Narrow Cosmic-Ray Showers

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It has been found that the cosmic-ray particles which occur in showers of small angular divergence are much more penetrating than those of the usual type of shower. The particles in such "hard showers" are clearly not electrons and are interpreted as medium and low energy mesotrons. The second maximum of the Rossi curve, which is accentuated for small-angle shower arrangements, can be accounted for in terms of such showers, produced by mesotrons. Hard showers are present also in the first maximum, probably being produced in this case by the soft component. In the first maximum 34 percent of the narrow showers are ascribed to ionizing primaries, as compared to 75 percent in the second maximum. The number of rays per hard shower is found both by counter and cloud chamber experiments to be small, in most cases, two. Present theory can account for the production of such mesotron showers, though some modification must be introduced regarding the limitation in angular spread of the emitted particles. Maier-Leibnitz and others have obtained evidence for the relatively frequent production of slow, absorbable mesotron secondaries. Because of the much higher rate of production of these mesotrons as compared with those of the hard showers, a different mode of formation may be present; speculation on this point is at present premature.

1. Penetrating Power of Narrow Showers

COSMIC-RAY showers as observed with one of the usual experimental arrangements have found a quantitative interpretation in terms of electrons and photons by the well-known cascade theory of Bhabha and Heitler, Carlson and Oppenheimer. In this connection the beautiful experiments on transition-curves between different materials, carried out by Morgan and Nielsen,[1] may specially be mentioned.

During certain investigations into the structure of cosmic-ray showers, undertaken in our laboratory by means of Geiger-Müller counters some three years ago, we were surprised, however, to observe that under certain conditions there occur secondary particles which are much more penetrating than ordinary shower particles.[2] It was found that the high penetrating power is connected with secondaries of small angular divergence only, the increase in penetrating power being rather abrupt at an angle of approximately 10°.[3]

Probably narrow showers have been observed by some other investigators too; in fact, they are less frequent than ordinary wide angle showers by no more than an order of magnitude. Further investigations into the properties of narrow showers and their connection with other phenomena have led us to consider the possibility that narrow showers are of different nature and origin than ordinary showers.

Figure 1 shows some absorption curves of showers as measured with the standard triple coincidence arrangement reproduced schematically in Fig. 2, for different angles of divergence.[4, 5] It is clearly to be seen that the penetrating power of showers (the half value thickness of lead) increases by about an order of magnitude if the counter arrangement is adapted as far as possible to small angle showers. A theoretical absorption curve, A, is also included in Fig. 1. This is substantially the absorption curve of the soft component of cosmic radiation itself, as calculated by Arley[6] on the basis of the cascade theory. In our case, for a comparison with the experi-

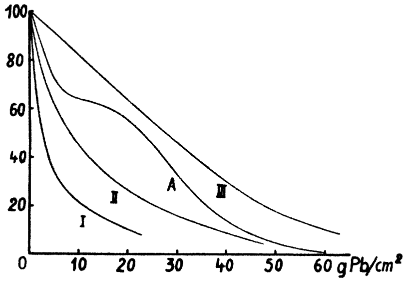

FIG. 1. Absorption curves of showers. I, $\vartheta \approx 60°$; 1.6 cm of lead (Zeiller). II, $\vartheta = 11°$; 1.5 cm of lead (Schmeiser and Bothe). III, $\vartheta = 4°$; 1.5 cm of lead (Schmeiser and Bothe). A, theoretical absorption curve of the soft cosmic-ray component (Arley, ordinates squared).

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[1] K. Z. Morgan and W. M. Nielsen, Phys. Rev. **52**, 564 (1937).

[2] W. Bothe, *Kernphysik* (Züricher Vorträge, 1936), p. 122.

[3] K. Schmeiser, Naturwiss. **25**, 173 (1937).

[4] O. Zeiler, Zeits. f. Physik **96**, 121 (1935).

[5] K. Schmeiser and W. Bothe, Naturwiss. **25**, 669 (1937); Ann. d. Physik **32**, 161 (1938).

[6] N. Arley, Proc. Roy. Soc. London **A168**, 519 (1938).

mental curves, the ordinates of the original Arley curve have been squared. This is necessary with the experimental arrangement of Fig. 2, because *two* shower particles have to pass through the absorber in order to produce a coincidence. It is well known that the soft component consists of electrons and photons. A comparison between the Arley curve and experimental shower curves makes it improbable that the same holds for the narrow showers. On the basis of Arley's calculations one may estimate the primary energy necessary for producing an electron-photon shower of the penetrating power indicated by curve III of Fig. 1; this primary energy comes out to be 10^{11} ev at least. Such particles are extremely rare in cosmic radiation at sea level, whereas penetrating showers are rather frequent. Therefore it seems difficult to account for the high penetrating power of narrow showers by assuming an ordinary cascade process involving electrons and photons only. We have made the assumption that the narrow showers contain mesotrons.

It can also be seen from results obtained in our laboratory that hard showers arise in the free atmosphere.[5] Atmospheric showers were easily detected with counters half a meter apart. Auger and collaborators,[7] and Kolhörster and collaborators[8] observed hard atmospheric showers even with a distance of 20 meters and more between the counters.

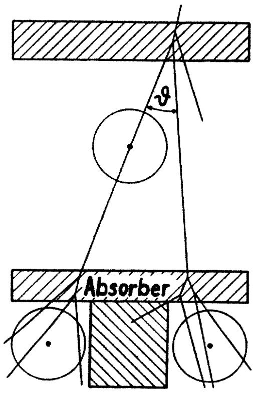

FIG. 2. Standard device for measuring absorption of showers.

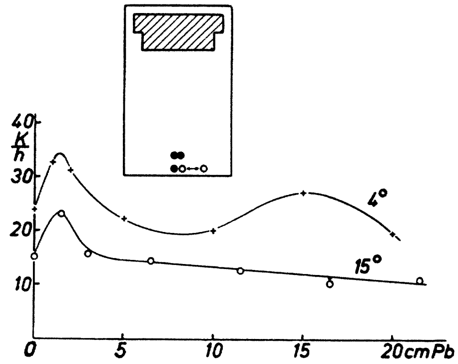

FIG. 3. Rossi curves for different angles of divergence.

2. THE ROSSI CURVE OF NARROW SHOWERS

The high penetrating power of small angle showers was expected to be evident in the saturation curve obtained by plotting the frequency of showers as a function of the thickness of the shower source (Rossi curve). This is exactly what was observed when the Rossi curve was taken for different angles of divergence: at small angles there appears, besides the ordinary "first maximum," fully explained by the cascade theory of electron showers, a well detached "second maximum" at about 17 cm of lead or 30 cm of iron. This effect has been established unambiguously by taking more than a dozen independent Rossi curves, the geometrical and other conditions having been varied in all directions. Two sets of such curves have been published elsewhere.[5, 9] In these experiments the effective angle of divergence was varied by altering the vertical distance between the counter arrangement and the shower producing layer. We have also effected the angular variation by shifting only one of the two lower counters in a horizontal direction. The result of these experiments is shown in Fig. 3. From these curves it is also evident that the second maximum appears only at small angles of divergence.

It must be understood that it is extremely difficult to give a complete quantitative analysis of such curves, the reasons being: the inevitable background caused by showers from the atmos-

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[7] P. Auger and R. Maze, Comptes rendus **207**, 228 and 907 (1938).

[8] W. Kolhörster, J. Matthes and E. Weber, Naturwiss. **26**, 576 (1938).

[9] The second maximum has been observed by several investigators, first by Ackemann and Hummel (Naturwiss. **22**, 169 (1934)), while others failed to find it, because the dependence on the angle of divergence was not known at that time.

phere and surrounding objects; the rather complicated geometric conditions; and, finally, the circumstance that ordinary soft showers are produced by the hard shower particles.[5] Therefore, stress can be laid only on the rise of the curve beyond the first maximum and the relative height of the second maximum, for this cannot be explained away by any assumptions concerning the background.

The second maximum of the Rossi curve is a direct proof for the generation of secondary particles penetrating through 17 cm of lead or more. These particles cannot be electrons; it appears most reasonable to interpret them as mesotrons.

Taking the relative height of the second maximum as a measure for the relative frequency of hard showers, it could be concluded that hard showers are produced in thick layers of matter by the hard component of cosmic radiation at a rate approximately proportional to the atomic number of the shower source.[5, 10]

4. NUMBER OF PARTICLES IN A HARD SHOWER

If, in an arrangement of the type Fig. 2, adapted to a small angle of divergence, the two lower counters are replaced by three or four, and four- or fivefold coincidences are counted, the frequency of coincidences is reduced to a small fraction.[5] From this it was concluded that, generally, a hard shower is composed of very few particles only.[11] Recently H. Maier-Leibnitz,[12] using a "slow" cloud chamber, has obtained 67 photographs of narrow showers originating in a layer of 5 cm of lead. Table I gives the frequency of these hard showers as a function of complexity. It is seen that 90 percent or more of all hard showers contain two particles only.

TABLE I. *Frequency of hard showers of given complexity (Maier-Leibnitz).*

Number of particles	2	3	4	10
Number of showers	63	2	1	1

If the penetrating showers coming from thick layers of lead were built up of electrons and photons in the same way as soft showers are, one would expect that they would generally contain far more particles than soft showers. The fact that the contrary is true lends further support to the assumption that mesotrons play an important rôle in hard showers.

5. THE NATURE OF THE SHOWER PRODUCING RADIATION

Several authors[13] have dealt with the question whether the shower producing radiation is mainly of an ionizing or non-ionizing type. The results obtained so far show very poor agreement and, in part, seem to contradict each other. We felt that here again the angle of divergence might be of considerable influence. K. Schmeiser[14] has recently made an attempt to go somewhat deeper into this matter, applying the counter arrangement shown in Fig. 4. The fourfold coincidences (1345) and (2345) and the fivefold coincidences (12345) were recorded simultaneously. This somewhat intricate method has the great advantage that reliable corrections may be determined for the background showers and their absorption by the shower producing layer. Allowing for the background, the ratio of frequencies of (12345): (2345)—coincidences may be identified with the fraction of showers produced by ionizing primaries. Table II shows that this fraction depends on ϑ, the angle of divergence, as well as on the thickness of the shower producing layer.

Considering that in the second maximum of the Rossi curve hard showers can only be produced by the hard component of the cosmic radiation, it may be concluded that most of these showers are generated by charged mesotrons, and the rest possibly by neutral mesotrons. The existence of neutral mesotrons in cosmic radiation is also indicated by earlier observations of Maass.[15]

In the first maximum of the Rossi curve the

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[10] K. Schmeiser and W. Bothe, Naturwiss. **25**, 833 (1937).

[11] In generalizing this observation, it may be expected that the second maximum of the Rossi curve may be suppressed to a certain extent by using any fourfold, instead of triple coincidence arrangement, because such an arrangement would tend to favor the complex soft showers. Observations of this kind have been made by a few investigators.

[12] H. Maier-Leibnitz, Zeits. f. Physik **112**, 569 (1939).

[13] B. Rossi, Zeits. f. Physik **82**, 151 (1933); Thos. H. Johnson, Phys. Rev. **45**, 569 (1934); H. Geiger and E. Fünfer, Zeits. f. Physik **93**, 543 (1935); J. Clay and A. van Gemert, Physica **3**, 763 (1936).

[14] K. Schmeiser, Zeits. f. Physik **112**, 501 (1939).

[15] H. Maass, Ann. d. Physik **27**, 507 (1936); N. Arley and W. Heitler, Nature **142**, 158 (1938).

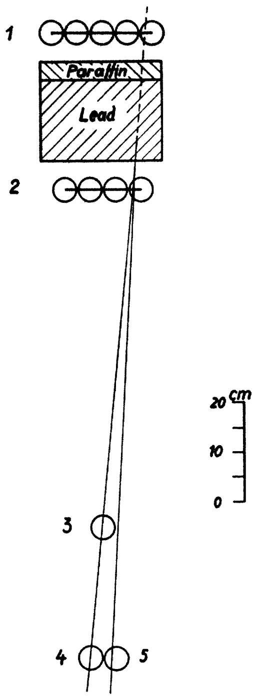

FIG. 4. Device for determining nature of shower producing radiation (Schmeiser).

narrow showers are also predominantly of the penetrating type, as shown by the absorption curve.[5] But these hard showers are obviously generated in the main by a non-ionizing radiation, presumably photons. This assumption would account for the existence of a first maximum for hard showers also.

The evidence indicates that about $\frac{2}{3}$ of the soft showers ($\vartheta = 21°$), are generated by ionizing particles (electrons), and $\frac{1}{3}$ by a non-ionizing radiation (photons). This is about what would be expected from the cascade theory of electron showers.

6. THEORETICAL INTERPRETATION OF HARD SHOWERS

The whole of the experimental evidence indicates that hard showers are built up substantially of a small number of mesotrons of medium energy, released mainly by charged or neutral fast mesotrons in a nuclear reaction. Reactions of this kind have been studied from a theoretical viewpoint by Heitler.[16] Though the present state of theory does not allow one to make precise statements, the order of magnitude of the mean free path, λ, of a primary mesotron for production of a "two mesotron shower" can be calculated and comes out to be a few centimeters of lead. On the other hand, coincidence measurements as well as cloud-chamber experiments indicate a λ of as much as 200 cm of lead. Moreover the Heitler theory is unable to explain the small angular divergence of mesotron showers as observed by both of these methods.

A successful attempt to remove these difficulties has been undertaken by Wentzel.[17] It is well known that the Yukawa theory breaks down for energies as high as those occurring in cosmic radiation. In the theory of Wentzel this fact is accounted for by introducing a plausible "cutting off" rule. This leads automatically to a certain restriction of mesotron showers to an angular spread of a few degrees only. At the same time the mean free path, λ, comes out to be a few meters of lead, which seems to be compatible with the experiments.

Wentzel has further shown, that the production of narrow mesotron showers by *photons*, as probably observed in the first maximum of the Rossi curve, can also be understood by a corresponding argument.

These theoretical considerations seem to lend additional support to the interpretation of experimental results of narrow showers in terms of mesotrons.

7. SLOW SECONDARY MESOTRONS

Several investigators have observed cloud tracks of relatively slow mesotrons. On the whole, about a dozen mesotron tracks have so far been identified. This number appears small, but it must be considered, that a fast mesotron must first be slowed down to a residual range of no more than a few meters of air in order to be distinguished safely from an electron.

TABLE II. *Nature of shower producing radiation (Schmeiser).*

ANGLE OF DIVERGENCE	THICKNESS OF SHOWER SOURCE, CM OF LEAD	PERCENTAGE OF SHOWERS PRODUCED BY IONIZING RADIATION
3°	15.0	75±3
3°	1.5	34±8
21°	1.5	67±2

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[16] W. Heitler, Proc. Roy. Soc. London **A166**, 529 (1938).

[17] G. Wentzel, Phys. Rev. **54**, 869 (1938).

Recently H. Maier-Leibnitz,[12] using a "slow" cloud chamber covered by 5 cm of lead immersed in a magnetic field, has obtained evidence that mesotrons with ranges of no more than 0.15 cm of lead occur rather frequently. These are to be interpreted, most probably, as secondaries. Maier-Leibnitz observed five mesotron tracks ending within the effective volume of the cloud chamber. The total of the effective time of expansion (35 min.) and the total length of observed cosmic-ray tracks being known, it can be shown that 0.004 mesotron are stopped per hour per cm^3 of air, or one mesotron for every 70 meters of cosmic-ray track in air. These mesotrons cannot be identified with those composing the hard cosmic-ray component itself, for this would involve an absorption path of 70 cm of air or 1.5 cm of lead only, which is far too low a value. It may be assumed that these slow mesons are secondaries produced by the hard component. Then a simple calculation shows that the length of 1.5 cm of lead may be interpreted as the sum of the mean free path of a primary for production of a secondary, and the mean range of the secondaries. Both of these lengths therefore must be smaller than 1.5 cm of lead. Similar conclusions may be drawn from experiments of Williams and Pickup and of Kunze.

Further evidence concerning the production of slow secondary mesotrons may be obtained from cloud chamber experiments with thick metal plates within the chamber. Several authors[18, 19] have observed, that a few percent of hard cosmic-ray particles, after having penetrated a few centimeters of lead or copper, are accompanied by secondary particles. These secondaries may be either electrons, released by a Bhabha collision process, or mesotrons of the kind observed by Maier-Leibnitz. In the latter case the range of the secondary mesotrons could obviously not be greater than a few percent of 1.5 cm, or approximately 0.15 cm of lead. It is not easy experimentally to distinguish between these two possibilities. A simple criterion would be the thickness of the plate necessary to obtain the maximum percentage of secondaries. For Bhabha electrons, and electron showers produced by such electrons, more than 1 cm of lead would be required to obtain "saturation," whereas for secondary mesotrons 0.15 cm would be sufficient. Experiments of this kind have been performed only recently by Hopkins, Nielsen and Nordheim.[19] These authors state that 0.3 cm of lead, or less, are sufficient for obtaining a maximum of secondaries. This result, if confirmed by further experiments, would be in favor of the interpretation of secondaries as consisting, partly at least, of slow mesotrons.

In the generation of a secondary mesotron energy is absorbed to an amount of 7×10^7 ev or more. Therefore the primary mesotron will suffer an additional absorption of about 5×10^7 ev per cm of lead. In fact, it has been observed that the energy of fast cosmic-ray particles is absorbed at a rate considerably higher than can be explained by radiation and ionization losses. According to Blackett and Wilson[18] the observed energy loss may reach values up to 35×10^7 ev per cm of lead. It seems not unreasonable to assume that the production of secondary mesotrons plays an important part in the absorption of fast mesotrons. Considering the possibility that *neutral* mesotrons may also be produced, it is perhaps not so hard to understand that fast mesotrons frequently suffer a considerable energy loss in a thick metal plate without any secondary ray becoming visible, as observed by several investigators.

The question arises, whether there is any connection between slow secondary mesotrons and mesotron showers. Slow secondaries with a range of 0.15 cm in lead have an energy smaller by about an order of magnitude while their rate of production is about 100 times higher than that of mesotron showers. Therefore, if both were produced by the same Heitler process discussed above, the spectrum of shower mesotrons would have a steep descent in the direction of increasing energy. Such a spectrum can perhaps not easily be understood on the basis of the considerations of Heitler and Wentzel. Perhaps a different process is responsible for the production of slow mesotrons. But probably such considerations should be postponed until more experimental and theoretical information is available.

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[18] P. M. S. Blackett and J. G. Wilson, Proc. Roy. Soc. **A160**, 304 (1937); J. G. Wilson, Proc. Roy. Soc. **A166**, 482 (1938); Nature **142**, 73 (1938).

[19] J. I. Hopkins, W. M. Nielsen and L. W. Nordheim, Phys. Rev. **55**, 233 (1939).

Another point of interest is the radioactive decay of the mesotron predicted by the theory of Yukawa. In the five slow mesotron tracks ending within the chamber volume, observed by Maier-Leibnitz, there is no indication of a decay electron. It seems that the evidence which other investigators have obtained concerning this point, is also rather meager.[20] Therefore, it may be supposed that, for slow mesotrons, there exists another mode of annihilation.

CONCLUSION

Though further evidence is required on some of the points mentioned above, there are several experimental facts which may be explained in the simplest way by assuming production of secondary mesotrons of medium or low energy by the fast mesotrons of the hard cosmic-ray component, and by photons:

1. Generation of narrow, penetrating showers by the hard component (second maximum of the Rossi curve), and by a soft non-ionizing radiation, probably photons (first maximum of the Rossi curve);
2. Occurrence of stopped mesotrons at a considerable rate;
3. High energy losses of fast mesotrons in metal plates, frequently not connected with observable secondaries.

This interpretation is not out of harmony with present theory.

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[20] P. Ehrenfest (Comptes rendus **206**, 428 (1938)) has obtained a photograph which probably has to be interpreted as a mesotron entering the wall of the cloud chamber, and the decay electron leaving the wall.

DISCUSSION

W. M. Nielsen and J. E. Morgan, *Duke University* AND **K. Z. Morgan,** *Lenoir Rhyne College:** Measurements have been made of 7° and 28° cosmic-ray shower production in iron up to thicknesses of approximately 320 g/cm. A comparison of the data here presented and measurements previously reported for 38° showers leads to the conclusion that there is no significant difference in the ratio of counting rates at the first maximum of the Rossi transition curve to that under 200 g/cm for either large or small angle showers. It is concluded that the processes which are responsible for the character of the transition curve under large thicknesses of material are not necessarily restricted to small angles.

J. Clay, *Amsterdam:* To check the results of Professor Bothe, Mr. Jonker and I tried to find the second maximum of showers under lead by taking small angle showers. We placed one counter directly under the lead and two counters so far below that we could measure the showers with a maximum deviation of 7.2° and of 3.9°. (See Fig. 1.) The measurements were extended so long that we had about 1600 coincidences for every point; so that we have an uncertainty of about 2 percent for each point. The indication of the second maximum is there, but smaller than in our earlier observation with the larger angles. We do not find the second maximum as large as did Professors Bothe and Schmeiser.

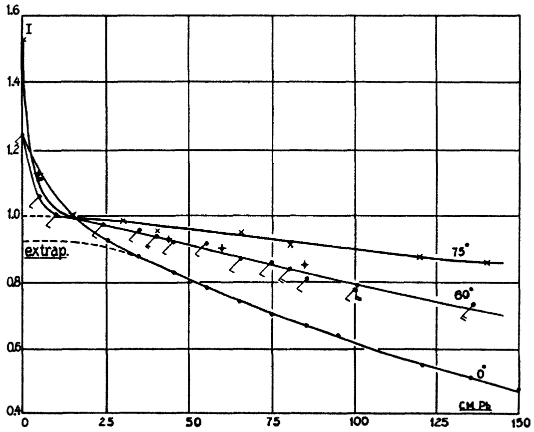

FIG. 1.

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* Cf. Phys. Rev. **55**, 995 (1939) for complete paper.