The Energy Spectrum of Cosmic-Radiation Particles and Photons

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SHORTLY after the discovery of cosmic radiation it became clear that there were two components, a hard penetrating component and a much softer and more absorbable one, which was nearly totally absorbed by 10 cm of lead. In the beginning the latter radiation was called surrounding rays (Umgebungstrahlung[1]). After 1932 it became evident that both radiations were corpuscular, and we thought the penetrating rays were protons (but later on they turned out to be mesons), and the more absorbable ones electrons.

PRODUCTION OF KNOCK-ON ELECTRONS

For a time opinions differed as to whether there was a close relation between the two rays or not. It seemed that there was not, because the proportion of their intensity changed very much with height. But when it was found that under thick layers of water the soft component always accompanied the penetrating one,[2] it became obvious that the soft component was a secondary effect of the penetrating one. Now there are three possibilities regarding the origin of the soft component at sea level. The first to suggest itself was that part of it might have its origin outside the earth or in very high layers. Today this possibility is, I think, no longer acknowledged, but two other possibilities remain. The first is that the electrons are produced by mesons by knock-on processes, and the second that they result from decay processes of mesons. We tried to find the origin of both groups and also the energy spectrum of the electrons, i.e., because the latter is an indispensable element to prove the cascade theories. Hence we made a systematic investigation (Fig. 1), of the cascade processes in five different materials (Al, Fe, Pb, Hg, and Au). At first we dealt with the production of the electrons by knock-on processes and this was done for Pb, Fe, Al, H_2O, and C (Fig. 2).[3] In order to separate the two processes of production and absorption, the production was measured in very thin layers, and from these results, combined with the absorption measurements in thin sheets, we could conclude, firstly, that the production is directly proportional to the number of the electrons in the material (Fig. 3) and, secondly, that the number of electrons accompanying the primaries in a thick layer (where they are in equilibrium with the primaries) is reversedly proportional to z, because the absorption is proportional to z^2, z being the atomic number. Figure 4 gives the relation of the production to the number of electrons contained in different materials.

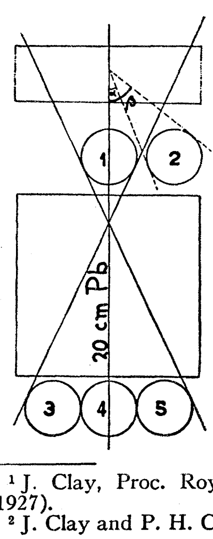


FIG. 1. Arrangement of the counters in order to measure the production of secondary electrons by mesons.

We then proceeded to investigate the number of electrons produced in the atmosphere in order to know the spectrum of the electrons in free air.[4] Therefore, it was necessary to measure the number of secondaries on a surface small in relation to the distance of the primary meson which produced the electron. We used hereto the arrangement given in the graph (Fig. 5), with the four crossed counters and measured fivefold coincidences. The distance was, in this case, that from A to $D=B$ to C and the surface was four times the hatched surface (Fig. 6). We found that the

[1] J. Clay, Proc. Roy. Acad. Amsterdam, Ece. *XXX* (1927).
[2] J. Clay and P. H. Clay, Physica 2, 551 (1935).
[3] J. Clay and A. Venema, Physica 10, 735 (1943).
[4] J. Clay, Physica 13, 433 (1947).

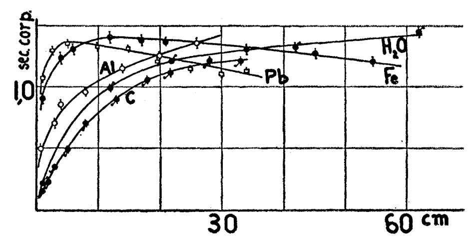


FIG. 2. Production of secondary radiation in layers of different materials.

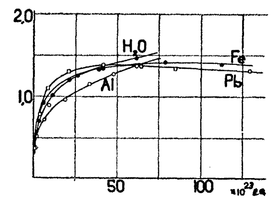


FIG. 3. Production of secondary radiation in different layers with equal quantity of electrons.

number decreased exponentially with the distance to the primary meson (Fig. 7) and could calculate the total number of coherent electrons surrounding the meson. The absorption could be measured as well, and a correction could be made for coherent mesons by putting 10 cm Pb between the counters (1, 2) and (3, 4). In three sets of measurements we found that the production of electrons by collision in the air was 18 percent, 12 percent, and 9 percent.

The coherence of mesons turned out in one series about 100 percent and in another 41 percent, which means that practically all the mesons produced in one process come down by two's and more.

A long series of measurements was made by producing the secondaries in a plate of 2 cm of Fe and measuring the absorption spectrum in four different directions. From these data (Figs. 8 and 9), the energy spectrum could be derived with the help of a method which will be described below. The result appears to contain an effect which we have not been able to explain thus far, for when we apply the laws of energy and impulse, as seems to be justified by Wilson chamber photographs, the energies found are much too high.

We also investigated the production and coherence of photons, but here we obtained results which are still unexplained.

DECAY ELECTRONS

As mentioned above, we found that about $\frac{2}{3}$ of the particles in the electron component are knock-on electrons. We then tried to find the decay component. For this purpose, experiments were performed by Clay and Swiers with two sets of counters side by side, both of which had very great resolutions, *viz.*, 0.25×10^{-6} sec. The impulse of the set A was delayed by a kappa-cable of 150-m length, the delay being 0.7×10^{-6} sec. This arrangement made it possible to record the coincidences of two particles, one in A and one in B, in which the one in B comes 0.7×10^{-6} sec. or more later than the one in A. We thus registered the presence of a meson in A and the decay electron of a meson produced by the first. That this was the case could be demonstrated. Ten cm of Pb above A caused hardly any difference in the number of coincidences, but 10 cm of Pb above B reduced the number to about zero.

Then the decrease was measured with the distance r and, as it could be considered as nearly exponential, the total number of decay electrons could be measured in relation to the mesons in the center, which proportion amounted to 7 percent.

ENERGY SPECTRUM OF ELECTRONS

Now that we know the origin of the electron component, we may give the result of our measurements of the energy spectrum. These measurements were published in 1940.[5] They consisted in the absorption measured by threefold coincidences with layers of different material between the counters, *viz.*, Pb, Fe, Al, H_2O, and paraffin. The results are given in Fig. 10. Preliminarily, we may mention that Mr. Scheen,[6] assistant of our

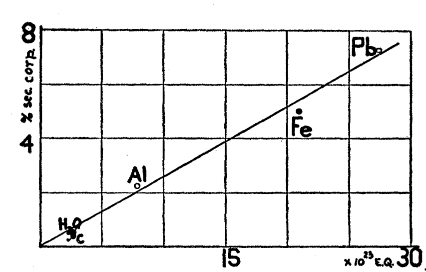


FIG. 4. Production in very thin layers of different material in relation to the electron density.

[5] J. Clay, Proc. Roy. Acad. Amsterdam **43**, 1260 (1940).
[6] W. L. Scheen, Physica **13**, 669 (1947).

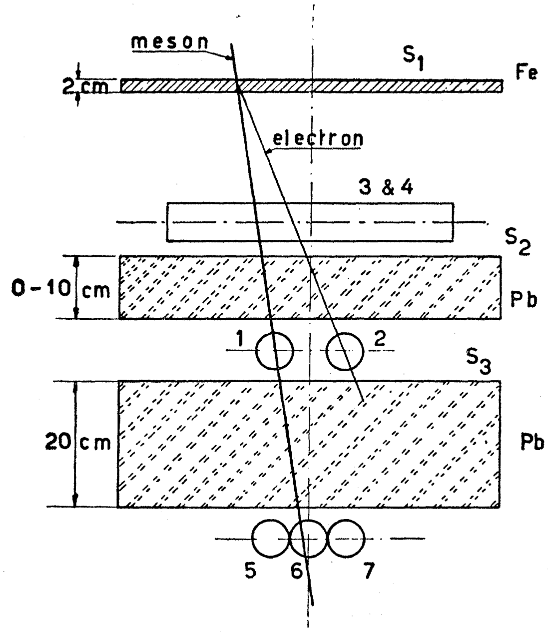


FIG. 5. Arrangement of the fivefold coincidence apparatus to count the secondaries produced by different material.

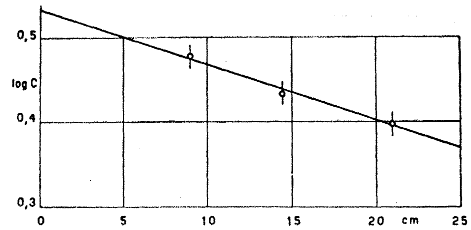


FIG. 7. Logarithmic decrease of the number of coincidences of the secondaries in the air in relation to the distance from the penetrating meson.

laboratory, succeeded, with the help of the cascade theory, in finding a formula for the range of the electron and its secondaries in different materials, given by $\lambda = 1/\beta 1g(1+\beta E)$ in which λ stands for the thickness of the layer expressed in Furry units and E for the energy expressed in the critical energy for the material. β is a constant slightly dependent on the energy, but can be taken as approximately $\frac{1}{4}$.

I have explored earlier[7] the relative absorption of mesons in different materials by measurements in large columns. This absorption proved to be not strictly mass proportional. We know it for water, aluminum, iron, and lead, and for these materials we can construct the curves for equal meson absorption. To this end we take, for example, the absorption curves for Pb and Al (Fig. 11), and we reduce Al so that the absorption for the meson is the same as for Pb. Then we find two points A and B, 30 cm Al and 10 cm Pb, for which the absorption of the mesons is the same. The difference AB gives us directly the number of electrons which were absorbed in 10 cm Pb and not in 30 cm Al. The energy for a range of 10 cm Pb is 8×10^{10} ev; for 30 cm Al it is 3.7×10^{8} ev.

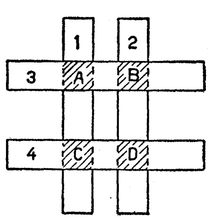


FIG. 6. Arrangement of the crossed counters.

Then we take the point C on the Pb curve, which gives the range in Pb for electrons of 3.7×10^{8}-ev energy. The absorption for mesons in 11 cm Al is the same. This means the difference CD gives us the number of electrons between 3.7×10^{8} and 7.8×10^{7} ev.

We proceed to E in Pb for the same energy 7.8×10^{7}, and EF is the number of electrons between 7.8×10^{7} and 4.0×10^{7} ev. Ultimately we find that from a total of 120 per minute the particles absorbed in 10 cm Pb number 25 in all. Of these, 18 are electrons and 7 are slow mesons with energies up to 1.6×10^{8} and the differential energy spectrum (Fig. 12) for the electrons is

$$N = N_0 E^{-1.27}.$$

This differs fundamentally from what is usually assumed, but it is not very different from what we have calculated earlier with less careful experiments. Essential, however, is the fact that the absorption for water gives us reduced points, which are nearly coincidental with those of Al. This means that the absorption of electrons and slow mesons happens in the same proportion and, since also the lower part of the spectrum of the electrons is found to be the same, this is a proof of the exactness of the result. The result calculated from measurements in Fe and C give a spectrum $N = N_0 e^{-1.35}$.

Here we may quote the publication of Williams,[8]

[7] J. Clay and A. G. M. van Gemert, Physics 6, 649 (1939).

[8] E. J. Williams, Proc. Roy. Soc. A172, 194 (1939).

who measured the energies of electrons in the Wilson chamber, and when we take his results from the five different groups in question, we find the spectrum $N = N_0E^{-1.13}$.

With regard to the results of Anderson and Neddermeyer,[9] who reported upon the energy spectrum of the electrons found in the Wilson chamber, we find that the line in the graph given by $N = N_0E^{-2.0}$ gives a good account of the integral spectrum. For the spectrum in Pasadena, we can calculate from their results $N = N_0E^{-1.2}$ for energies <50 Mev and $N = N_0E^{-2.0}$ for energies >50 Mev.

We later repeated the experiments in another part of the laboratory which has a flat concrete roof, and we find that here the spectrum of the electrons is totally different. There has been a cascade multiplication in the layer, and the amount of low energy electrons is much bigger.

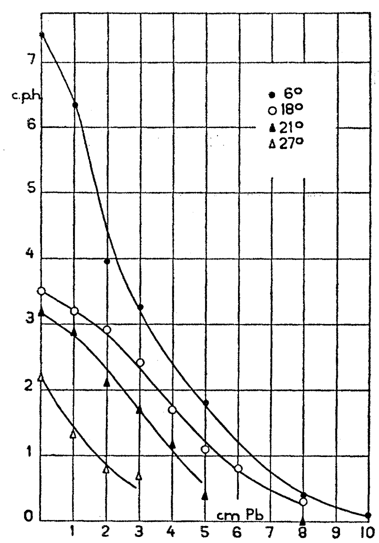


FIG. 8. Decrease in lead by absorption in four directions of the number of secondary electrons produced in iron.

Our earlier mentioned measurements were made under a very thin wooden roof. At present, the latter are being repeated with a set of counters of very great surface constantly controlled by an extra set next to it. We have measured also the secondary radiation under thick layers of different material, and we find a very reduced percentage—especially under dense material.[10] We may, however, draw attention to the phenomenon that for very thick layers of material the number of secondaries increases again and reaches a maximum under layers of matter of 300 to 400 m water equivalent. It must be assumed that the production processes of secondaries will more and more increase as the mean energy of the meson increases, and we think it is most probable that we here come in the energy region where the radiation process of the mesons might play an important role. The amount of secondaries indicates that the spin of the meson with an absorption as was calculated lately by Bernardini is 1 and not 0.

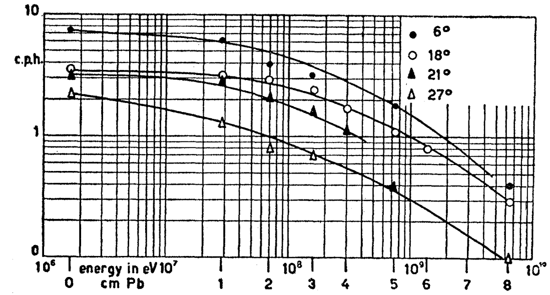


FIG. 9. Absorption and energy spectrum of secondary electrons produced in 2 cm Fe by mesons in four different directions.

NUMBER OF PHOTONS

We will now consider the photon component of the radiation. The photon component is mostly neglected by experimenters of cosmic radiation, because of the difficulty of detecting them with counters and because they are not seen in the Wilson chamber. We know that a very low per-

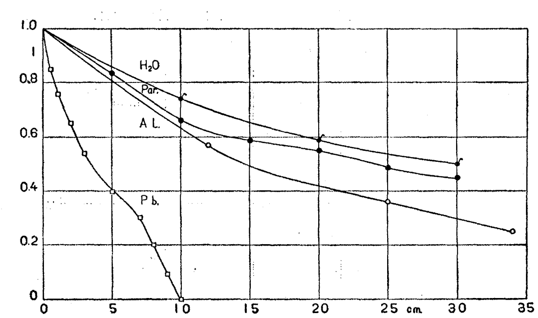


FIG. 10. Absorption of the electron component in Pb, Al, paraffin, and H_2O.

[9] C. D. Anderson and S. H. Neddermeyer, Phys. Rev. **50**, 263 (1936).

[10] J. Clay, Rev. Mod. Phys. **11**, 128 (1939).

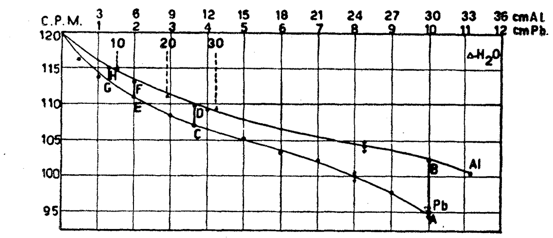


FIG. 11. Absorption of the complex radiation in Pb, Al, and H_2O. The difference gives the number of electrons between known energies.

centage of the photons give a Compton electron in the wall of the counter and discharge it. So the following experiment was performed by Clay and Levert.[11] Three counters were set in a pile (Fig. 13). The number of twofold coincidences was measured in 1 and 3, the threefold coincidences in 1, 2, and 3. The number of discharges in one counter was measured as well, and this was done separately in different directions. The distribution of the photons could be found along the vertical. It was a mathematical problem to find the integral value of the photon radiation in an angle just equal to the angle limited by the cone of the two- and threefold coincidences. The calculations are given by C. Levert in his thesis. From the three values S(imple), D(ouble), and T(hreefold) coincidences, and the number of C(orpuscles) and of P(hotons), the efficiency λ can be derived because $S=C+\lambda P$. $D=C+\lambda^2 P$ and $T=C+\lambda^3 P$. λ is small, so that $T=C$ and from the first two values (3 percent and 6 percent) λ and P can be found. This was done for eight different directions from 0 to 90° with the vertical, and the distribution of photon radiation and of corpuscular radiation could be calculated. We found that the proportion from photons to cor-

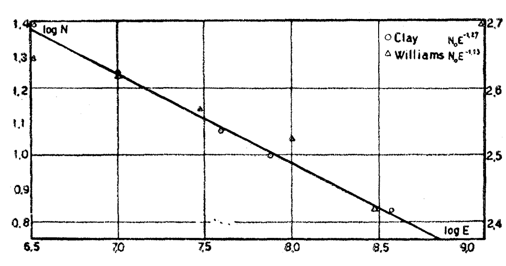


FIG. 12. ○ Clay energy spectrum, power law exponent is 1.27. △ Williams spectrum taken from cloud-chamber measurements in a magnetic field.

[11] J. Clay and C. Levert, Physica 9, 158 (1942).

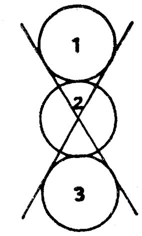


FIG. 13. Clay and Levert. Arrangement of counters to find the photon component.

puscles strongly increases with the angle with the vertical (Fig. 14). For 0° it is 10 and for 90° it is 60. The value of the distribution, if δ is the angle with the vertical, is $C=0.016+0.50\cos^2\delta$ and $P_\delta=1.17+4.27\cos^2\delta$. λ is between six percent and four percent. The total incoming photons from all sides on 1 cm^2 is 9 per minute and for corpuscular rays $0.81/min/cm^2$.

We then made a special investigation, as was also done by Janossi and Rossi,[12] for high energy photons by the arrangement[13] given in Fig. 15. A

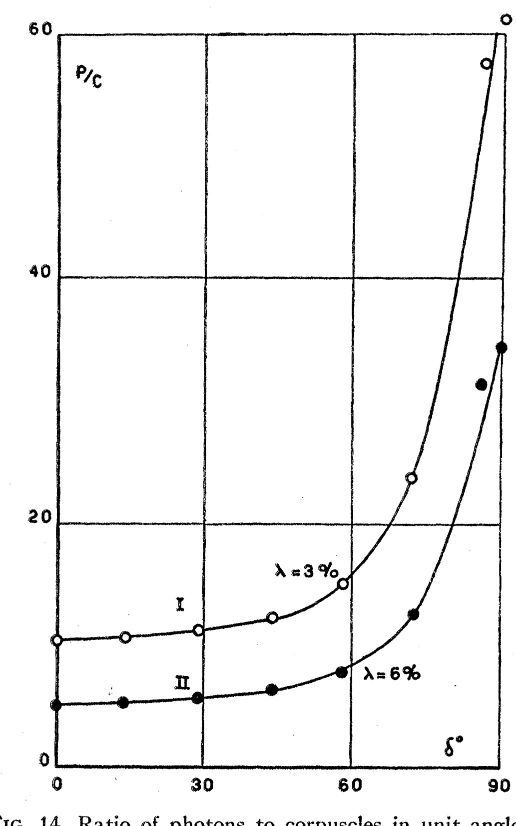


FIG. 14. Ratio of photons to corpuscles in unit angle in relation to zenith angle for two λ-values.

[12] L. Janossi and B. Rossi, Proc. Roy. Soc. A175, 88 (1940).
[13] J. Clay and C. Levert, Physica 12, 32i (1946).

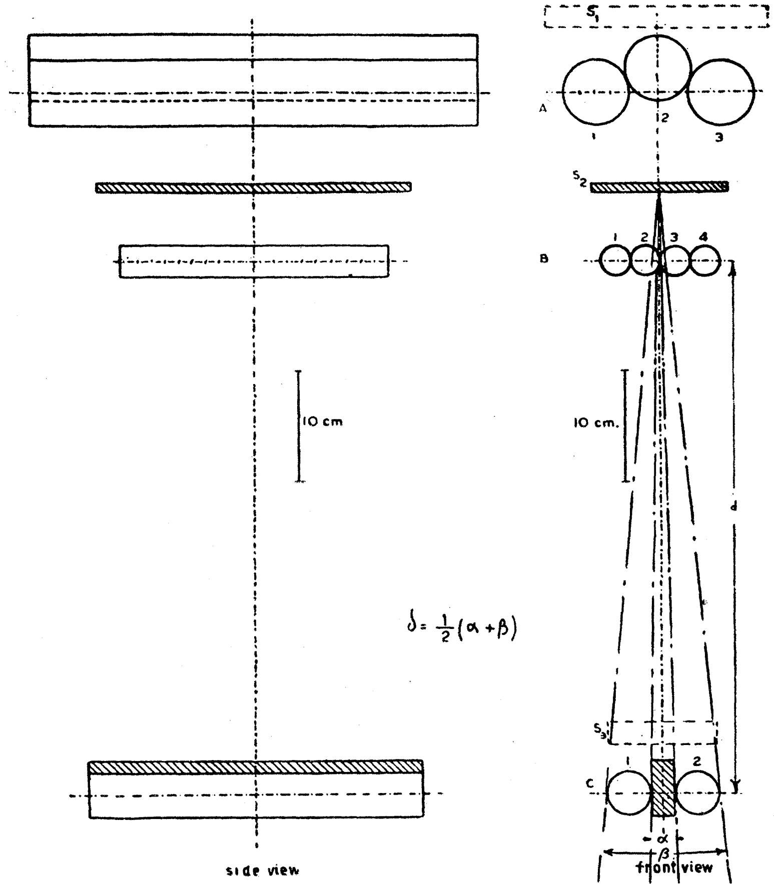


FIG. 15. Arrangement of the counters in front and side view.

number of three- and fourfold coincidences were made, and the influence of the thickness of the production layer S_2, of the absorption layer S_1 for the producing particles, and of the absorption layer of the produced particles S_3 was investigated. The particles which were produced where a photon was concerned as primary could have been Compton electrons, when the counters C were in series. So a distinction was made between the two cases and, in both, the absorption of the producing photon could be measured by S_1. That we were concerned with photons was proved by the fact that the particles did not discharge the counters A. By this effect we could separate the number of cases where one corpuscle of high energy had produced a pair from the cases where a photon was the producer. The outcome was that the number of high energy photons stands to that of the high energy corpuscles as producers of an electron pair as 70 to 30. The absorption coefficient for the high energy photons which give a pair in S_2 is 1.05 cm^{-1} Pb. This is four times the value of the coefficient for the lower energy photons 0.29 cm^{-1} Pb, which give a Compton electron (Fig. 16).

ENERGY SPECTRUMS OF PHOTONS

For the region between 10^6 ev and 10^7 ev, we may take the absorption coefficient to be inversely proportional to the energy. In this case, when we suppose that the number of the incident photons is given by $N = N_0 E^{-s}$ and $\lambda a/E$ is the absorption in the layer a, the number of the photons penetrating through S_1 is

$$N_0 \int_0^P E^{-s} e^{-(\lambda/E)a} dE.$$

As we have found by absorption experiments, P is the critical energy for which the production

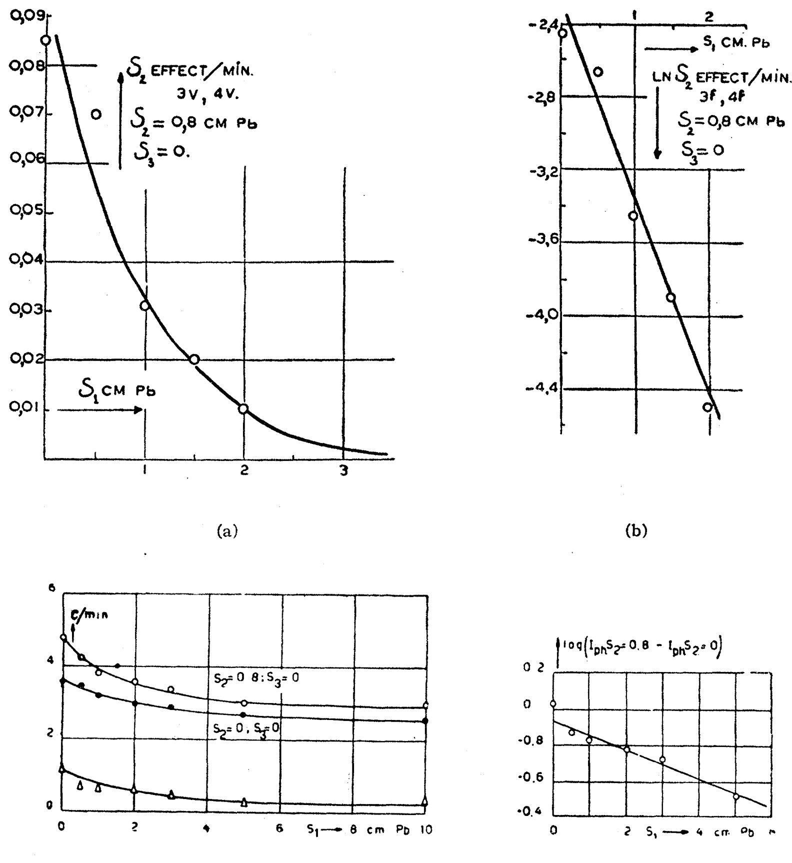


FIG. 16. (a) Absorption of photons in S_1 (Pb) which produce electron pairs in 0.8 cm Pb. (b) Logarithmic decrease of electron pairs produced by photons in 0.8 cm Pb by the influence of a layer of lead S_1 from 0 to 2 cm Pb. (c) Absorption of photons in S_1 (Pb) which produce Compton processes in S_2=0.8 cm Pb. (d) Logarithmic decrease in Pb of Compton electrons produced in 0.8 cm Pb.

of pairs is stated and is $P=10^{+7}$ ev. From every two values of a the value of S_1 can be calculated, and we find, in this way, for $a_1=1$ cm Pb and $a_2=2$ cm Pb $S=1.27$. So this is the same spectrum as that for the corpuscles. For values of the energy above the critical energy which is about 10^7 ev for Pb, the absorption coefficient is about proportional to the $\log E$ for energies up to 5×10^8 ev and can be taken to be $\alpha \log E+\beta$. For

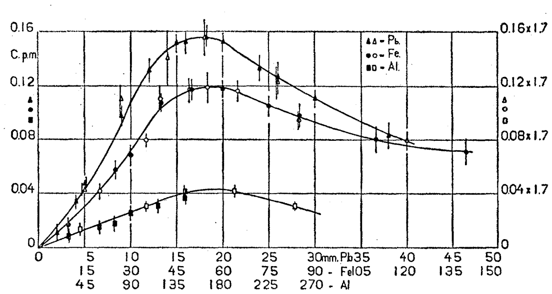


FIG. 17. Clay and Jonker. Fourfold coincidences in Pb, Fe, and Al.

absorption values under a layer a we get

$$N_0\int_P^\infty E^{-S_1}\cdot \exp[-(\alpha \log E+\beta)a]dE.$$

By taking the relation P for the values under $a_1=1$ cm and $a_2=2$ cm, we find $S_1=1.1$. The values for α and β for Pb were taken in accordance with the theoretical values given by Heitler (*The Quantum Theory of Radiation*, p. 216). This means that we may say that there is conclusive evidence for the energy spectrum of the photons being of the same sort as that of the electrons.

SECOND SHOWER MAXIMUM

We mentioned above that we made a series of experiments about the shower curve in different materials. Clay and Jonker[14] have given a systematic report about the curves for 2, 3, and fourfold showers in Al, Fe, and Pb (Fig. 17). After-

[14] J. Clay and K. H. J. Jonker, Physica 7, 921 (1940).

wards, the investigation was extended by Clay and Scheen to Hg and Au, and these last two materials were especially tested with a view to the much discussed problem of the second maximum. In course of time, we investigated this problem in different ways and by ionization measurements which had an accuracy of 0.5 percent we arrived at the certainty of the existence of this second maximum under a layer of lead of about 15 cm Pb. We got the same result when using counters. From the experiment on the subject of the knock-on electrons by mesons we expected to find the best results with the densest materials, so we tested the production in Hg and Au layers (Figs. 18 and 19). We measured two-, three-, and fourfold coincidences for two dis-

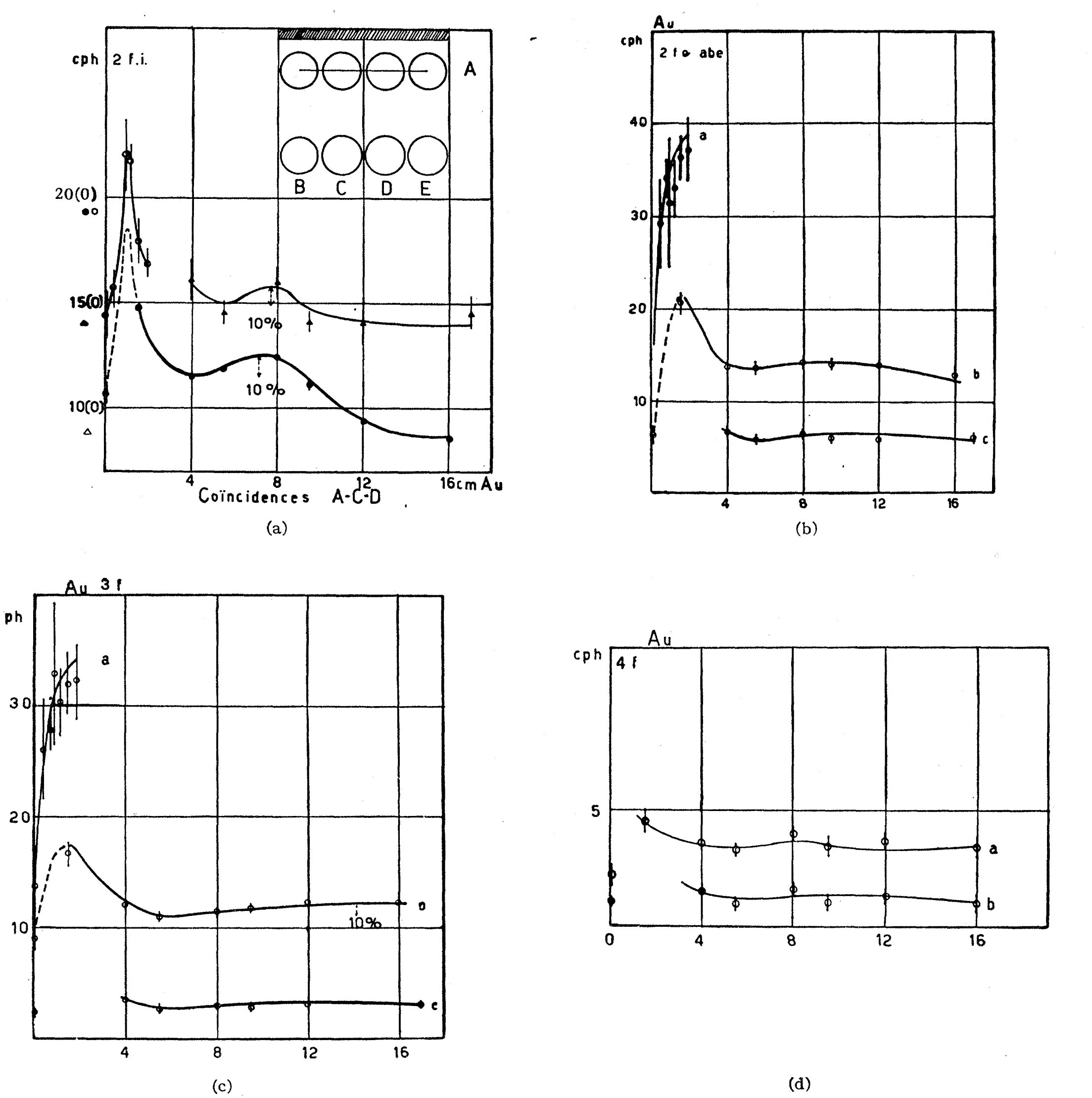


FIG. 18. Second maximum in the shower curve under gold. (a) Two particles (threefold inner coincidences A, C, D) two lines, the higher line for the counters 20 cm under the gold layer, scale 10. The lower line for 8.5 cm in distance, scale 100. The values were taken in the Cellar cf the Bank. The left part of the line above was taken in the free atmosphere at a distance of 20 cm under the plate. (b) Two series of values for two particles (threefold outer coincidences of A, B, E) Distance for a and b 8.5 cm under the plate, a in the free atmosphere, b in the cellar, c for a distance of 20 cm under the plate. (c) Shower curves for 3 particles (fourfold coincidences A, B, C, D), a and b for a distance of 8.5 cm under the plate. a in the free atmosphere, b in the cellar, c for a distance of 20 cm under the plate. (d) Shower curves for 4 particles (fivefold coincidences A, B, C, D, E). a for 8.5 cm under the plate, b for 20 cm under the plate.

tances in the same time. We got results of perfect clearness, and the circumstance that our layers of gold had only a small surface 22.3 by 13.4 cm and that we made the Hg and Pb surfaces of the same extension proved to be favorable for the experiments. We found with lead that the best results were obtained with small surfaces. Herewith we give the curves for the different cases (Fig. 20). To our knowledge no attempt has been made thus far, to explain this effect, perhaps because its existence has been denied by most of the experimenters. We think that a maximum will be reached with a thickness x, when the decrease of production by absorption of a layer dx is compensated by an increase of the production of knock-on electrons in the same layer. In this way x can be calculated.

In order to evaluate this relation, we find that when the layer of Pb is increased by dx, the number of secondaries produced in this layer x decreases. If the integral energy spectrum is given by $N=N_0E^{-2}$ and the range of the mesons is given by the equation $x=E/a$ (for lead $a=1.6\times10^7$ ev), and if the number of the secondaries produced by a meson per cm Pb is p_0, then the decrease is $2p_0N_0x^{-3}a^{-2}dx$. When, now, E_1 is the energy of a secondary necessary for penetrating the layer x, we know that if f is the Furry unit,

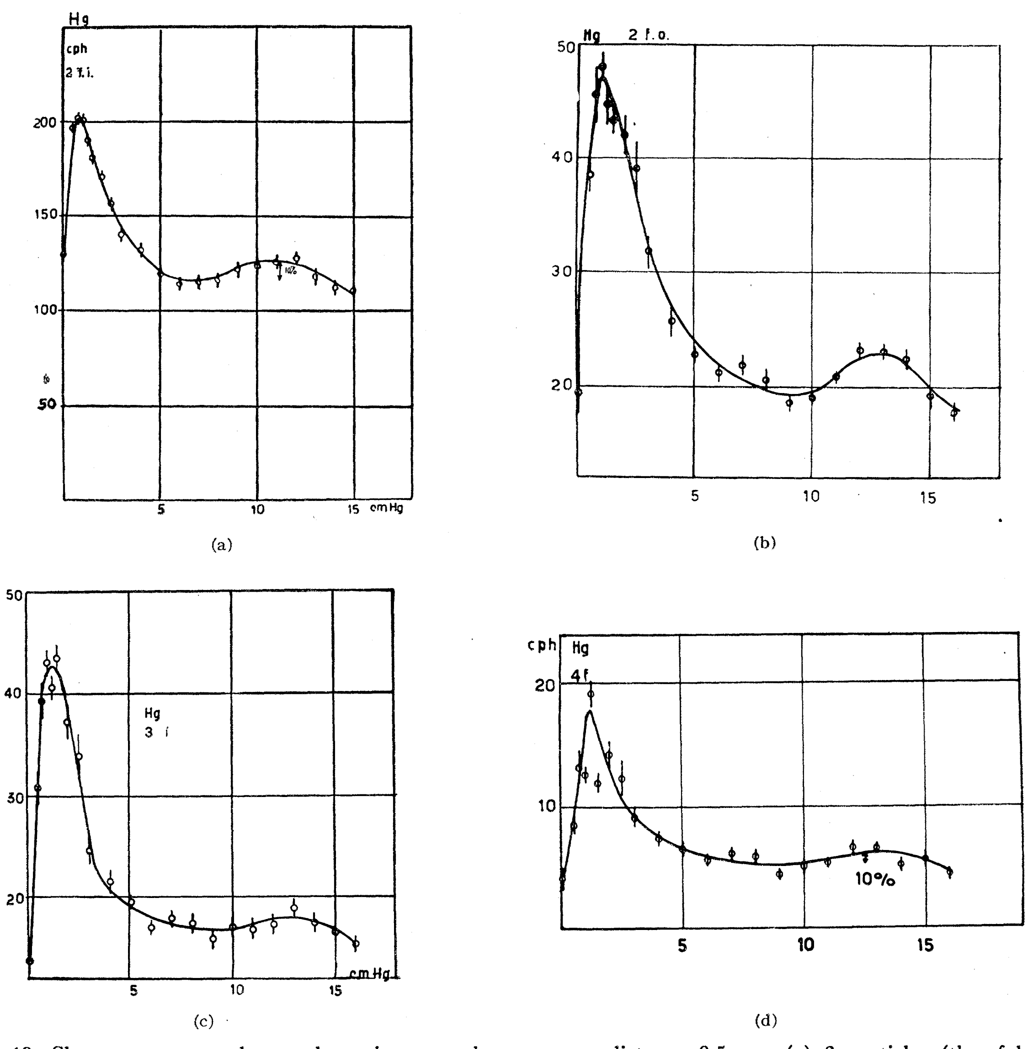
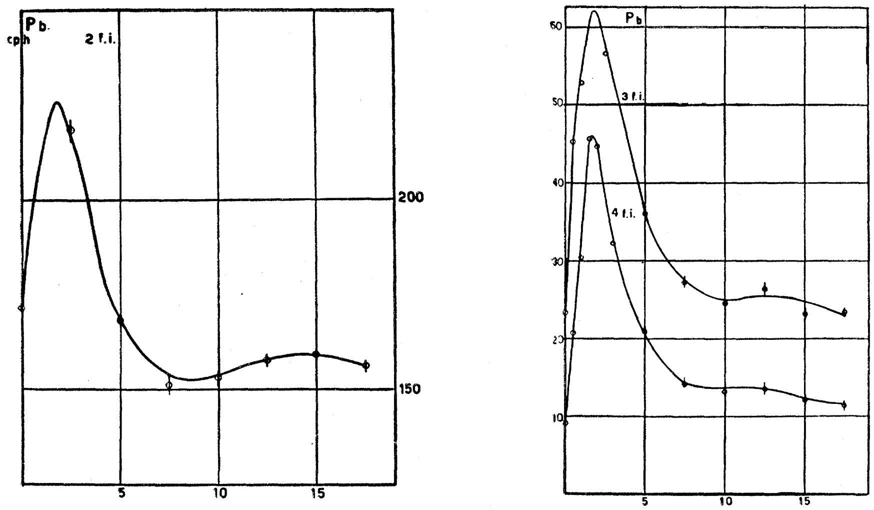


FIG. 19. Shower curves and second maximum under mercury, distance 8.5 cm. (a) 2 particles (threefold inner coincidences A, C, D), (b) 2 particles (threefold outer coincidences A, B, E), (c) 3 particles (fourfold coincidences A, B, C, D), (d) 4 particles (fivefold coincidences A, B, C, D, E).



(a) (b and c)

FIG. 20. Shower curves and second maximum under lead; for 8.5-cm distance under the plate. (a) For two particles (threefold inner coincidences A, C, D), (b) For three particles (fourfold coincidences A, B, C, D). (c) For four particles (fivefold coincidences A, B, C, D, E).

$x/f = 4\log(1+\frac{1}{4}E_i)$, with the energy E_i expressed in the critical energy as unit. The increase of production by adding a layer dx can only be furnished by those particles which can produce a secondary with energy E_i. Besides that, the energy of the incident meson must be at least E_i; the angle between the secondary and the meson must be so small that both the energy of the electron and of the meson will suffice to penetrate the layer x at which the maximum occurs. However, in the first instance we shall leave the latter influence aside.

A maximum can only arise if the decrease by absorption in dx is compensated for by an increase of production of secondaries in dx. This gives

$$2p_0N_0x^{-3}a^{-2}dx = p_0N_0E_i^{-2}dx,$$

and

$$E_i^2 = 16[\exp x/2f]x/2f = 2.3[\log(a^2/32)+3\log x],$$
$$a = 1.6\times 10^7.$$

We use our knowledge that x is about 20, and we find

$$x = 2f\times 2.3[\log(a^2/32)+3\log 20]$$
$$= 2f\times 2.3(12.9+3.9) = 22\text{ cm}.$$

In our experiment we got $x = 16$ cm.

Now we found, as was mentioned, with ionization chamber another maximum between 21 and 24 cm. This was the reason that we directly looked for a higher maximum under Pb and found it at 21 cm. But we also found this higher maximum under Hg at 17 cm. The curves are given hereby. We can now argue that every process which produces secondaries which can penetrate the material concerned can give rise to reach a maximum, so that it seems that we are also with other processes, such as the production of secondary electrons, and that this may be the production by nuclear process. The ratio of the maxima in Pb to those for Au and Hg, which must be proportional to f for these materials, is found to be 1.9 to 1.3 to 1, and the Furry units are in the ratio 1.7 to 1.2 to 1.0.

The number of mesons falling on the plate (300 cm^2) per hour is about 21,000. For gold the number of particles which are produced in the upper 1 cm of the plate is of the order of 1.5 per hour, that means 1 to 14,000, from which we may conclude that the energy is about 110 times the mean energy in the radiation which is $110\cdot 2E_0 \approx 10^{11}$ ev, i.e. of the same order as is necessary to penetrate these layers.

PENETRATING SHOWERS AND THE PRODUCTION OF MESON PAIRS

In 1941 we[15] published our results on the subject of the electron showers and penetrating

[15] J. Clay, Proc. Roy. Acad. Amsterdam 44, 888 (1941).

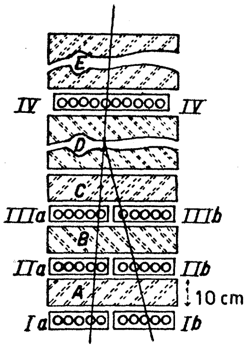


FIG. 21. Arrangement for sixfold coincidences in *Ia*, *Ib*; *IIa*, *IIb*; *IIIa*, *IIIb*; in order to count the number of meson pairs produced in *D*. Arrangement for sevenfold coincidences in order to prove the nature of the producing particle.

showers under layers of different materials, and we especially compared the difference of the divergence of the particles in both cases. The particles were absorbed at fourfold coincidences in two sets of two boxes with counters with an active surface of 846 cm^2—first the two boxes without Pb between them, then with 10 cm between, and finally one pair of counters separated by 10 cm Pb and the other pair without Pb between. Subsequently, they were absorbed under a thick water layer and also with an Al layer above the sets of counters. The production of penetrating pairs of particles was without any doubt larger than without such a layer of matter above. Under Fe and Pb the number of penetrating pairs was smaller. Last year the production of pairs was very carefully observed again with an arrangement as given in Fig. 21. Pairs of mesons were also observed by Wataghin,[16] and

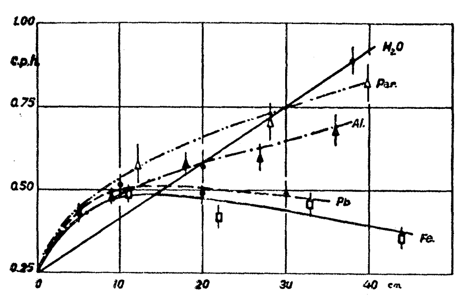


FIG. 22. Clay. The production of meson pairs in Pb, Fe, Al, paraffin, and H_2O.

[16] G. Wataghin, de Souza Santos, and Pompeia, Phys. Rev. **57**, 61 (1940).

Janossi and Rochester[17] made a careful study of the production and the producers.

In the course of our experiments concerning the production of secondaries, we have come across the possibility that in every layer a secondary electron might be produced and, therefore, it might happen that, instead of two penetrating particles which could give a fourfold coincidence in the first experiment, one penetrating particle with two secondaries in the upper and lower box without production layer next to the first could give the same coincidences. Since, however, in every case we could subtract the effect as it occurred without any covering over the counters, the evidence of relatively greater production in lighter material stood out still more plainly. Apparently, however, the separation of the two cases could be avoided in two ways. The first way was to separate the two columns by 10 cm Pb or more, but this was not practicable because, as became evident, the angle between the penetrating particles was always small. When the boxes were shifted horizontally with regard to each other for angles 24°, no pairs were found. So another way was devised for distinguishing between the two possibilities by taking three sets of two boxes above each other, every set covered by 10 cm Pb. It was found that in two boxes covered with 10 cm of Pb the number of coincidences was three percent of the number of incidental primaries. Thus the probability that one primary gives a secondary electron in the three pairs of boxes is 9×10^{-6} of the primary ray, which is negligible against the number of penetrating pairs produced in the layers *D* above the counters. Over the layer *D* two boxes of counters IV were put, in series with the other six, so that it was possible to distinguish between the number of cases where the pairs of penetrating particles were produced by an ionizing or a non-ionizing primary particle.

This experimental method has the disadvantage that it only indicates a pair, when both particles can penetrate 30 cm Pb, the particles of smaller energy escaping detection.

Another difficulty is that the production is only found as a difference in result with and without

[17] Janossi and Rochester, Proc. Roy. Soc. **A179**, 361 (1941); Proc. Roy. Soc. **A182**, 180 (1943); Proc. Roy. Soc. **A183**, 181 (1944).

the layer D, and it appears that the number of coherent penetrating mesons varies with changing atmospheric conditions. Therefore, we made a very long series of observations of about 4320 hours, in which we alternated the situation with and without a 40-cm layer D of paraffin. E was absent then, and another long set of measurements was made with the boxes IV next to the pile of counters.

The fact is that we have to distinguish three different cases of penetrating pairs in sixfold coincidences. Firstly, we found that nearly every meson is accompanied by one or more coherent mesons, some of which will penetrate the boxes next to those in pile. Secondly, there are penetrating extensive showers, and from such a shower two particles can penetrate, one in each of the two piles in juxtaposition. According to an experiment by Clay and Swiers with two pairs of boxes, each pair separated by 10 cm Pb, the proportion of first to second pairs was 7 to 1. In this case the number of penetrating particles from every direction was measured and found to be 3 and 4 per hr., and 0.5 per hr. When we used three layers above each other, the total number of coherent mesons and penetrating pairs from showers varied from 0.1 per hr. to 0.3 per hr. In the mean it was 0.25 per hr. Consequently, these results represent the number of sixfold coincidences without a layer D.

When we now subtract the number of coincidences of two particles without a layer from the total value found in the case of different layers of matter, Pb, Fe, Al, H_2O, and paraffin, we get the values given in Fig. 22.

There are two striking results. When layers with the same number of nuclei are taken, we find nearly the same production of penetrating pairs. The production is proportional to the number of atomic nuclei, and certainly not to the number of nucleons (protons and neutrons). When we take layers of the same numbers of atoms as in 10 g cm^2 in H_2O, we find the production per hr. in paraffin, H_2O, Al, Fe, and Pb to be 0.27, 0.29, 0.26, 0.23, and 0.27, respectively.

The other striking result for the production is that in 0.93 percent of the cases the particles which produce the effect are non-ionizing. With Fe and Pb at a thickness of 10 cm, the maximum of production is reached; the range cannot exceed about 10 cm in heavy material, but in the light materials, such as H_2O and paraffin, no absorption of the producing particles is ascertained at all. At first we were inclined to look for a neutron or a neutretto to be the producer, but at the present moment we can only conclude that high energy photons are the producers. This is in agreement with the results of Bostick[18] and Tabin[19] at higher altitudes.

We have mentioned already that shifting the boxes in horizontal direction gave for 16° and 20° the same production as for 0°, but for angles larger than 24° no production was found.

Another result could be ascertained. During 1440 hours the apparatus for registering the production of pairs sixfold was connected with the boxes IV next to the two piles of 3 boxes, and in this way we could control whether the production was correlated with extensive showers. No correlation was found, so that the production seems not to be caused by particles within the showers.

The number of processes per unit of time is 1/16,000 of the meson component of the radiation.

[18] W. H. Bostick, Phys. Rev. **61**, 557 (1942).
[19] T. Tabin, Phys. Rev. **66**, 86 (1944).