Extensive and Penetrating Atmospheric Showers

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INTRODUCTION

WE have attempted in the present work to obtain precise data on the properties of particles contained in extensive atmospheric showers: we had shown in 1938 that these showers contain some particles having a larger penetrating power than normally attributed to electrons. The investigations have been made:

(1) By absorption measurements conducted with counters: these measures at the same time make possible the study of the spatial distribution of trajectories.
(2) By measurements of the shower-producing properties of particles having traversed variable thicknesses of lead.

In the measurements of absorption and of spatial distribution, we attempted to observe the differences of distribution as a function of the shield thicknesses protecting every counter. We distributed the counters, nine in number, over a horizontal distance of 15 meters, in the open air at sea level. Coincidences of 3 or more counters were recorded, and in every case the individual indications of the tripped counters were obtained, thus allowing some conclusions about the distribution of the particles.

NARROW, LOCAL SHOWERS, AND EXTENSIVE SHOWERS

For a long time rather frequent coincidences had been observed between counters placed in the open at small distances from one another, over a total distance of less than 50 cm. We had described these coincidences as due to local atmospheric showers of limited extension. Indeed, it is known that above 50 cm the numbers of recorded coincidences decline to much smaller values (especially, at sea level) and that these values then change very slowly with increasing total distance. In order clearly to separate these local showers from extensive showers, we placed the 9 counters in 3 groups of 3, of which the central group recorded the local showers. Two experimental set-ups were used:

	4 m	25 cm	4 m
(I)	0 0 0	0 0 0	0 0 0
	A	*B*	*C*
(II)	0 0 0	0 0 0	0 0 0
	1 m	50 cm	4 m
	1 2 3	4 5 6	7 8 9

With the set-up (I) the individual shields covering every counter attained 7.5 cm. With the set-up (II) they attained 20 cm.

Without shields, one observes in both set-ups the counting rate of the triple coincidences (456), i.e., of the group *B*, to be much larger than of the groups *A* or *C*. We can reason as follows to distinguish local from extensive showers: there are 84 combinations of 3 counters in our system of 9. With (I) the number of coincidences other than (456) was 276 as compared with 149 coincidences (456). If the effect of local showers were not superposed upon that of the extensive showers, we should have in (456) during the same time interval only 276/83 = 3.6. There remain 145 coincidences (456) due to local showers. Carrying out the same study with the set-up (II) we find that the central group *B* of 50-cm spread counts only twice as many coincidences as *A* and *C* (1 m and 4 m) instead of 40 times as many. The effect of the local showers is thus

TABLE I. Data taken at Paris and at 5000 m.

Multiplicity	Calculated	Measured at Paris: Coincidences	Measured at Paris: Per 1000	Measured at 5000 m: Coincidences	Measured at 5000 m: Per 1000	Denoted by N_3^{-6} any event such that
N_3^{-6}	556	280	596	2052	530	3 counters tripped 6 not tripped
N_4^{-5}	203	85	199	834	210	N_8^{-1} 8 tripped 1 not tripped
N_5^{-4}	98	41	87	436	110	N_9^0 all 9 counters tripped
N_6^{-3}	56	23	50	243	62	N_3^{-6} is the total number of triple events contained in the records and carried in the columns
N_7^{-2}	36	20	42	159	41	
N_8^{-1}	21	8	17	109	28	
N_9^0	30	4	9	68	19	
Total of events	1000	461	1000	3900	1000	

almost suppressed. Between A (1 m) and C (4 m) there is no more any measurable difference.

EXTENSIVE SHOWERS

Having performed this separation, we can eliminate the effect of local showers, and study the distribution of the particles of extensive showers between the 9 counters. A simple derivation can be made of the relative frequencies to be expected for triple, quadruple, quintuple, sextuple, septuple, octuple, and nonuple coincidences. We assume distribution of extensive showers according to the law Δ^{γ}, where Δ is the density of particles and γ an exponent experimentally found to be 1.5 for altitudes from 0 m to 5000 m. Table I shows the comparison of the values found in Paris and at 5000 m. To be noticed is the higher value of the computed nonuples, because they include also the coincidences of higher order. Experimentally, the value is found to be smaller. In this calculation, the spectrum of densities is assumed to extend indefinitely towards high densities, while this is not true experimentally, since γ varies with Δ. However, the table shows an excellent agreement with the theoretical predictions. The ratio of triples to the total number of coincidences $N_3/\sum N$ gives a simple way of checking this agreement. This ratio is 0.53 at 5000 m and 0.59 in Paris, as against the computed 0.56.

It is interesting to consider the number of times each individual counter has been tripped in any of the combinations. Thus we find in set-up (I) a great difference between the counting rates of 1, 2, 3 or 7, 8, 9 and of the narrowly spaced counters 4, 5, 6, the latter being about twice as large. In arrangement (II), this difference all but vanishes, and only a small decrease is observed in passing from the counters of a 50 cm spread to those of 1 m, then to those of 4 m.

This set of observations shows that the distribution of particles of extensive showers without shielding is uniform. Superposed is a local distribution of numerous showers of small area and of comparable densities. In previous work, we measured the altitude variation of these two types of showers, and showed that local showers increase distinctly less rapidly than extensive ones up to 3000 m. Above this altitude the behavior of both types is not appreciably different.

TABLE II. Set-up (I) and (II) without lead.

Group	Counter	Set-up (I) Number of pulses	Set-up (I) Total for group	Set-up (II) Number of pulses	Set-up (II) Total for group
	1	160		318	
A	2	188	558	319	940
	3	210		303	
	4	349		312	
B	5	344	1023	342	971
	6	330		312	
	7	185		313	
C	8	188	551	322	923
	9	178		288	

We attributed this to the presence of secondary showers produced by mesons in the lower atmosphere, a phenomenon which becomes negligible above 3000 m.

ABSORPTION UP TO 10 CM OF LEAD

It was impossible to place lead shields of more than 7.5 cm over the counters of set-up (I) because of the proximity of the central counters 4, 5, 6. But the absorption measurements (Tables II and III) made with this set-up have the advantage of permitting a comparison of the decrease of local showers and of extensive showers. The result is that the 7.5 cm of lead introduce no observable change either in the spatial distribution of the coincidences or in the relative counts of individual counters, or in the ratio of local showers (456) to extensive showers. We find for this last ratio 40 percent instead of 33 percent without lead. The computed exponent γ has the same value 1.5. The ratio of triple to total coincidences is 0.57. To be sure, all these events have their frequencies decreased by an absorption divisor approximately equal to 5.8. Everything happens as if we had reduced the areas of all the counters 10 times.

The only small difference consists in a slightly smaller decrease of local coincidences, i.e., coincidences between the 3 narrowly spaced counters. We wanted to feel sure that these coincidences have the same meaning as when they are observed without lead, and that they are independent of the events affecting the other counters. Therefore, we took the lead off all the counters except 4, 5, 6 so as to increase considerably the counting rates of the unprotected counters and to transform into quadruples, and so forth, all the triples (456) which are not really due to an

TABLE III. Set-up (I) under 7.5 cm of Pb.

Group	Counter	Number of pulses	Total for group	Coincidence	Number	Total
	1	127				
A	2	125	384	N_3^{-6}	170	
	3	132				
				N_4^{-5}	70	
	4	228				
B	5	267	748	N_5^{-4}	22	292 (extensive showers only)
	6	253				
				N_6^{-3}	15	
	7	130				
A	8	128	363	N_7^{-2}	8	
	9	105				
				N_8^{-1}	7	
				N_9	5	

isolated local phenomenon. No change was introduced in the counting rate of triples (456) whose local character is thus proved. The similitude of the penetrating powers of these local showers and of extensive showers is also proved, at least up to 7.5 cm Pb.

ABSORPTION UP TO 20 CM OF LEAD

With the set-up (II) we were able to study the same phenomena under 11, 13.5, and 20 cm of lead. With 11 cm a spatial concentration of the extensive shower coincidences, as well as a decrease of their density, begins to be noticeable. It is already very marked with 13.5 cm; at this thickness we obtain a distribution very different from the ones described heretofore (Table IVA). If we assume that local showers have only a small importance in this set-up (since counters of 50-cm spread record in the open only twice as many isolated triples as counters of wide spread) and if we simply compare the number of times the different counters are tripped, we find that the counters of 50 cm, 1 m, and 4 m are tripped with frequencies which are approximately in the ratio of 2.5 to 1.5 and 1.0. Moreover, triples are much more numerous than other multiples. Even in not counting coincidences (4, 5, 6), we have N_3/total$=0.73$. If the triple coincidences of 50-cm spread were counted, there would result N_3/total$=0.81$. These effects are even more marked under 20 cm of lead where we find N_3/total$=0.9$. Also the distribution of pulses between the 9 counters is more concentrated (Table IVB).

It is interesting to observe what happens with set-up (II) for smaller thicknesses. The experiment was made with 5.2 cm lead, and it showed an important relative increase of triples at 50-cm spread, and even at 1 m, as compared with the experiment without shielding. The concentration effect described for 13.5 cm already begins and has the same characteristics. This effect has been observed with set-up (I) only with difficulty because the abundance of local showers for 25 cm was masking any such effect. One could, however, attribute to it the relative increase of triple coincidences for 25 cm in relation to the total count.

We find ourselves, therefore, in presence of two effects caused by lead shields, spatial concentration of trajectories, and change of the density spectrum (increase of the exponent γ). These two effects could be explained by assuming that the very penetrating particles observed in this way (more than 10 cm of lead) are gathered in a little extensive portion of the shower (central portion?) and that the frequency of occurrence of these showers varies more rapidly in a function of particle density than in the case of ordinary particles.

LOCAL EFFECTS OF EXPLOSIVE TYPE

Our attention has been drawn, however, to the possibility of the occurrence of phenomena other than atmospheric showers proper. We had observed earlier[1] some relatively rare effects producing coincidences between counters strongly shielded and separated by lead. These effects, which seem due to local bursts seated in the shield itself, produce an abundance of particles, some of very small penetration, others pene-

TABLE IVA. Data under 13.5 cm of lead.

Group	Total of pulses per group	Coincidence	Number	Total
A	147	N_3^{-6}	81	
		N_4^{-5}	20	
B	226	N_5^{-4}	4	105 (extensive showers only)
		N_6^{-3}	3	
C	91	N_7^{-2}	1	
		N_8^{-1}	0	
		N_9	0	

[1] Phys. Rev. 61, 549 (1942).

trating enough to pass out of the shield and to be observed in the cloud chamber outside. The measurements described here under thick shields, correspond to a counting rate small enough for such effects to occur, even though rarely. It is thus possible to attribute at least a part of the coincidences between narrowly spaced (50 cm) and highly protected counters to such local effects, which are then not necessarily or closely related to an extensive shower, as we have shown in reference 1. Obviously, these local effects cannot be used to interpret coincidences between widely spaced counters, for instance, those of 4-m spread, which require for their explanation separate trajectories simultaneously coming from the air.

In order to elucidate this point, we have grouped our counters quite differently, in a way more similar to the one used in the study referred to above.[1] The first 7 counters, placed under 20 cm of lead, formed a closely spaced set in a horizontal plane as represented in Fig. 1. The 8th could be placed in the open air (actually, under 4 mm of lead) either very near to the central group (8*A*) or at 1.50 m (8*C*). The 9th and last was placed in the open at a horizontal distance of eleven meters. With this set-up, coincidences between the 7 first counters may be due either to penetrating particles coming from the air, forming parts of an extensive shower, or to local explosive phenomena, accompanied or not accompanied by an atmospheric shower. In the first case it seems that the counters 8 and 9

TABLE IVB. Data under 20 cm of lead.

Group	Counter	Pulses	Total for group	Coincidence	Number	Total
	1	30				
A	2	29	84	N_3^{-6}	37	
	3	25				
				N_4^{-5}	7	
	4	56				
B	5	62	180	N_5^{-4}	3	48 (extensive showers only)
	6	62				
				N_6^{-3}	1	
	7	23				
C	8	15	49	N_7^{-2}	0	
	9	11				
				N_8^{-1}	0	
				N_9	0	

Number of coincidences (456) = 45 which are not counted in this table as being due to local effects.

TABLE V. Data for arrangement of Fig. 1. Number of coincidences.

	8 without 9	9 (and 8)	9 without 8	neither 8 nor 9
8 near (*A*)	18	11	(1)	3
8 at 1.50 m (*C*)	6.8	8	(1)	6
8 at 1.50 m perpendicular (*B*)	6.5	55	0.7	4

must be tripped in about the same way and often at the same time as the covered counters. In the second case, the (near) counter 8 must be tripped more often than the (distant) 9, and the oftener, the nearer it is.

Here are the results of the experiments. First of all, it almost never happens for the uncovered distant counter to be tripped without the uncovered near counter being tripped. This shows that always only extensive showers of large density are in question. I recall that always at least one of the counters placed under 20 cm of lead is tripped so as to give a triple. On the contrary, it is very frequent for 8 (near) to be tripped when 9 (distant) is not. This case, about as frequent as that of the extensive showers tripping 8 and 9, is due to a local phenomenon (Table V) very sensitive to the distance of this near counter 8 from the center of the group under lead. Thus when this uncovered counter 8 is placed directly over the lead shield (but not directly over one of the counters, in order to avoid double coincidences due to penetrating vertical particles) these local effects are almost twice as frequent as the extensive showers, whereas they fall below them as soon as counter 8 is displaced by 1.50 m from the group under lead.

Finally, it occurs that neither of the uncovered counters is tripped; this is the manifestation of a local effect not accompanied by an air shower (large or small)—undoubtedly, one of those penetrating showers of explosive nature (very divergent trajectories). The study of the distribution of pulses among the covered counters shows a very strong concentration, the central counters being more frequently tripped than the peripheral ones. This concentration is not found in pulses due to extensive showers. It appears possible, therefore, to separate cleanly the exten-

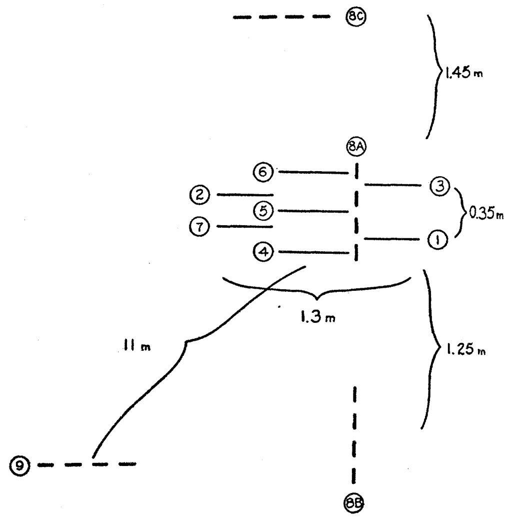

FIG. 1. Arrangement and spacing of counters.

sive showers with penetrating parts from the unaccompanied local effects inherent in the shield. It will be necessary to make extensive statistical studies of these different phenomena in order to determine their geometrical structure (as well as cloud-chamber photographs) in continuation of the work already referred to.

A first statistical analysis (Table VI) made it possible to show that the point of divergence of numerous local effects is located well within the lead shield. The counters placed on the side where the uncovered near counter (No. 8) is situated count distinctly more than those located on the other side of the group under the shield. It seems that an important part of the pulses tripping the counter 8, but not the counter 9, is to be attributed to such effects, induced within the shield, in which some secondary particles come out and reach the counters located at small distances. The question of the proportion in which they are superposed upon the very narrow showers of atmospheric origin is in course of being studied.

TABLE VI. Data for arrangement of Fig. 1.

Frequency of pulses for the coincidences including the far counter (9)		Frequency of pulses for the coincidences not including either counter 9 or counter 8 (local effects)	
Counter	Number of pulses	Counter	Number of pulses
1	23	1	7
2	9	2	8
3	22	3	15
4	15	4	32
5	16	5	39
6	22	6	40
7	11	7	10

TABLE VII. Absorption effects.

Shield thickness in cm of lead	Relative number of triple coincidences (low altitudes)	Remarks
0	100	
0.6	122	Effect of transformation of photons onto electrons
2	100	
4	50	
8	21	
14	4.5	
19	3.5	

CHARACTERISTICS OF THE PENETRATING PORTIONS. ABSORPTION

We have seen that notable portions of the extensive showers still produce pulses in counters protected by 20 cm of lead. We wanted first of all to measure as correctly as possible the absorption of these penetrating parts in lead, then to examine their properties, mainly with respect to their power of producing secondary showers.

In what concerns absorption, measurements made at sea level with 9 counters permit the derivation of a coefficient, if a certain spectral distribution of showers is assumed giving their frequency as a function of their density (density of particles per unit of horizontal area). With a law of the form $\Delta^{-\gamma}$ and an exponent $\gamma=1.5$ our measurements show that between 5 and 15 cm of lead the coefficient is equal to about 0.025 cm g^{-1}. This coefficient is not constant and decreases appreciably when the measurements are carried to 20 cm of lead shield (Table VII).

We had also used another method (Daudin) which consists of measuring, even showers of very small density (the most numerous ones), and protecting by a lead shield only one counter out of the 3 which determine the measured coincidence. One can then assume that the decrease of the number of pulses observed as the shield is made thicker is due to absorption only and not to selection. These intensities were measured, at a small altitude, with an apparatus consisting of two groups, A and B, composed of 15 counters in parallel (total area about 0.20 m^2) which could be placed at 5 m or at 70 m from each other, and of a third counter C of small area under a shield of variable thickness. The values of the intensity decreased only very slowly after 14 cm of shielding. Between 4 cm to 14 cm there is a reduction by a factor 11 for 10 cm of lead. This corresponds to a mass coefficient of about $\alpha=40$ g cm^{-2}, in reasonable agreement with the coefficient obtained by the preceding method, so different in its principle. The value of this coefficient does not agree well with the properties of either electrons or mesons.

SHOWER-PRODUCING PROPERTIES

With a view of studying the properties of penetrating particles, the counter of small area C was replaced by two counters CC' in coincidence, and the triple coincidences ABC were compared with the quadruples $ABCC'$. Let us recall that the groups A and B could be placed at either 5 m or 70 m from each other. In these conditions the ratio Q/T of quadruples to triples gives an indication of the properties of penetrating particles, observed to produce secondary effects under shields protecting the pair CO'. Table VIII shows that this ratio, which is 0.28 in the open, increases to 0.53 under half a centimeter of lead because of Rossi showers induced in it by the electrons from extensive showers. But when the shield is increased to 8 cm, the ratio still remains equal to 0.34. This is true for a base of 70 m as well as one of 5 m.

This effect corresponds to the production of electron showers, as can be shown by interposing a lead partition of 0.8 cm between C and C'. The decrease of quadruples amounts to 40 percent. Such an absorption of almost one-half in 0.8 cm of lead is quite characteristic of electrons of small energy showers. I recall that we deal here with phenomena connected with an extensive shower and not with local effects induced in the lead shielding by isolated particles. Here again the properties of penetrating particles of these extensive showers are neither those of mesons, nor of electrons. Mesons could be accompanied only by less than 10 percent of secondary electrons, and this percentage would fall even lower with the interposition of a partition. Double mesons coming from the air would not be sensitive to the partition. Electrons which succeed in passing through 19 cm of lead would be accompanied by a shower of very large density, insensitive to the partition.

TABLE VIII. Ratios of coincidences under lead.

Shield thickness in cm	Triples (relative numbers)	Quadruples (relative numbers)	$\frac{\text{Quadruples}}{\text{triples}}=\frac{Q}{T}$
0	100	100	0.28
0.6	132	250	0.53
2	92	166	0.51
4	73	133	0.54
8	20	31	0.45
14	4.3	5.2	0.35
19	3.3	3.9	0.33

CONCLUSION

Insofar as any clean cut conclusion can be derived from the measurements in their present state, it seems that they are the following:

(1) There are two types of groupings of particles in the showers originating in the middle of the atmosphere. One is very local since the opening of its branches does not exceed 50 cm at sea level. The second is very extensive since simultaneous particles can be detected at several hundred meters from one another. These two groups of particles are independent. In the lower atmosphere they do not vary with altitude in exactly the same way.

(2) Under lead shields, these two groups of particles undergo an absorption of the same order of magnitude, but in the group of small extension the measurements are complicated by the intervention of secondary phenomena in the shield itself. The particles of the widely spread type (extensive showers) are absorbed to such an extent that their number declines by a factor of 10 for 10 cm of lead in the region between 5 cm and 12 cm of lead. This corresponds to a mass coefficient of absorption of about 40 g cm^{-2}.

For larger thicknesses, such as 20 cm of lead, the absorption coefficient decreases materially, indicating a hardening of the radiation which is able to pass through these shields. The absorption coefficient in the region of from 15 cm to 20 cm of lead is certainly higher than 100 g cm^{-2}.

(3) At the same time with this change in the absorption coefficient, a difference in the distribution of the particles is noticeable. The horizontal spread of the very penetrating frac-

tions of extensive showers becomes much smaller than that of their highly absorbable parts.

(4) The very penetrating parts of extensive showers (beyond 20 cm of lead) produce in the lead numerous secondary electrons.

(5) In the study of coincidences between near counters, under thick lead shields (10 cm to 20 cm), a local phenomenon produced in the lead is substituted for the local atmospheric phenomenon, and it is uncertain whether it has the same cause. The absorption coefficient of this local secondary phenomenon is of the order of 100 to 200 g cm^{-2}, that is to say, of same order as the decrement of extensive showers in the atmosphere and also of local showers above 3000 m.

An explanation of this set of observations cannot be found in the hypothesis that in cosmic radiation only mesons and electrons are present. It is impossible to attribute to mesons either the important secondary effects observed even under 20 cm of lead in the penetrating parts of extensive showers, or without doubt the "explosive" effects observed for penetrating particles which are not parts of extensive showers. The absorption of extensive shower particles between 5 cm and 15 cm of lead does not correspond either to electrons or to mesons.

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The Penetrating Particles in Cosmic-Ray Showers

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I. INTRODUCTION

DURING the past two years the Blackett electromagnet has been used in the study of cosmic-ray showers, and a summary of the main results is given in this paper.* Two aspects of showers are considered; firstly, the nature of the heavily-ionizing particles occurring in showers, and secondly, the lightly-ionizing particles in penetrating showers.

Two counter arrangements (Rochester and Butler[1]) were used to trigger the cloud chamber. Neither arrangement was rigidly selective for any particular kind of shower and even though the counters were connected in fivefold coincidence to reduce the rate of random coincidences, the cloud chamber could be set off by a shower consisting of two particles. In order to identify the showers in the cloud chamber connected with extensive showers, a tray of 14 counters connected in parallel, effective area 1700 cm^2, was placed 1 m from the chamber. An indicator lamp at the cloud chamber showed whether one or more ionizing particles crossed the extension tray within 2 μsec. of the fivefold master pulse. For most of the showers described in this paper the counter trays above the chamber were covered by a layer of lead 5 cm in thickness. There was, moreover, a layer of lead immediately in contact with the chamber wall. The thickness of this lead is indicated in the tables.

The cloud chamber was 30 cm in diameter and 9 cm in depth and was filled to a pressure of 1.5 atmospheres with a gas mixture consisting of 80 percent argon and 20 percent oxygen. Across the chamber was a lead plate 30.5 mm in thickness faced above and below with brass reflecting plates 1.8 mm in thickness.

II. MEASUREMENT OF CURVATURE AND ACCURACY OF MOMENTUM DETERMINATION

The curvatures of most of the low energy tracks were determined by direct measurement on a travelling microscope fitted with a Zeiss micrometer eyepiece. The results for good tracks

* This work has been carried out in collaboration with Dr. C. C. Butler, Dr. S. M. Mitra, and Mr. W. G. V. Rosser.

[1] G. D. Rochester and C. C. Butler, Proc. Phys. Soc. London 61, 307 (1948).