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High Energy Particles in Auger Showers

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The results are given of counter experiments carried out at an altitude of 10,618 feet (Echo Lake, Colorado) on extensive atmospheric showers, or Auger showers, of a minimum spread of 22 meters. An efficient method (the master group method) of investigation of such showers is described. It was found that high energy electrons or photons, initiating a shower below a lead screen of 10-cm thickness, are accompanied, above the absorber, by a shower of high particle density, located either in the central part of the core of the Auger shower or in its close neighborhood.

DURING the summer of 1943, different kinds of counter experiments on extensive atmospheric showers, or Auger showers (here referred to as A showers) were carried out at Echo Lake, Colorado, at the altitude of 10,618 feet above sea level. A detailed account of all the results obtained, of the experimental arrangements, and of the method used in these investigations will be given at a later date. In this paper we will describe only experiments on particles which are able to penetrate up to 10 cm of lead and belong to A showers having a spread of at least 22 meters.

PRINCIPLE OF THE METHOD

The general principle of the method, which we shall call the master group method, is the following:

n counters $M_1, M_2 \cdots M_n$ are in coincidence, and p counters $T_1, T_2 \cdots T_p$, in coincidence between themselves, can be connected in anticoincidence to the first set of n counters. These two sets of counters together form the master group. k other counters (analyzing counters) $A_1, A_2 \cdots A_k$[1] are connected to the master group in such a way that a discharge, which occurs in any one of these k analyzing counters, can be recorded only if it is coincident with an output pulse of the master group. A photographic record of neon lamp flashes—each of the neon lamps being flashed only by its corresponding analyzing counter—thus shows directly how many and which ones of these analyzing counters were discharged simultaneously with the master group.

Now, this record gives not only the coincidences between the master group and any of the analyzing counters, but also, at the same time, all the possible 2^k-1 combinations of coincidences between the k analyzing counters, provided a simultaneous discharge of the master group occurs. In addition, the same record gives a number of anticoincidences, that is, coincidences which are *not* accompanied by other types of coincidences.

For instance, if $k=10$, the total number of

[1] More generally, an analyzing counter can be replaced by a set of coincident and anticoincident counters.

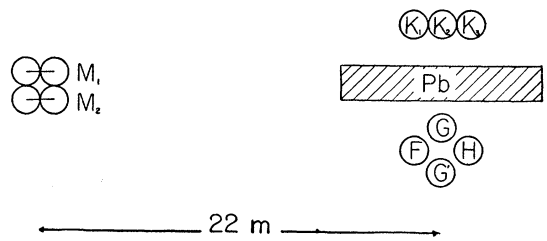

FIG. 1. Arrangement of counters.

possible types of coincidences provided by the record exceeds 1000. However, there is a practical limit on the number of analyzing counters to be used which is set by the prohibitive time required for evaluating the coincidence data. It should, on the other hand, be pointed out that frequently it is not really important to evaluate all the coincidence data thus available since many are of minor interest because various factors, like the geometry of the counter arrangement, prevent a direct interpretation of the corresponding data.

This shows directly that the method described above has a much higher efficiency than all other methods previously[2] used in experiments on A showers.

EXPERIMENTAL ARRANGEMENT AND RESULTS

In the particular case of the present experiment, the master group consists of only two counters, M_1 and M_2,[3] put in a vertical twofold coincidence (Fig. 1). Seven counters, F, G, G', H, K_1, K_2, K_3, are placed at a horizontal distance of 22 meters from the master group. The lower set of counters, F, G, G', H, can be separated from the upper set of counters, K_1, K_2, K_3, by lead absorbers up to a thickness of 10 cm. The whole outfit thus records only particles in an A shower having a minimum spread of 22 meters.

With k equal to 7, in the present case, the number of available coincidences was 127; but only 31 were actually evaluated.

These 31 types of coincidences are divided into 3 categories: In the first category are listed 7 types of coincidences, according to whether *only* one, or *only* two, or all three upper counters K_1, K_2, K_3 are discharged. The second category comprises three types of coincidences in the lower set, namely: (a) when a discharge occurs in both counters G and G' *alone;* (b) when the (a)-type discharge is accompanied by a discharge in counter F or H, but not in both; and (c) when it is accompanied by a discharge in both. The third category consists of the 21 combinations of all individual cases of the first two categories. It must be borne in mind that in each of the 31 cases the master group was simultaneously discharged.

The first type of coincidences of the second category and the corresponding 7 cases of the third category are of special interest since they might be attributed to penetrating non-shower producing particles, like mesotrons or protons. However, these particular cases will be discussed in another paper, and here we shall give only the results concerning high energy shower-producing particles in A showers, such as electrons or photons.

These results are given in Table I. The first column gives the time of recording for measurements with thicknesses of lead which are indicated in the second column. All the data in the other columns represent frequencies expressed in number of coincidences per 10 hours. The third column gives the frequencies of the sixfold coincidences $M_1M_2FGG'H$ in different thicknesses of the lead absorber. Columns IV to X give the frequencies of the coincidences between $M_1M_2FGG'H$ and the 7 cases of the first category, which have already been mentioned. The last column Δ represents, for a given thickness of lead, the difference between the frequency of $M_1M_2FGG'H$ and the sum of the frequencies listed in columns IV to X. The Δ values give the frequencies of the $M_1M_2FGG'H$ events which are *not* accompanied by a discharge in any of the upper counters. The mean coincidence-frequencies in this upper set alone (first category) were, respectively, 320, 80, and 170, when *just* one of the K counters was discharged, *just* two of the K counters were discharged simultaneously, and all three counters K_1, K_2, K_3 were discharged simultaneously. All the counters used in these experiments have a diameter of 5 cm, and an

[2] P. Auger, R. Maze, T. Grivet-Meyer, Comptes rendus **206**, 1721 (1938). P. Auger, P. Ehrenfest, R. Maze, J. Daudin, Robley, and A. Freon, Rev. Mod. Phys. **11**, 288 (1939). W. Kolhörster, J. Matthes, and E. Weber, Naturwiss. **26**, 576 (1938). N. Hilberry, Phys. Rev. **60**, 1 (1941).

[3] Actually, M_1 and M_2 consist, each, of two counters connected in parallel.

TABLE I. Coincidences, per 10 hours, occurring between the master group M_1M_2 and the different analyzing counters F, G, G', H, K_1, K_2, K_3. In column Δ are listed such coincidences $M_1M_2FGG'H$ which are *not* accompanied simultaneously by discharges in any of the upper counters K_1, K_2, K_3.

I Hours of recording	II cm Pb	III $M_1M_2FGG'H$	IV K_1	V K_2	VI K_3	VII $M_1M_2FGG'H$ K_1K_2	VIII K_1K_3	IX K_2K_3	X $K_1K_2K_3$	XI Δ
7	2.5	66	3	3	4.5	9	3	12	22.5	9
29.8	5.0	64.8	1.7	3.7	3.4	6.4	3.7	6	33	6.8
20.5	10.0	26	1	0.5	0.5	1	1	0.5	20	1.5

effective area of 250 cm^2; they are filled with a mixture of argon and alcohol and operate at 1200 volts. The resolving time of the coincidence circuits is about 4×10^{-6} sec., so chance coincidences were negligible in the case of the higher order coincidences here reported. The question of the solid angles, subtended by any counter or set of counters, is of minor importance in the present experiment since the particle-densities in the showers which are involved here are high, as will be seen hereafter.

DISCUSSION

Consider first values obtained for a lead absorber of 10-cm thickness. An event $M_1M_2FGG'H$ represents then a shower of at least 3 particles, emerging below a lead screen of a thickness equivalent to about 20 radiation units; moreover, this shower is associated with one or more particles which reach the counters placed at a horizontal distance of 22 meters from the counters located below the lead. The same shower must have originated from at least one particle of an energy sufficiently high to penetrate such a thickness of lead. However, if the particle responsible for the creation of the shower emerging below the lead is a mesotron, its energy could have been relatively low—of the order of a few times 10^8 ev. But since the probability of a mesotron being in an A shower and, moreover, creating in the lead absorber even a small shower is quite low, this possibility might be disregarded. Therefore, the creation of the shower emerging below the lead should be attributed mainly to high energy electrons or photons. In this case, the energy of such particles (electrons or photons) must be of the order of magnitude of at least 10^{10} ev.

Now, particles of such high energy can be created only in the central part of their parent A shower because the average angle of their emission, with respect to the direction of the particle from which they directly originate, is given approximately by the ratio between the rest energy of an electron and the energy of the created particle. For an energy of 10^{10} ev, this angle is extremely small—of the order of a few seconds—and has a negligible influence on the scattering of the particle. A mechanism which could play here a more appreciable role would be the multiple scattering of the particle out of the core of the A shower, since the average angle of this scattering, per radiation unit, is about 40 times as high as the mean angle of emission mentioned above.[4] Even in this case, the distance of the particle from the core of the A shower would not become appreciable, unless the particle was created very far above the observation point—for example, in the first few radiation units from the top of the atmosphere. But then, in order to reach the absorber with a residual energy of at least 10^{10} ev, the initial energy of the particle created close to the top of the atmosphere should have had a much higher value. Such a particle would have to cross a thickness of air equivalent to some 15 radiation units, and, consequently, would arrive at the lead absorber accompanied by its own cascade shower. Hence one sees that the particle initiating a shower under the lead would always be accompanied, either by a shower of particles belonging to the core of the same parent A shower, or by its own cascade shower, or by both.

The values given in Table I are in agreement with the foregoing interpretation. Indeed, in 20 out of 26 cases an event $M_1M_2FGG'H$ is accom-

[4] B. Rossi and K. Greisen, Rev. Mod. Phys. **13**, 240 (1941).

panied above the lead by a shower discharging all three upper counters K_1, K_2, K_3. The table shows, furthermore, that cases where none, or only one, of the K counters is discharged, or only two of the K counters are discharged simultaneously with the event $M_1M_2FGG'H$, are very infrequent. This indicates that the mean particle density in the portion of the showers which strikes the lead absorber, under the described conditions, must be very high and, as calculations show, of at least several hundred particles per m^2.

Now, counters of the size used in the present experiments become practically saturated for such particle-densities. This means that the probability of discharging such a counter is then very close to unity. Therefore, the actual densities might have had much higher values than those just quoted. More accurate values could be provided by using counters of a much smaller size. But then, the time required to carry out such experiments would be considerably longer.

Let us notice now that the ratio between the coincidence frequencies of an $M_1M_2FGG'HK_1K_2K_3$ event and an $M_1M_2FGG'H$ event decreases with decreasing thickness of the lead absorber. This is in agreement with the fact that a particle able to produce a shower below the lead absorber might have a lower energy in case the lead absorber has a smaller thickness, and thus could be present in a lower density region of the A shower. Inversely, one can expect that the same ratio will reach a value of 100 percent for a sufficient thickness of the absorber. This point should be carefully verified because if confirmed, it could give a different interpretation of counter experiments on multiple mesotrons,[5] even though the absorber thicknesses used in such experiments might have been very large. Indeed, since a knock-on shower accompanying a mesotron should be considered as a very infrequent event, the most reliable criterion for the identification of a mesotron in counter experiments is its practical inability to produce showers in absorbers of a thickness equivalent to a sufficiently high number of radiation units. Therefore, so long as it is not proved, by means of several counters as there are in the present experiment, that a particle is not accompanied by a shower below a thick absorber, there will always be a high probability that the shower below the absorber is initiated by a high energy electron or photon, and is accompanied, *above* the absorber, by a dense shower belonging to the core of an A shower.

The same remarks apply to experiments on the presence of mesotrons in the A showers.

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[5] M. Damy de Souza Santos, P. A. Pompeia, and G. Wataghin, Phys. Rev. **59**, 902 (1941). V. Josephson, D. K. Froman, and J. C. Stearns, Phys. Rev. **57**, 335 (1940).