Physics. — *Cosmic Ray Showers.* By J. CLAY.

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Summary.

A summary is given of a number of experiments concerning showers. Especially a comparison is made between the divergence and the penetrating power of showers with small spreading in the first maximum (1,5 cm Pb) and the second maximum (25 cm' Pb). The spreading is greater in the second case and the hardness is less. The proportion of the maxima moves between 4 and 3.

Next a distinction is made between the occurring hard showers (of mesons) and shoft showers (electrons) and mixed showers, under thick layers of different matter: air, water, aluminium, iron and lead. The variation with the electron density is determined. The number decreases with increasing atomic number.

The meson showers have greater spreading than the electron showers.

§ 1. When cosmic rays pass through matter bundles of rays (showers) occur, which are formed in consequence of the interaction of the rays and the field of the atomic nuclei. The process of multiplication is such, that in consequence of the reactions the charged corpuscle throws off part of the energy in the form of a photon and this photon loses its energy in forming pairs of electrons, one with a positive, one with a negative charge. Thus arises a multiplication. This process has been treated by many authors, but now BRUINS (1) has succeeded in accounting for it quantitatively. He has been able to describe the process that occurs in the higher layers of the atmosphere and from the phenomena he has estimated the energy distribution of the original spectrum of the incident particles, *which proves to be mostly identical* to the spectrum which has been measured of the mesons in the atmosphere.

§ 2. However in thin layers of matter — where the process was originally found — it is more complicated, because the loss of energy of the particles through ionization is a factor not to be neglected. The theory of it has also been indicated by him in principle but it has not yet been worked out quantitatively.

On measuring *showers* in thin layers of matter there is a difference in relation to the geometrical proportion of the experiment; in the first place how many shower particles are counted and at what distance from the dispersing matter the counters are placed.

In the past year these circumstances have been carefully studied in this laboratory (2). The results have shown in how far the numbers found can be made independent of the geometry of the measuring apparatures.

In thin layers the production is proportional to the square of the atomic number. But the location and the height of the maximum of showers of varying number can only now be tested with the help of the theory of BRUINS.

§ 3. There was however another problem to which we have given our special attention. When the number of the showers formed under thick layers is examined, it is seen that there must be a second process of a different nature. There is namely a second maximum, indicating that there must be a corresponding multiplication phenomenon, but of particles of more penetrating power. For some time it had been suspected that this must be meson showers. So far, the phenomena found by different investigators, were greatly contradictory (3).

The second maximum, first found by ACKEMAN and HUMMEL (4) under lead, lies at about 16 cm and was also found by us in an earlier investigation under iron at about 26 cm. This was not at all confirmed by some investigators, while under some circumstances others found it, being so evident as to exceed even the first (6).

First of all we determined by three different methods that this maximum and a third maximum certainly exist (7).

Secondly, however, these maxima proved always to be much lower than the first in the proportion of 3 to 4 times. But an even greater difference may be noted. The second maximum, which according to BOTHE and SCHMEISER (6) consists of more penetrating rays, was thought to have less divergence than the showers of soft rays (electrons). In a systematic investigation, carried on for a considerable time, we found the opposite result.

In this investigation we made an arrangement as shown in Figure 1. Four counters of 1 cm diameter are connected parallel, close under a layer of lead A, successively

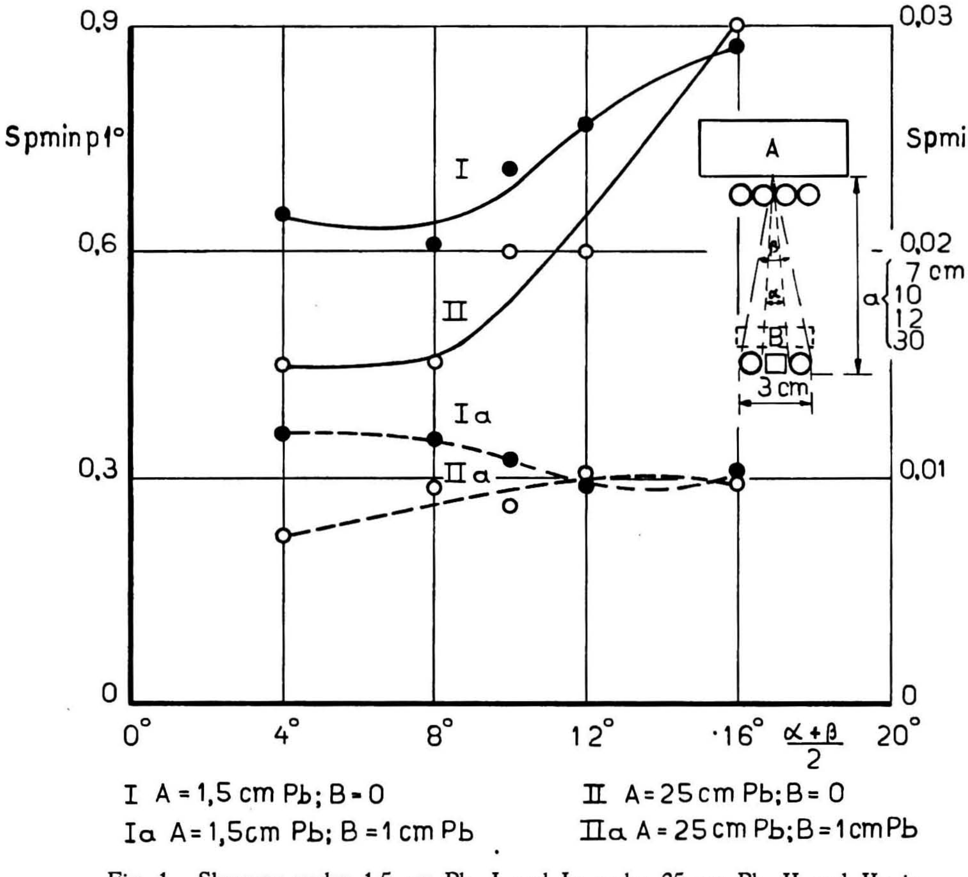

Fig. 1. Showers under 1.5 cm Pb, I and Ia under 25 cm Pb, II and IIa in dependence on their angle of devergence.

1,5 and 25 cm thick. Under it at a distance *a* there are two counters of 1 cm, separated by 1 cm Pb. The distance *a* was varied from 30 to 7,5 cm and thereby the angle of rays from the scattering lead was varied from 2°—6° to 8°—26°. Above the lowest counters layers of lead were placed, varying from 0,5 to 2 cm Pb, in order to measure the absorption of the shower rays. Because the opening becomes larger as the distance is smaller, the numbers were divided by the value of the opening angle and in that way comparable figures were found for different spreading. For 1,5 cm Pb above the counters the figures are given in column 4, the same for a layer of 25 cm Pb in column 7. All observations were continued until at least 150 showers had been observed, so that the uncertainty was no more than 8 %.

TABLE I.
Showers under thin lead, $A_1 = 1.5$ cm Pb and thick lead, $A_2 = 25$ cm Pb at different angles of divergence.

Divergence			$A_1 = 1.5$ cm Pb		$A_2 = 25$ cm Pb		$\frac{S_{A_1}}{S_{A_2}}$
α	β	$\frac{\alpha+\beta}{2}$	S/min	S/min/1°	S/min	S/min/1°	$\frac{\text{max } 1.5 \text{ cm Pb}}{\text{max } 25 \text{ cm Pb}}$
2°	6°	4°	0.256	0.065	0.062	0.015	4.1
4°	12°	8°	0.49	0.061	0.12	0.015	4.0
5°	15°	10°	0.72	0.072	0.22	0.020	3.6
6°	18°	12°	0.93	0.077	0.24	0.020	3.9
8°	26°	17°	1.51	0.086	0.54	0.030	3.0

The relative increase of the numbers with the angle of divergence are found in columns 5 and 8. It is seen that under the thick layer the divergence is greater than under the thin one, while further the proportion of the numbers is given in the 8th column. It is seen that this proportion decreases with the divergence. This is in accordance with our experience that the second maximum works out better for greater angles. It is contradictory to the result of BOTHE and SCHMEISER, but in keeping with the results of other investigators, especially TRUMPY (8), and with our results given in § 7.

TABLE II.
Absorption of showers under a thin and under a thick layer of lead at different divergences of the rays.

$\frac{\alpha+\beta}{2}$	4°		8°		10°		12°		17°	
B cm Pb	A 1.5 cm Pb	A 25 cm Pb	A 1.5 cm Pb	A 25 cm Pb	A 1.5 cm Pb	A 25 cm Pb	A 1.5 cm Pb	A 25 cm Pb	A 1.5 cm Pb	A 25 cm Pb
0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
0.5									0.50	0.44
1.0	0.56	0.50	0.58	0.64	0.44	0.45	0.38	0.52	0.35	0.33
2.0	0.24	0.37	0.32	0.29	0.22	0.25	0.22	0.29		

Under a thin layer (1,5 cm Pb) the divergence is therefore less than under 25 cm Pb (Table I, Fig. 1) and the hardness of the showers under the thick layers is not greater than under the thin layer (Table II, Fig. 1). TRUMPY (8) found lately that the hardness is even less under the thick layers and we found the same for a greater divergence.

This is clear from Table II and Fig. 1.

§ 4. In order, however, to distinguish between softer electron showers and hard meson showers, a separate investigation was made, in which four-fold coincidences were measured, but in such a way that the counters were placed two by two above each other, 10 cm, sometimes 15 cm Pb being inserted between them, Fig. 2 a. The experiments were made with four counter boxes of 3 counters, parallel to each other with sensitive area of 840 cm².

In this way 3 different cases could be distinguished. If between the two pairs of counters 10 cm Pb (B_1 and B_2) are inserted, it is certain that the two parts necessary for a four-fold coincidence must both have been mesons, for already at 5 cm Pb 10^{11} eVolts is needed, according to HEITLER's theory, and if the energy increases in the same way for the penetration of thicker layers, we arrive at values which do not occur for electrons on the surface of the earth.

TABLE III.
Absorption of soft and of hard shower particles under different kinds of matter in 100 min area 840 cm^2.

B_1 en B_2	0;0	0;1	0;2	0;3	0;4	0;5	0;10
Open	57	40	40	28	30	28	22
70 cm water	70	51	50	46			30
28 cm aluminium	59	44	39	41			23
33 cm iron	31	24	25	23	19		17.5
15 cm lead	33	25	21				15

By leaving the thickness of lead B_1 10 cm between one pair, and then stating the decrease which arises when the absorption layer between the other counters is varied

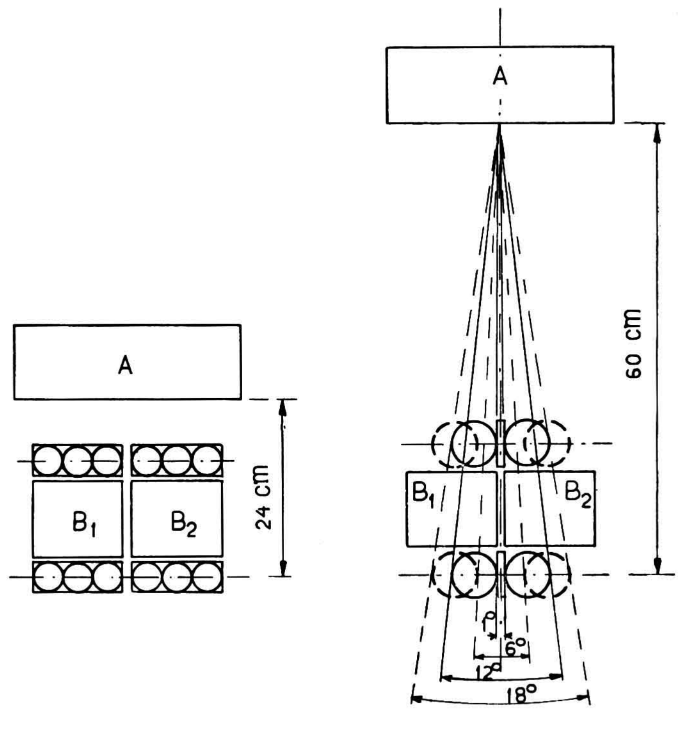

Fig. 2. Arrangement of the counters in order to distinguish between electron and meson showers.
a. Four-fold coincidences in 4 boxes each of 3 counters, each of 6 cm diameter and 47 cm long and afterwards 3 counters each 30 cm long and 4 cm diameter.
b. Four-fold coincidences in four counters each 47 cm long and 6 cm diameter in two positions.

from 5 to 15 cm, we finally obtain the absorption of the meson particles in the showers. This is given in Fig. 3 and Table IV. The number is seen to have decreased very little.

When one takes B_1 10 cm Pb, varying B from 0 to 5 cm the absorption is seen to be much greater. The additional showers which are obtained are showers in which one particle must be a meson, but in which the other is most probably an electron. Vide Table V.

TABLE IV.

B_1 and B_2	10; 0	10; 1	10; 2	10; 3	10; 4	10; 5	10; 10	10; 15
Open	22	18	15	13		11	10	7.3
Water	30	24	21			16	12	12.6
Aluminium	27	22	20	20		14	9.1	
Iron	17.5	13	13			10	9	
Lead	15	13				11	8.8	6.4

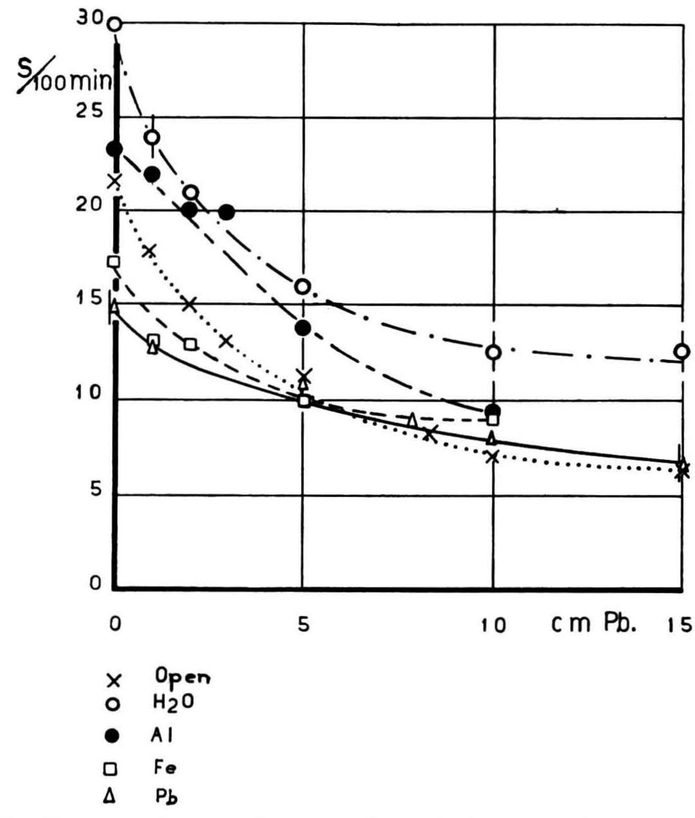

Fig. 3. Decrease of meson showers and mixed showers under air, water, Al, Fe, Pb by absorption in lead from 0—5 and from 5—15 cm. The uncertainty is given for 4 values, but for all the values it is less than 8 %.

TABLE V.

Decrease of soft showers and mixed showers by 1 cm Pb, number in 100 min.

	0; 0—10: 0	0; 1—10; 0	$\frac{0;\ 1-10;\ 0}{0;\ 0-10;\ 0}$	0; 10—10; 10	1; 10—10; 10	$\frac{1;\ 10-10;\ 10}{0;\ 10-10;\ 10}$
Open	35	18	0.52	12	8	0.67
Water	40	21	0.52	18	12	0.67
Aluminium	36	21	0.58	22	13	0.59
Iron	13.5	6.5	0.48	8.5	4	0.50
Lead	18	10	0.55	6.2	4.2	0.68

These are processes in which the meson throws off an electron from the atomic connection, the processes in which the secondary electron rays are formed. These processes have been observed under thick layers of different material, water, aluminium, iron and lead, in order to attain the condition of saturation (Fig. 4).

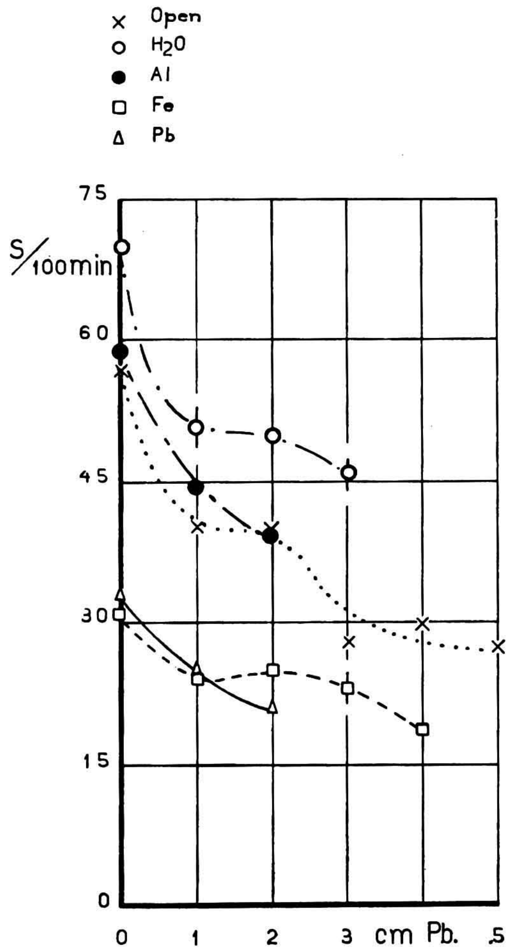

Fig. 4. Decrease of electron showers under thick layers of air, H_2O, Al, Fe and Pb in lead from 0 to 5 cm.

That there are here electrons is apparent from the fact that the decrease by 1 cm Pb (B_2) is of the same value, being only little less than that in soft showers. This is seen from the figures in Table V, where in column 2 the soft showers found are given and in column 3 the cases in which 1 cm Pb is placed in one of the two ways which must be taken by the showers particle; column 4 shows the percentage of the showers left after absorption by 1 cm Pb.

The same is given for the mixed showers in columns 5, 6 and 7. From this it is clear that in this case the remaining particle is not a meson but an electron, although the average energy is a little greater than in the first case.

So in this case we are confronted by a coincidence, in which there is certainly one meson and certainly one electron. A number of such cases is known from WILSON-chamber photographs, namely that an electron rich in energy is produced by a meson (9). When further we deduce the number of coincidences found with $B_1 = 10$ and $B_2 = 0$ from the number with $B_1 = 0$ and $B_2 = 0$, there is left the number of showers consisting of soft rays i.e. electrons. The decrease of the number in both cases is given in Table V, fig. 4.

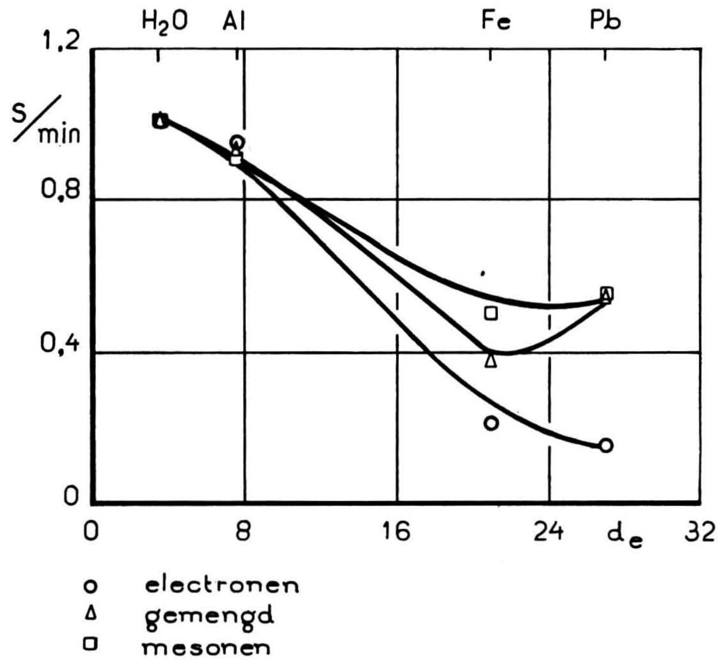

Fig. 5. Decrease of electron showers, mixed showers and meson showers with decrease of the electron density of the material: water, Al, Fe, and Pb.

§ 5. The measurements were all taken under thick layers of different matter. We see that the number of showers under thick layers decreases with the electron density and here we have the same phenomenon as when we measured the number of secondary rays (electrons) with regard to the number of mesons by which they are produced (10). The production is, indeed, proportional to the electron density, but the absorption in the material itself is proportional to the square of the atomic number and consequently, in condition of saturation under thick layers, the number of showers under the material will decrease in proportion to the atomic number.

The number of coincidences found, in which at least one meson and one electron are combined, is less rapid with the electron density of the dispersing material. Here is, however, an irregularity, namely that with lead the number is greater than with iron and this irregularity was tested several times and therefore seems to be real.

TABLE VI.

Number of showers observed under different layers with different absorbing layers, per 100 min, area 360 cm².

	B_1 B_2 0 0	B_1 B_2 0 10	B_1 B_2 5 10	B_1 B_2 10 10
Air	29	16	8.8	4.5
70 cm H_2O	60	22	10	6.9
28 cm Al	56	20	10	6.2
33 cm Fe	17	9	4.9	3.5
15 cm Pb	18	12	6.1	3.8

In order, however, to measure this with certainty a measurement was repeated with another set of four glass counters, this time in quicker succession, the different layers of material being exchanged in order to prevent insufficient constancy of the circumstances during the continued measurements necessary for the absorption. The sensitive area of these counters was 360 cm^2. It was seen that in the proportion of the hard meson showers the number had decreased approximately in the same proportion as the sensitive area, the proportion for the narrower areas being more favourable for the soft electron showers. This means that in the meson showers there is greater divergence than in the electron showers. This was confirmed in a further investigation, which will be described lower. The figures found are given in Table VI and these values were obtained from a number which was always greater than 150, so that the uncertainty was less than 8 %. The values of table VII were deduced from these data and figures were found for Al, Fe,

TABLE VII.

Number of electron showers (S), combined showers (S & H) and meson showers (H) under different layers of matter of great thickness.

	S		H & S		H		$\frac{S}{H}$	$\frac{H\&S}{P}$
Air	0.13		0.115		0.045		4	2.5
70 cm H_2O	0.38	100	0.15	100	0.069	100	5.5	2.2
28 cm Al	0.36	95	0.138	92	0.062	90	6	2.3
33 cm Fe	0.08	21	0.055	37	0.035	50	2.3	1.6
15 cm Pb	0.06	16	0.082	54	0.038	55	1.6	2.2

and Pb with regard to water. From them is seen the decrease, as the electron density in the material in which they are produced, increases.

§ 6. In figure 6 a separate series of figures is given under iron of varying thickness, in order to state the influence of the thickness of the producing layer of iron. It is seen that the number decreases to a greater extent with the thickness than would agree with the decrease of the entering mesons, except that with the greater thickness there is an irregularity which appears to be greater than only the uncertainty of the observations

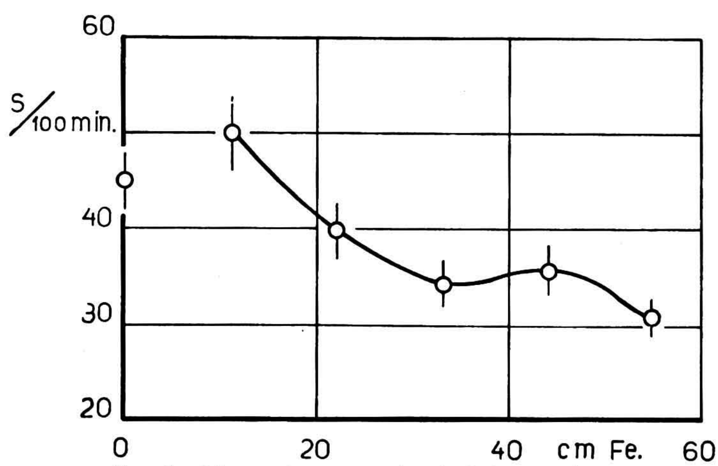

Fig. 6. Meson showers under thick layers of iron.

§ 7. In order to investigate the spreading of the two species of showers an arrangement was made as shown in fig. 2 b. We measured under 70 cm of water, the number was determined when the counters were only separated by 1 cm Pb, and secondly when placed at a distance of 6 cm. The results of the two series of measurements for soft and for hard showers given in table VIII clearly show that the divergence of the meson

TABLE VIII.

Comparison of the divergence of electron and meson showers.

Electron showers (no lead between the counters).

	min.	number	S/min.	
1°—12°	1841	975	0.53	1.00
6°—18°	1362	499	0.37	0.70
For hard showers (10 cm lead between the counters).				
1°—12°	2757	187	0.068	1.00
6°—18°	7593	407	0.055	0.80

showers is greater than of electron showers. This might be expected on the ground of the theory, but after BOTHE and SCHMEISER thought they had found the reverse, WENTZEL (11) investigated what modification must perhaps be made in order to bring the theory in agreement with the phenomena. Therefore it does not seem necessary to insist in this modification.

We will not, as some authors have done, from the decrease of the number of particles with the thickness of the absorbing layer, determine an absorption coefficient with the aid of an exponential absorption formula (12). When one knows the loss of energy of the particles in dependence on the energy, the spectral energy distribution of the entering particles may be deduced from the decrease of the number in layers of increasing thickness (9). This is easy in the case of heavy particles because the loss of energy varies very little with the energy. In the case of known formulas which have been tested in experiment, one should take into consideration the dependence of electrons on energy. For the soft primary rays produced by mesons the distribution is seen not to be exponential, but a proportional to E^{-n}, the value of n but little differing from 1 (10). It will only be possible to make a rough estimate in the case of the small number of shower particles, which can be measured.

In any case, however, it will only be possible to find the decrease of the electrons and the mesons together in thin layers of lead or iron and that of mesons only in thick layers.

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