Extensive Cosmic-Ray Showers

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Introduction

It is generally admitted that the soft group present at sea level is almost entirely due to the effects of mesotrons, that is to their decay electrons and their collision electrons. These electrons should then give rise in the lower atmosphere to local showers, the intensity of which should increase very slowly with the altitude, in the same way as the hard group (mesotrons).

But we know that the increase of the soft group with altitude is very rapid, so we must admit that electrons of another origin than that indicated above are adding their effects to those of the decay and collision electrons from mesotrons. It seems natural to suppose that they represent the end effects of the showers that the primary particles, probably electrons, which enter the high atmosphere produced there. If this is the case, we should be able to recognize it by the existence of a "coherence" of these shower particles, the multiple effects of a single initial particle remaining bound in time and in space.

We have shown the existence of these extensive showers[1] and studied their properties with counters and Wilson chambers partly at sea level, and partly in two high altitude laboratories, Jungfraujoch (3500 m) and Pic du Midi (2900 m).

Long Distance Coincidences

If two or three counters are arranged in coincidence in free air, a small number of coincidences is observable, due to "air showers" and this number decreases quickly when the horizontal distance of the counters is increased. Schmeiser and Bothe have studied these local showers with counter separations up to half a meter.[2] If the distance is increased further, the number of coincidences decreases much more slowly, and for distances of the magnitude of ten meters, there remains a quite measurable effect, although small.[1, 3] In order to continue this study efficiently, it is then necessary to use a coincidence system with a very good resolving power, especially in the use of two counters. The apparatus employed in the present work registered only multiple kicks which happened within the time lag of 10^{-6} second.[4] The "background" or accidental coincidences can be calculated by the formula:*

$$N=\frac{n^x\tau^{(x-1)}}{60^{(x-2)}},$$

where N is the number of accidental coincidences per hour, if n is the number of single kicks in the counters per minute, x the number of counters, τ the resolving time in seconds. For instance with two large counters of 200 square centimeters, we had a background of about 1 per hour, in high altitudes. With three counters, the background is always negligible.

With the simplest arrangement of two parallel and horizontal counters placed at progressively increasing distances,[5] we could obtain the results given here in logarithmic scale (Fig. 1). The greatest distance was 300 m, we did not think it wise to try greater distances, because of the uncertainty of the simultaneity in the single kicks in the counters, coming from distant particles of the same showers. The time difference can be of the same order of magnitude as the resolving power, since the showers are not necessarily vertical.

[1] P. Auger, R. Maze, T. Grivet-Meyer, Comptes rendus **206**, 1721 (1938); P. Auger and R. Maze, Comptes rendus **207**, 228 (1938); P. Auger, R. Maze, P. Ehrenfest, Jr., and A. Fréon, J. de phys. et rad. **10**, 39 (1939).

[2] W. Bothe *et al.*, Physik. Zeits. **38**, 964 (1937).

[3] W. Kohlhörster, I. Matthes, E. Weber, Naturwiss. **26**, 576 (1938).

[4] R. Maze, J. de phys. et rad. **9**, 162 (1938).

* Instead of this equation, many writers (e.g. C. Eckart and F. R. Shonka, Phys. Rev. **53**, 752 (1938)) use an expression equivalent to

$$N=x\frac{n^x\tau^{(x-1)}}{60^{(x-2)}}$$

differing from that here given by a factor of x.

[5] P. Auger, R. Maze, and Robley, Comptes rendus **208**, 1641 (1939).

Comparison with Shower Theory

We have compared these results with the calculations made by different authors, on the basis of the cascade shower theory. Euler, for instance,[6] gives a theoretical curve for the decrease of coincidences with distance which deviates from our experimental one at about 20 meters. From his calculation, the number of coincidences should be reduced to a small value at 30 m distance, while we could easily measure the coincidences at a distance ten times greater. As we have shown, these facts are in favor of a production of mesotrons in the showers, these mesotrons being able to penetrate the whole atmosphere so that with a small divergence angle they can hit the ground at large horizontal distances from the central beam of the shower, where the electrons and photons are concentrated.

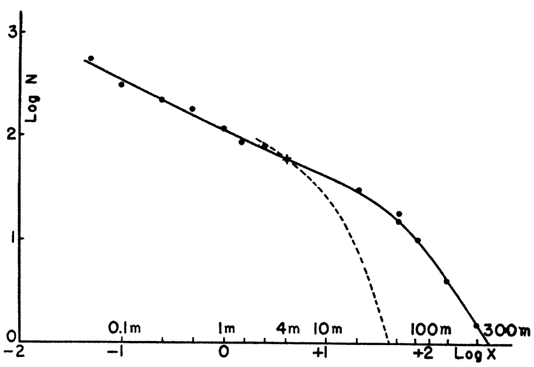

Fig. 1. Results with two parallel and horizontal counters.

Electrons and Photons

The composition of the central beam can be proved by the study of the secondary effects of the particles in heavy material. If we cover one of the counters with lead plates of increasing thickness, we get first a strong increase in the number of coincidences (at distances less than 50 m) then, after a maximum for 1.5 cm, a decrease takes place. This shows that the particles have a shower-producing power in lead, that is to say their energy is higher than 10^7 ev. The lead plate acts as a multiplicator, and the active surface of the counter is increased. We could show that a lead plate curved in the shape of a vault of a

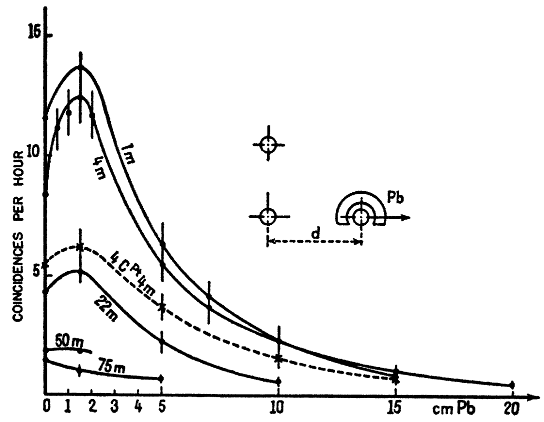

Fig. 2. Secondary effects of particles in lead.

diameter just greater than that of the counters is almost ineffective, but if the diameter is larger, the multiplication takes place, because some particles which would not have touched the counters, touch it now by the showers they produce in the lead. We could show that this multiplication effect was smaller at greater distance (Fig. 2) and that consequently the particles which are responsible for the coincidences far away from the shower center are mostly electrons of smaller energy (perhaps secondaries from mesotrons?).

Absorption of Particles

We have said that thick plates reduced the number of coincidences, and this effect is due to the absorption of the particles. We tried to separate the absorption from the multiplication effect, and for that purpose we used two counters, placed above one another and which could be separated by absorbing screens, and a third one at a few meters distance. The system of two counters was protected against side showers by thick lead walls. We obtained an absorption curve (Fig. 3) which extended farther than 20 cm of lead. We think that the presence of bundles of electrons of high energy is sufficient to account for these penetrating powers, as our Wilson photographs have shown, up to 10 or 15 cm of lead. If the existence of a much more penetrating part is confirmed, the presence of a small proportion of mesotrons in the showers would have to be supposed.

[6] Private communication.

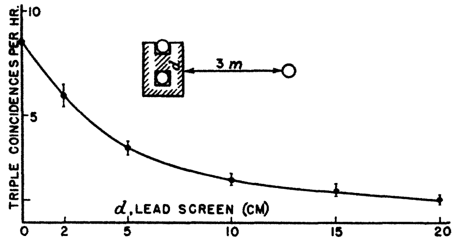

FIG. 3. Absorption curve obtained with the three counters as shown.

Barometer Effect

A very strong variation of the number of showers with the barometric pressure was found. The change was as large as 15 percent for a variation of 15 mm Hg. The mass absorption coefficient that can be deduced from these measurements is $\mu/\rho=0.007$ (in g per cm^2). From this coefficient, the decrease calculated for a screen of 3.5 meters water (equivalent to 3500 m of atmosphere) is in good agreement with the ratio of showers measured in Jungfraujoch and at sea level.

Density of Tracks

The simplest method for measuring the density of tracks consists in comparing the number of coincidences with 2, 3 and 4 counters. The proportion between these numbers gives the probability for a counter to be touched by a particle in a shower. The density can be calculated, in particles per square meter, if we know the surface of the counter, and if we suppose a regular statistical distribution. We found densities from 10 to 100 particles per square meter.

But the distribution is surely not uniform, as it is for raindrops for instance. If one counter is touched, the probability of a second counter placed nearby to be touched is much greater than if the second counter is far away. This kind of distribution gives rise to local concentrations separated by relatively empty spaces. This makes the evaluation of the total number of particles a little difficult. From the measurements of density obtained at great distances (about 10 per square meter) and the total covered surface (about 10^5 square meters) we derive a total number of 10^6 particles in the large showers.

Number of Showers

With a system of three counters arranged in double coincidences we could register, at sea level, about 30 coincidences per hour. From the surface of the counters and the density of tracks we calculated that about one-half of the real showers was detected and that the number of extensive showers is of the order of 60 per hour at sea level. This number increases very rapidly with altitude; as the density of tracks changes also, the increase of the real number of extensive showers is not known with precision, but is of the order of a factor 10 between sea level and Jungfraujoch.

Wilson Chamber Photographs

We have obtained a great number of cloud-chamber photographs of portions of the extensive showers,[7] and could derive from the statistics a confirmation of the nature of the particles in the central beam; we could not prove definitely the existence of mesotrons. With a special controlling system only sensitive to the penetrating part of the showers, a number of photographs were taken, showing very dense and narrow showers. This shows that the inequalities of distribution must be taken into account in the interpretation of the absorption curves. The part of the showers which traverses 10 cm of lead seems to be constituted chiefly of narrow beams of very energetic electrons. The proportion of mesotrons in the ionizing particles is surely much smaller than 10 percent. An abnormally high number of slow proton tracks was also recognized on these photographs: about 12 tracks per 100 photographs, instead of one or two percent as we have obtained with an ordinary shower-sensitive controlling system. It shows the frequency of nuclear disintegrations in the penetrating part of the extensive showers, due perhaps to the presence of photons of very high energy and of neutrons.

Energy of Showers

A simple evaluation of the energy of these showers is obtained by the consideration of the total energy of the particles which reach the

[7] See also Jánossy and Lovell, Nature **142**, 716 (1938).

low atmosphere. We have seen that we may take 10^6 as the total number of particles present. The energy of the majority of these particles is probably, the critical energy for air, that is 10^8 ev. We obtain in that way 10^{14} ev as the total energy of the shower particles, and have to add a factor 10 to account for the energy lost during the traversal of the atmosphere so that 10^{15} is likely to be the energy of the primary particle.

The calculations of Bhabha-Heitler lead to the same value if we consider that the atmosphere is equivalent to 30 radiative units, and that the showers contain more than 10^5 particles. For showers of about the same number of particles reaching only the Jungfraujoch (20 radiative units) the minimum energy would be of the order of three times smaller.

Energy Spectrum of Primaries

It is interesting to see if our measurements are consistent with the spectral distribution which has been found in the case of the penetrating particles. The number N of particles with an energy higher than E is proportional to E^{-2}, so that the ratio of the numbers of showers reaching two levels should be equal to the inverse ratio of the squares of the energies of the primaries necessary to produce them. In the case of sea level ($l=30$) and Jungfraujoch ($l=20$), we have measured $N(20)/N(30)=10$ and if the energies are in the ratio 1 to 3 as computed above, the agreement is good.

We may also try to give an evaluation of the number of primary particles with an energy higher than 10^{15} ev. We may reasonably think that we detect generally the showers if their densest central part falls on the counter systems, so that the effect of one incident primary extends to a surface of the order of 10^4 square meters. As we have found 60 showers per hour, it gives 10^{-9} particle of $E>10^{15}$ ev per minute and per square centimeter in the upper atmosphere. But from the measurements in the upper atmosphere we may infer that the total number of particles with energies $E>5\times10^9$ ev is of the order of 50 per minute and square centimeter. So that the ratio of numbers of these two categories of primaries is $0.5\ 10^{-11}$ and the inverse square ratio of their minimum energies is $2.5\ 10^{-11}$. The agreement is sufficient if we consider the very rough evaluations we have taken as basis.

Conclusion

One of the consequences of the extension of the energy spectrum of cosmic rays up to 10^{15} ev is that it is actually impossible to imagine a single process able to give to a particle such an energy. It seems much more likely that the charged particles which constitute the primary cosmic radiation acquire their energy along electric fields of a very great extension.