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# High Energy Particles, Bursts, and Showers

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THROUGH a series of experiments we tried to come to a conception of the structure of extensive showers and their relation to the phenomena of bursts, as we anticipated a close relation between them.

We early found with three sets of four counters that the density computed in the showers was different if we used different numbers of counters. From various experiments with sensitive surfaces of different size, we have ascertained that the probability of finding showers of different densities depends on the size of the surface selected, and the best way to find showers of great density is to detect them with small surfaces.[1] This was confirmed by systematic experiments of Cocconi.[2] But we came to the conclusion that condensation of particles in some places must be expected[3] and several Wilson photographs give support to this expectation.[4] Also, it could be surmised in advance that the secondary particles which are present in such great numbers must be produced along the path of some very energetic primary particles. Hence we came to the conclusion that the original shower might be a meson shower, every meson being surrounded by a cluster of secondary particles (electrons).[1] When this is true there must be some numerical relation between the mean density of the penetrating particles and the soft secondary particles. Along two different lines we reached the conclusion that the number of soft particles stands to that of the penetrating ones as 10–20 to one. This was found in a series of experiments with two sets of two boxes of counters (Fig. 1) at a certain distance from each other.[1, 2, 5] When there was no lead screen between the counters, coincidences of soft particles could be registered and, with 10 cm of Pb between them, the penetrating particles were found.

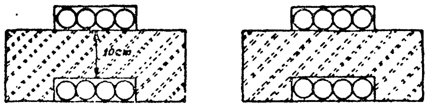

FIG. 1. Arrangement of four sets of counters with shield (which can be removed).

As we see from Table I, the ratio of soft to hard particles is between 12.5 and 9.5. We also found by direct measurements (Fig. 2) with small surfaces of crossed counters that the total number in a cluster was between 10 and 20.[3] That there is a close connection between burst and extensive shower is most obviously demonstrated by the graph (Fig. 3) which gives the results of the number of bursts in connection with the altitude above sea level by C. G. and D. D. Montgomery[6] and the same relation for extensive showers by Hilberry.[7]

Now the assumption is that a burst can be found in an ionization chamber when a number of clusters are coincident in the chamber, and this could be proved by measuring the burst of coincidence in two chambers next to one another as described below.

We took two vessels with active surface 0.25 m$^2$ and 0.08 m$^2$ and placed these vessels (Fig. 4) near one another, changing their mutual dis-

TABLE I. Coincidences of soft and of hard particles.

| Distance in Mtr. | Counter distance 16 cm (coincidences p. hour) $C_0$ | $C_{10}$ | $C_0/C_{10}$ |
|---|---|---|---|
| | No lead | 10 cm lead | |
| 0.24 | 34.6±1.4 | 3.4 ±0.3 | 10 |
| 1 | 11.4±0.07 | 0.91±0.1 | 12.5 |
| 3 | 4.9±0.63 | 0.52±0.1 | 9.5 |
| 5 | 4.6±0.5 | 0.45±0.15 | 10.2 |
| 10 | 4.2±0.8 | 0.32±0.08 | 11.7 |
| 27.5 | 2.1±0.6 | 0.19±0.06 | 11 |

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[1] J. Clay, Physica **9**, 897 (1942).

[2] G. Cocconi, A. Loverdo, and V. Tongiorgi, Phys. Rev. **70**, 841 (1946).

[3] J. Clay, Physica **11**, 311 (1944). H. Geiger and W. Strubbe, Abh. Akad. v. Wiss. Berlin **10**, 1 (1941). J. Daudin, thesis, University, Paris (1942).

[4] Brode, unpublished photo. A. C. B. Lovell, Endeavour **5**, 74 (1946).

[5] J. Clay and H. Swiers, Versl. Ned. Acad. Amsterdam **53**, 80 (1944); Proc. Roy. Acad. Amsterdam **47**, 139 (1945).

[6] C. G. and D. D. Montgomery, Phys. Rev. **47**, 429 (1935).

[7] N. Hilberry, Phys. Rev. **60**, 1 (1941).

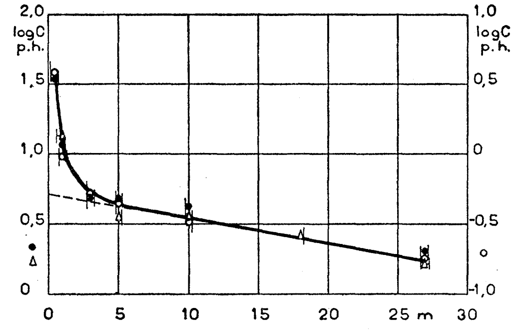

FIG. 2. △ Measurements without shield, counters directly on each other. ● Without shield (electrons). ○ With shield (mesons). Right-hand scale, with shield. Left-hand scale, without shield, Clay and Swiers.

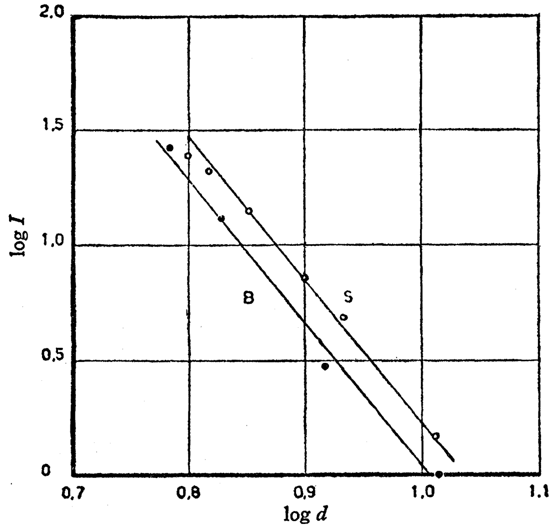

FIG. 3. Decrease in the atmosphere of the bursts according to C. G. and D. D. Montgomery (*B*) and of the extensive showers according to Hilberry (*S*).

tance from time to time, and counter systems above and below the vessels;[8] the active surface 0.045 m$^2$ of the counters could not cover the whole ionization vessel, so that the bursts in the vessels were not always accompanied by a fourfold coincidence, but there were many cases where we got two coincidental bursts without a fourfold coincidence in the counters. It was proved that the correlation coefficient of the bursts increases with the intensity of the burst and becomes unity for the very great burst; this is the most direct proof that the bursts are produced by a number of condensed clusters. Further proof of this will be found below.

In order to test the hypothesis that the clusters of electrons are produced as secondaries of the primary penetrating mesons, we carried out the following experiments. At first the coincidences were measured with 2 cm of lead above the ionization chambers. This layer is the most effective for developing the multiplication of soft particles in the radiation. Ten cm of lead were placed below and above, and a counter system was placed below and above both chambers. It could be controlled when there was a triple coincidence, since the bursts were photographically recorded on the same film with the lead above and below as shown in Fig. 5, and the fourfold coincidences were recorded by a lamp producing a mark in the middle of the film between the lines for the ionization chamber. It happened that in a certain period (Fig. 5) two coincidences of bursts and counters occurred in an interval of only 30 sec., and 4.5 min. later came a coincidence of bursts without a fourfold coincidence of the counters. To give some idea of the intensity of the burst, we may note that the first burst in the large chamber with an active surface of 0.25 m$^2$ was 470 tracks and the burst of the second vessel of 0.08-m$^2$ active surface was 81 tracks; the second burst 30 sec. later was 110 tracks in the large and 29 tracks in the smaller vessel. Now a second experiment was made with the 10-cm shield above the chamber. In both cases we were able to ensure by the counters that there were penetrating particles in the bundle of rays, while the frequency was the same. However, in the case of the 10 cm of lead below the counters, we expected that the cluster of electrons would develop to a larger cascade, whereas, with the lead above, the electrons accompanying the penetrating par-

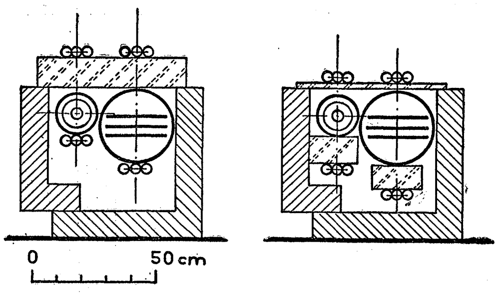

FIG. 4. Clay and 'tHooft. Coincidences of bursts in two vessels and a fourfold coincidences counter discharge with lead above and lead below the chamber.

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[8] J. Clay and G. G. 'tHooft, Physica 10, 185 (1943).

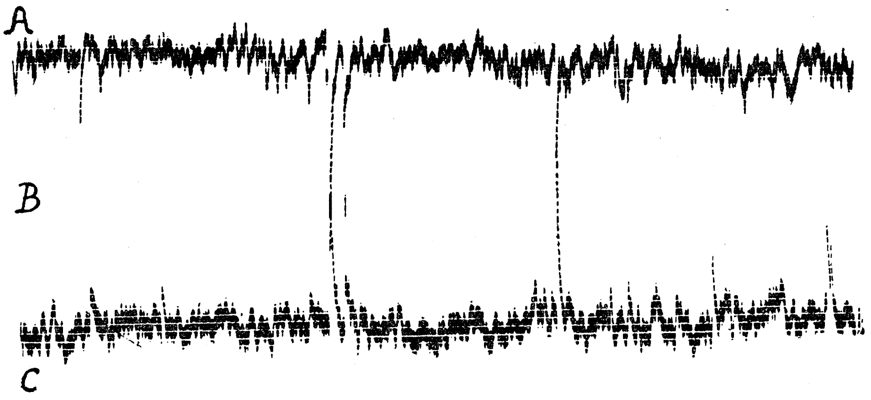

FIG. 5. Record of ionization.

ticles would be stripped off, the frequency of the bursts would be less, and the intensity smaller. Indeed, the intensity was half and the frequency one-fourth of those with the 10 cm of lead below (Fig. 6). Moreover, the correlation of the bursts was small when the lead was above the vessels and large when it was below (Fig. 7). From the frequency and the intensities of the bursts in both vessels without field (Fig. 8), we may conclude that the bursts cannot be a process of explosion in the wall of the vessels, but must be a process of simultaneously penetrating particles with their clusters. If it were a process of explosion at one point, the frequency of bursts of the same number of paths should be proportional to the active surfaces of the vessels, which were in a proportion of 3.6:1. It is found, however, to be 20:1. If the burst is a phenomenon of a number of clusters falling on the surface at the same time, the intensity of the burst which has the same frequency in both vessels will be proportional to the active surfaces and this is what, in fact, we find to be the case. In order to obtain an equal number of tracks in both vessels, the intensity of the burst in the small one must be 3.6 times that in the larger one. This means that, for equal energy of all particles, the total energy of the burst in the small chamber must be 3.6 times that in the large one. As we know, the frequency of such a primary particle is about $3.6^2=13$ times smaller, which is approximately what we find.

We do not, therefore, require Heisenberg's explanation of the explosion process in the wall; this does not imply that there may not be small explosion processes of disintegrations in the wall. There is no point in calculating a cross section for the bursts in the material above the chamber.

In all these cases it may be possible that either the penetrating rays, which are—without question—present in the showers, are produced by electrons as primaries (cascade theory), or that the electrons are the secondaries of meson primaries, as is assumed here. We believe it very improbable that the coincidental mesons should have been produced in two places at the same moment in a layer of only 2 cm of lead, as in our first case of coincident bursts and fourfold countercoincidence.

In the experiments with the two vessels de-

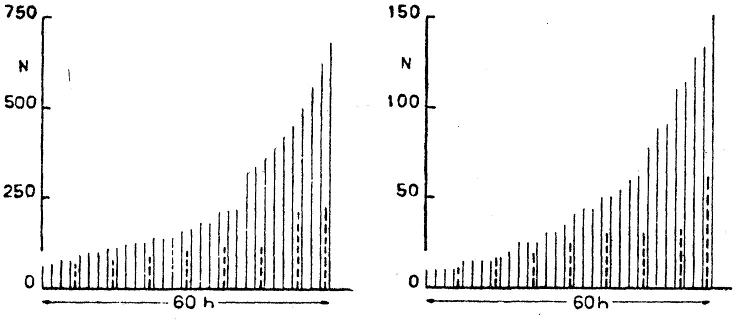

FIG. 6. Bursts simultaneous with fourfold coincidences in counters. $N$ = number of tracks in one burst. Drawn line = lead below, dotted line = lead above vessels, left in large vessel, right in small one.

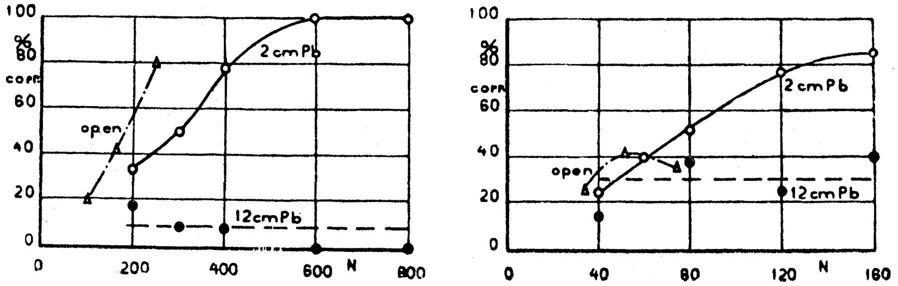

FIG. 7. Clay and 'tHooft correlation of bursts in a small vessel with those in large one plotted against their size in the other (left), and vice versa (right).

scribed above, we were able to measure the frequency of the burst of a density of between 200 and 1200 tracks per m$^2$, but we succeeded in including in our considerations coincident bursts of far greater intensity, by using the results of recordings made in our laboratory during several years, in four ionization vessels of large active surface of the order of 0.25 m$^2$ (Clay and 'tHooft[2,3]). The data for the vessels are given in Table II, and the arrangement of the vessels and their shields is shown in Fig. 9. The result of our survey was that the very great bursts of about $10^5$ tracks per m$^2$ were found simultaneously in the upper vessels. In our paper[2] an account is given of different coincidences in the vessels. Out of a number of 120 big bursts recorded, it happened 37 times that there was a coincidence in the upper and lower vessels. There is no doubt in this case that penetrating mesons were the origin of the bursts. The results are given in Fig. 10. It was impossible to distinguish bursts with a density of tracks either lower than $2\times10^4$ or higher than $2\times10^5$ per m$^2$. For comparison, the results of Montgomery (M), Carmichael (C), Schmid (S), and Hoffmann (H) are also given in Fig. 10. Although it is not easy to reduce the data of different authors to the same scale for the frequency according to the density of tracks, the results show that different authors agree fairly well, and it is certain that the inclination of the integral frequency curve for the smaller densities is higher than for the greater densities. If the curve for open vessels has such a sharp bend as was found by Car-

TABLE II.

Data for the ionization vessels

| Number | 6 | 5 | 7 | 8 |
|---|---|---|---|---|
| Vol. in 1 | 32 | 45 | 40 | 40 |
| Active surface in m$^2$ | 0.22 | 0.27 | 0.25 | 0.25 |
| Cm Fe shielding | 0 | 12 | 110 | 110 |
| Atmos. | 40 | 40 | 95 | 58 |
| Rec. hours | 21 384 | 19 848 | 18 336 | 20 280 |
| Rec. period sec. S. Ch. (Standard Charge) | 150 | 83 | 95 | 81 |
| Ions $10^8$ per. S. Ch. | 3.65 | 3.42 | 2.56 | 2.70 |
| Ions per. path | 32 000 | 40 000 | 35 000 | 40 000 |
| Paths per. S. Ch. $10^4$ | 1.1 | 0.83 | 0.64 | 0.76 |
| Paths per. S. Ch. p. m.$^2$ $10^4$ | 5.5 | 2.74 | 2.5 | 3.0 |

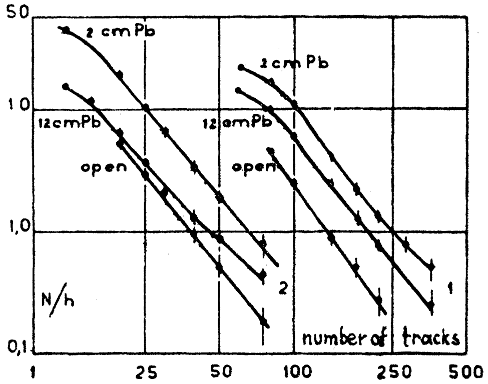

FIG. 8. Clay and 'tHooft frequency curves in two vessels (1 and 2) with different surfaces, ratio 3.6:1 for three different shields.

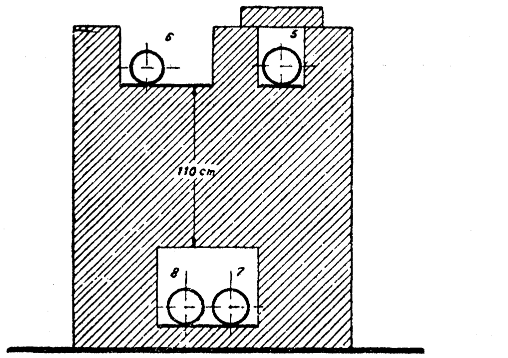

FIG. 9. Arrangement of four ionization vessels under various shields in Amsterdam. Details are given in Table II.

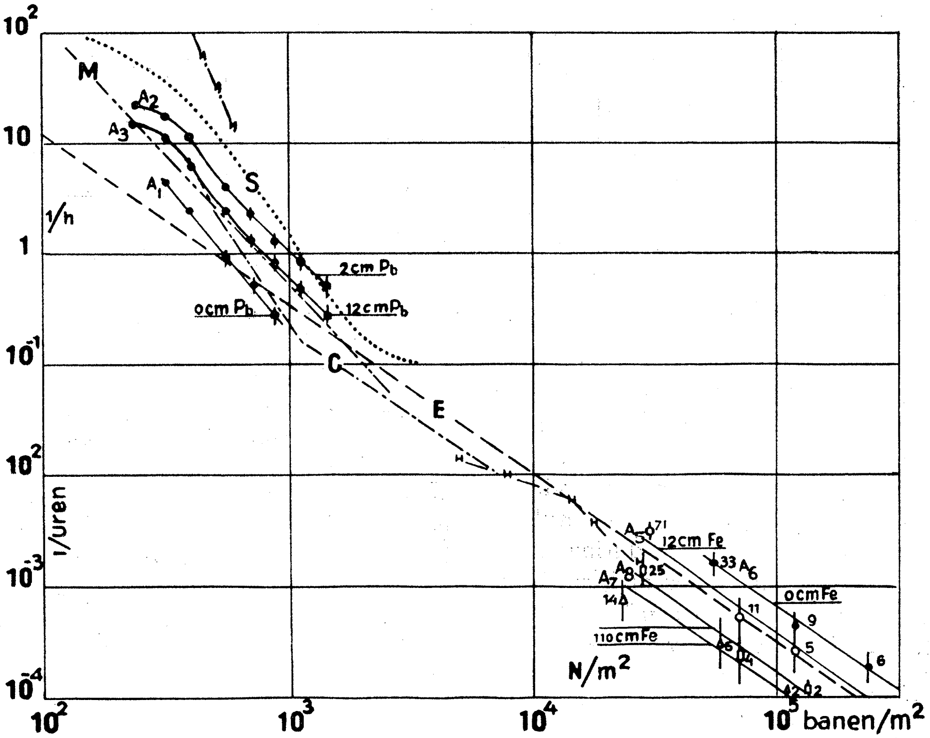

FIG. 10. Frequency of bursts with respect to the density of the tracks. Calculated per square meter. $A_1$ open, $A_2$ under 2 cm of Pb, $A_3$ under 12 cm Pb, $A_5$ under a 12-cm Fe shield, $A_6$ open, $A_7$ and $A_8$ under a 110-cm Fe shield ($A$: Amsterdam 20,000 h Clay). $C$: results of Carmichael open. $S$: those of Schmid. $M$: observations of the Montgomerys. $H$: Hoffmann. $E$: theoretical curves of Euler.

michael, this is not confirmed either by the results of the Montgomerys or by those of Schmid. I believe, however, that the explanation of this smaller inclination for the higher densities is that the track density cannot be exactly proportional to the energy, because in those cases where the density of the tracks is very high (which means that the shower will be in a later phase of development) the mean energy of the individual tracks will be smaller. Therefore, it is probable that, when the frequency is plotted against the energy, we should find a steeper frequency curve for the higher energy than for the track densities.

A very remarkable result was found with the bursts of the very high densities. In this case it

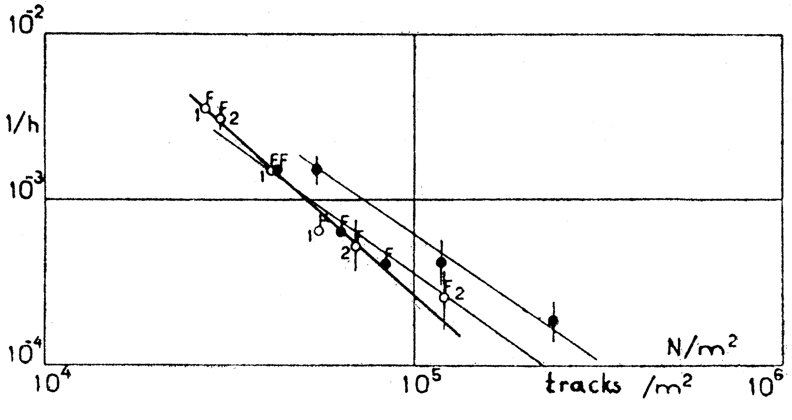

FIG. 11. Frequency of bursts during two periods, one of 20,000 hours with vessel 5 under 12 cm Fe and vessel 6 without shield (●), and one of 3280 hours with both vessels shielded by 12 cm Fe (○).

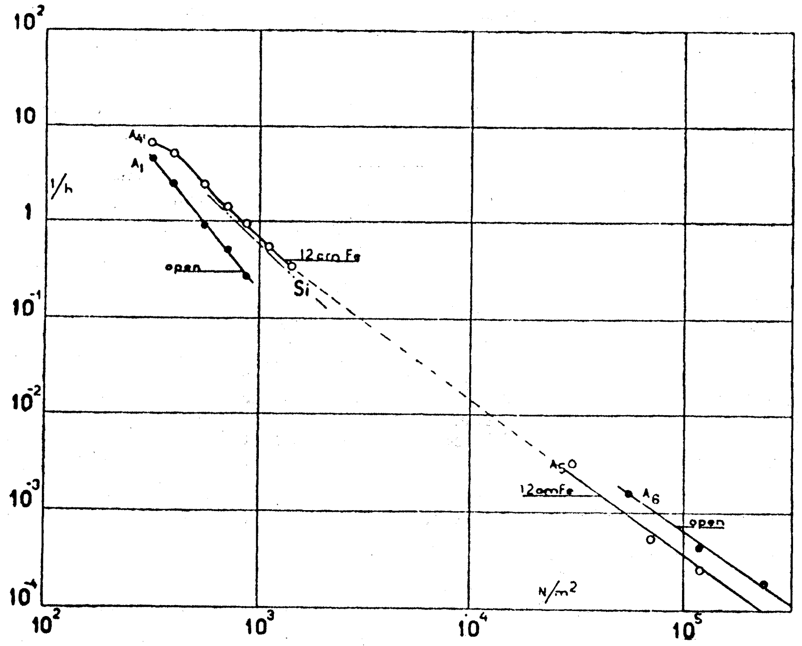

FIG. 12. Frequency of small bursts, density between 150 and 1200 paths per m², and of large ones, density from $1.2\times10^4$ to $2\times10^5$ tracks per m², in an open vessel and under a 12-cm Fe shield (Clay). Si = observations of Sittkus.

appeared that both the frequency and the intensity were smaller under 12 cm of iron than they were for an open vessel, exactly contrary to the result found by all measurements for smaller bursts. In order to make sure of this, two control measurements were taken (Fig. 11). First, for 3280 hours the two upper vessels were both shielded with 12 cm of iron, and it was confirmed that both their frequency curves were in agreement. Secondly, an experiment was taken with the vessels first described, where bursts between 200 and 1200 tracks per m² could be measured. This result confirmed that, for these densities, a frequency curve (Fig. 12) was higher under 12 cm of iron than for the open vessels. We believe we can explain this phenomenon in the following way. When the showers are in an early phase of development, the number of tracks is smaller, the energy more concentrated, and it is possible to have a cascade multiplication in

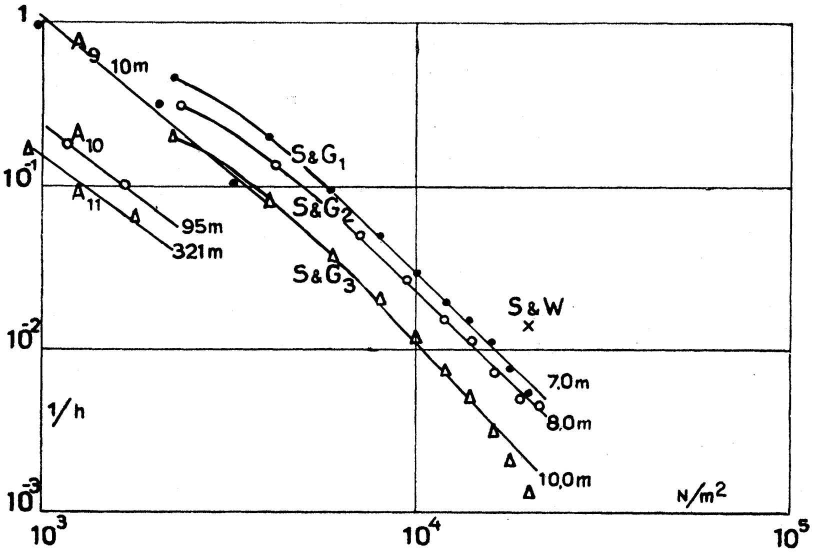

FIG. 13. Frequency of bursts $A_9$ at sea level (Amsterdam) with 10-cm Pb. $A_{10}$ under 95-m water equivalent with 10 cm of Pb. $A_{11}$ under 321-m water equivalent $S$ & $G$ 1, 2, and 3, Schein and Gill in the atmosphere. 7 & 8 for meters under the top of the atmosphere in water equivalent.

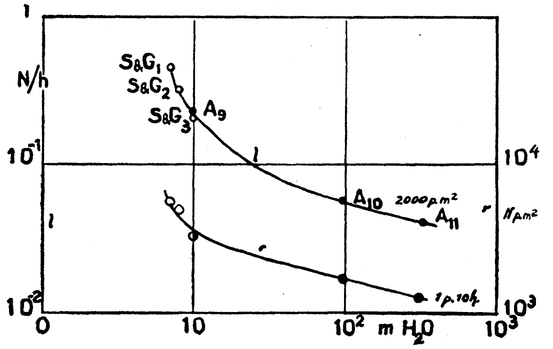

FIG. 14. Comparison of frequencies of bursts of the same size (2000 tracks per m$^2$) under different depths below the top of the atmosphere, left scale; and comparison of large bursts of the same frequency (1 per 10 hr.) at different depths, right scale.

12 cm of iron. When the shower is more developed the mean energy of the tracks is smaller, so that they cannot penetrate the shield of 12 cm of iron with multiplication.

Now, it is precisely this circumstance which gives us a good opportunity to estimate the energy of the primary particle which produced the shower. Compare Fig. 10. For the high densities such as $10^5$ tracks per m$^2$, it appears that the particles cannot multiply in 12 cm of iron and, therefore, we can calculate from the cascade theory that the mean energy cannot exceed $2\times10^9$ ev. On the other hand, three-quarters of it can penetrate and multiply in 10 cm of iron. Therefore, since the best chance for coming through would be by the loss of nothing but the ionization energy, this energy cannot be smaller than $3\times10^8$ ev. Now the total energy is of the order between $3\times10^{13}$, and $3\times10^{14}$ ev per m$^2$. And since we know from our measurements of showers[5] that the extension is between $3\times10^2$ and $10^3$ m$^2$, we may conclude that the lowest estimate of the energy of big showers with a frequency of 1 in 6000 hours is of $10^{16}$ ev.

At the end we may again stress that these phenomena cannot possibly be produced by electron showers, for we could detect bursts at a depth of 314-m water equivalent. In Fig. 13 the results are given for sea level,[8] under 95-m and under 321-m water equivalent. Comparing our results with those of Schein and Gill[9] at different altitudes in the atmosphere, we see that they are in close agreement—not only for the frequency, but also for the ratio between frequency and track density.

In Fig. 14 we see that the frequency for a burst of given magnitude, 2000 tracks per m$^2$, increases rapidly when the layer above the apparatus decreases (left scale) and so the magnitude of the density for a fixed frequency increases in a similar way with the decrease of the layers of material above the apparatus. It is not impossible that this means that the center of production of the producing particles lies in a lower layer of the atmosphere although it is exceedingly improbable that an amount of mesons like there must be present in a big cascade (about 10,000) should be created in the atmosphere which equals a layer of 10 m of $H_2O$. This indicates that if we assume a cascade process, $2^x$ would amount to 10,000. In this case the critical length of the multiplication process would be equal to about 0.7 m of water.

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[9] M. Schein and P. S. Gill, Rev. Mod. Phys. 11, 267 (1939).