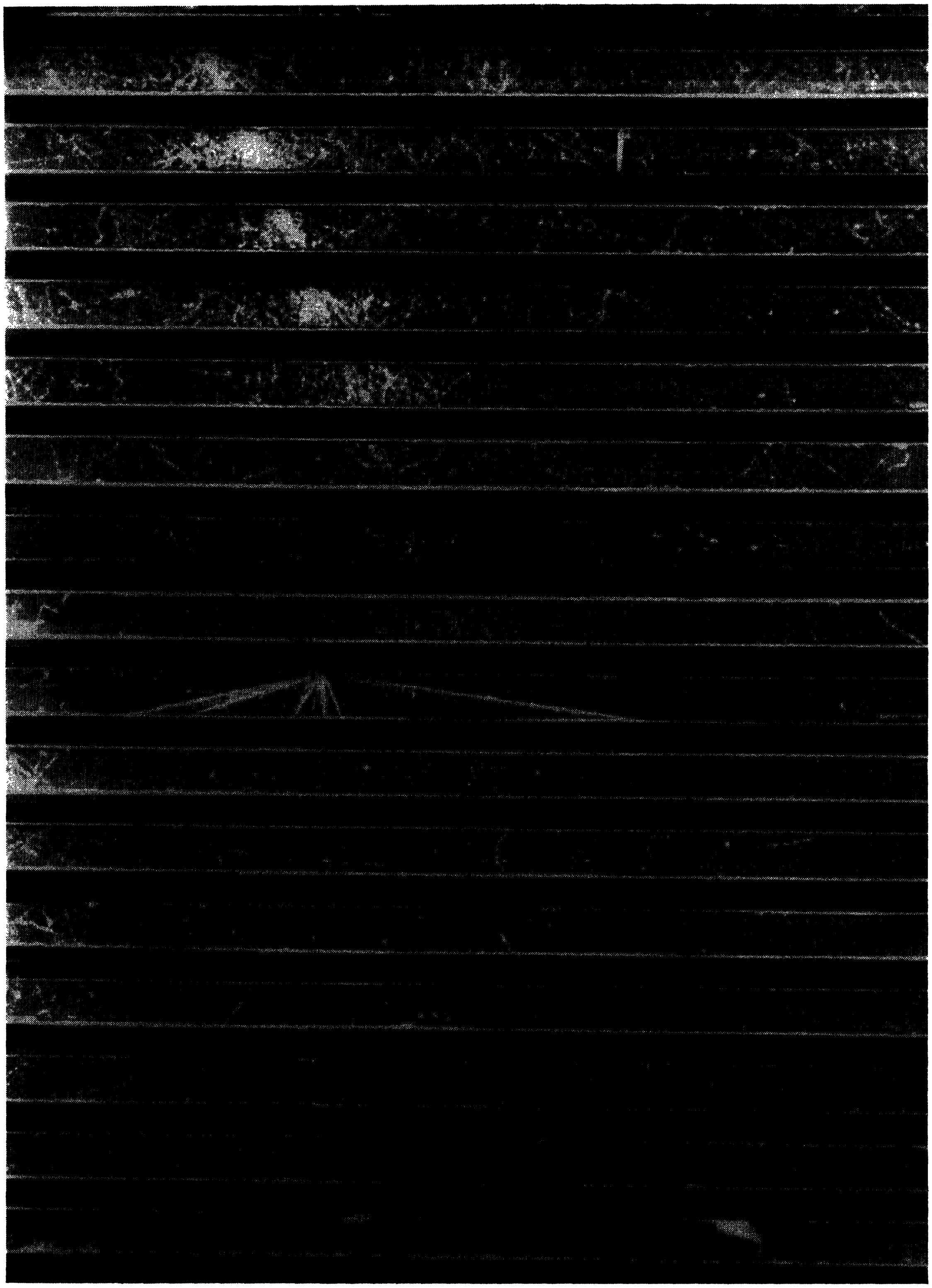

FIG. 8. Local production of penetrating particles by component of extensive shower.

topmost plate, but several tracks of penetrating particles which cannot be identified as being simultaneous with the extensive penetrating shower recorded by the threefold coincidence. Two pictures show no tracks at all, being possibly accidental coincidences.

Two pictures showed local production of penetrating particles in the lead plates of the cloud chamber and the better of these is reproduced in Fig. 8. A number of slow particles and two fast penetrating particles were created by a penetrating particle accompanying the air shower.

Although the statistics are not good, the relative number of penetrating particles and the relative number of nuclear events are the same order of magnitude in this series of pictures as in those triggered by the penetrating shower arrangement.[28]

Production of mesons by 300 Mev γ-rays has been reported[30] and it might be expected that occasionally mesons should emerge from cores of electron showers. It is difficult to identify this event in the cloud chamber because of the large amount of electronic radiation present. In any individual case one could argue that the meson pre-existed in the shower, or that it was created by a pre-existing nucleon. There were, however, 23 photographs of electron showers which could be interpreted as showing production of mesons by electronic or γ-radiation.

Calculation of a cross section for production of mesons by γ-rays from these data must necessarily be rough and may be completely wrong if the events are due to some other cause. We must take into account the minimum energy required to make a meson and try to estimate the number of γ-rays above this energy which exist in the average incident shower. The average number of high energy (150 Mev) γ-rays incident is estimated as roughly equal to the number of electrons, or 5 to 10 per picture. If half of these are capable of producing mesons, and remembering that the γ-rays degrade rapidly in the lead, we can estimate that the number of traversals of $\frac{1}{2}$-inch lead plates might have averaged 10 per picture and certainly could not have been more than 100 per picture. Using the first figure, we get that $\sigma \sim 2\times 10^{-26}$ cm^2 per lead nucleus or $\sigma \sim 10^{-28}$ cm^2 per nucleon. This is larger than the cross section reported by McMillan and Peterson,[30] obtained with a glass target, although he predicted that the true cross section might turn out to be larger when higher energy mesons could be counted. Recent measurements by McMillan[31] support this view and indicate that the cross section is probably somewhat higher than the original estimate. It may also be that (1) there is a higher cross section in lead than in glass or carbon, (2) we underestimated the average number of γ-rays per shower capable of creating mesons, (3) some of the events we observe are due to nucleons or mesons which were already present in the shower.

VI. ACKNOWLEDGMENTS

We wish to thank Mr. Carl P. Russell, Superintendent, Yosemite National Park, and the National Park Service men at Tioga Pass for their generous cooperation in our experiment. Discussions of the results with Professor R. B. Brode have been very helpful in the preparation of this paper.

[30] E. M. McMillan and J. M. Peterson, Science **109**, 438 (1949).

[31] E. M. McMillan, private communication.

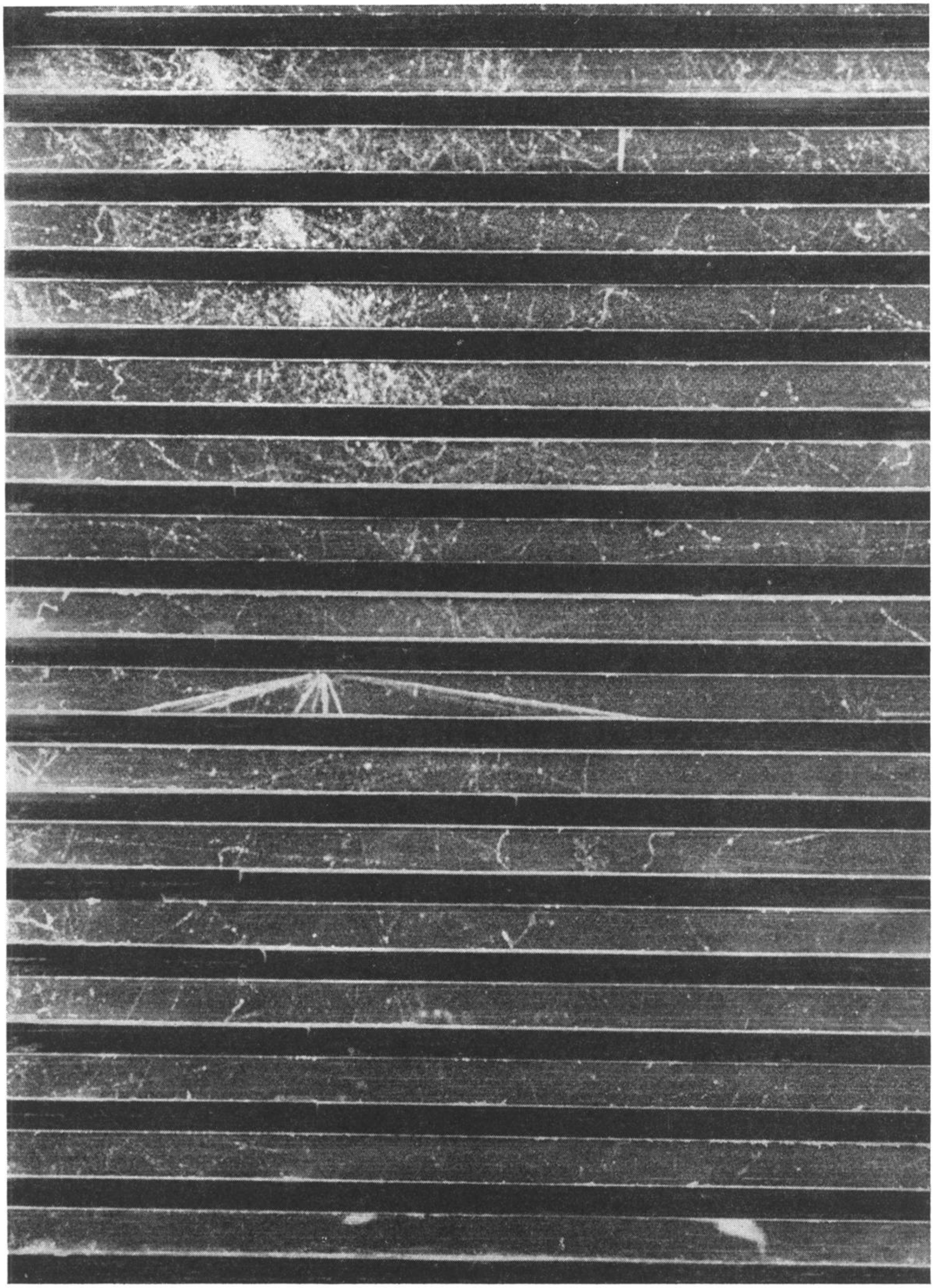

Fig. 8. Local production of penetrating particles by component of extensive shower.