very interesting phenomenon—namely, tracks which are almost parallel in the cloud chamber. In at least three of the cases the tracks project rather accurately back to the lead absorber which is 75 cm above the center of the cloud chamber. It is thus quite possible that the showers are originally star-like and that geometrical factors cause the selection of an almost parallel core of particles in the cloud chamber. Low energy penetrating particles, if not lost by their emission at wide angles, may be lost by absorption in the lead. Thus the showers presented here are quite consistent with the beautiful photographs of Hazen and Fretter showing the development of star-like penetrating showers in multiple lead plates in the cloud chamber.

V. CONCLUSION

The following are the main results which follow from the analysis of the small sample of penetrating showers presented in this paper:

(1) Although many of the penetrating particles may be ordinary (μ) mesons, an appreciable fraction of the particles have properties different from μ-mesons. Thus, out of twenty particles, with momenta greater than 10^9 ev/c, four are anomalously scattered in the 3-cm lead plate and three produce no visible particle.

(2) The penetrating particles which interact with matter may be protons, π-mesons (Lattes, Occhialini, and Powell[14]), or heavier mesons. The positive bias suggests protons. Identifiable slow protons are often present in the showers.

(3) Some of the showers are very complex. There are complex showers which consist mainly of electrons and a few penetrating particles, and others which consist of large collimated groups of positively charged penetrating particles.

Note added in proof. It now seems probable that the mass ratio m_π/m_μ is 1.33 and not 1.65 as assumed when the paper was written. The identification of the slow mesons as π- or μ-mesons is therefore more uncertain than is indicated in Section III.

[14] G. M. G. Lattes, G. P. S. Occhialini, and C. F. Powell, Nature **160**, 453, 486 (1947).

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Results and Problems Concerning the Extensive Air Showers

G. Cocconi†

Cornell University, Ithaca, New York

THE extensive air showers constitute the only known phenomena in which energies as large as 10^{15}–10^{18} ev are involved; this is the reason why at present and surely at least in the near future the deepest interest is attached to them. After ten years of research in the extensive showers, experimental and theoretical results are grown enough to allow a fairly accurate description of some of the involved processes and a rather clear definition of the still open problems.

In the following we shall attempt to give a description of the results and problems concerning the extensive cosmic-ray air showers, facing the topics primarily from the experimental point of view. Before entering the argument we want to state an "instrumental" definition of extensive air showers. We think that this is quite important, because in our opinion, several discrepancies in the results of different authors arise from different criteria in considering a recording system suitable to detect extensive showers.

Before claiming to deal with an extensive shower, we think the following requirements must be fulfilled: $n(>1)$ detecting devices must be crossed simultaneously each by at least one ionizing cosmic-ray particle, such devices being placed in a horizontal plane at a distance one from the other at least of $10/n$ to $20/n$ times the average horizontal dimension of their sensitive surfaces, provided that this distance is not

† On leave from the University of Catania, Italy.

smaller than 2–4 meters. This definition probably cuts off some of the extensive showers smaller and poorer in particles, but surely avoids considering as extensive showers single particles accompanied either by a few secondaries generated in the air or by many secondaries locally produced.

Two or more trays of G-M counters as well as two or more ionization chambers, of proper surfaces and at proper distances, satisfy the above requirements and the coincidences recorded with such systems are in the very great majority caused by showers in which a large number of particles is present, at least some hundreds, spread on surfaces of several square meters, often several thousands. By recording the extensive showers with proper devices, three components so far have been identified:

1. the soft component
2. the penetrating component
3. the neutronic component

Our knowledge about these components is quite far from being complete. We face here the same situation which is peculiar to nearly all cosmic-ray topics: the behavior of the soft component is fairly well known and theoretically explained, while the behavior of the penetrating and neutronic components, though known in several particular points, still lacks a satisfactory synthetic picture.

I. THE SOFT COMPONENT

When an extensive shower is recorded by unshielded devices (G.-M. counters or ionization chambers in open air), the very great majority of the recorded coincidences is due to electrons, constituting more than 95 percent of the ionizing particles present in the shower.

From the experimental point of view the more significant results concerning the electronic component are:

a. the decoherence curve, i.e., the variation of the rate of coincidences of two recording systems, *versus* distance between the systems. Experiments performed by Auger and co-workers[1] and by Skobeltzyn and co-workers[2] have revealed the existence of showers spread over distances as large as 1000 meters.

b. the density spectrum, i.e., the rate of the extensive showers *versus* the density (number of particles per unit surface) of the showers. The experiments have been performed by Cocconi, Loverdo, and Tongiorgi[3] with the result that in the density range between 10 and 1000 particles per square meter the following power-law is very well fulfilled:

$$N(\Delta) = K\Delta^{-\gamma},$$

where $N(\Delta)$ is the rate of showers with densities $>\Delta$, K and γ are constants depending on the altitude above sea level. At sea level, measuring Δ in m^{-2} and N in $sec.^{-1}$, $K=0.18$, and $\gamma=1.46$.

c. the altitude dependence, i.e., the variation of rate of extensive showers *versus* altitude above sea level.

Experiments up to 4300 m have been performed by Hilberry[4] and up to 12,000 by Kraybill.[5] They found an exponential increase with altitude with a mean free path of ~ 130 g cm^{-2}, in the lower atmosphere, followed by a plateau and a decrease after 8500 m.

The results listed in *a*, *b*, and *c* can be explained from the theoretical point of view by assuming that the soft component of the extensive air showers consists of electrons and photons generated through multiplicative cascade processes started by very energetic (10^{14}–10^{18} ev) primary electrons in high atmosphere.

The agreement between theory and experiment is quite satisfactory also quantitatively,[6, 7] if one chooses for the primary electrons the same power-law energy spectrum which appears to be suitable for justifying several other phenomena connected with the total soft component of the cosmic radiation.

A still controversial point, however, is the altitude dependence of the exponent γ in the density spectrum. The theory predicts an in-

[1] P. Auger, R. Maze, and J. Robley, Comptes Rendus **208**, 1641 (1939).

[2] V. D. Skobeltzyn, G. T. Zatsepin, and V. V. Miller, Phys. Rev. **71**, 315 (1947).

[3] G. Cocconi, A. Loverdo, and V. Tongiorgi, Phys. Rev. **70**, 846 (1946).

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

[5] H. L. Kraybill, Phys. Rev. **73**, 632 (1948).

[6] G. Molière, *Vorträge über Kosmische Strahlung* (Berlin, 1943), p. 24.

[7] G. Cocconi, Phys. Rev. **72**, 974 (1947).

crease of γ with altitude, but some experimental results seem to indicate the opposite behavior.[8,*]

It is necessary to point out that the assumption of the existence of a single primary electron of extremely high energy (10^{14}–10^{18} ev) is by no means essential, as well as the validity of the cascade theory for such energies. Any primary particle, whose energy undergoes any degenerative process giving rise in the high atmosphere to several electrons of energies even not larger than to 10^{11}–10^{12} ev may be responsible for an extensive shower in which the soft component behaves as in the theoretical picture assumed before. This, of course, is due to the fact that the main characteristics of the multiplicative theory principally depend on the behavior of the less energetic electrons and photons.

For this reason, the soft component of the extensive showers, though the more abundant one, is probably not the best tool for obtaining information about the processes occurring at the highest energies. A more promising way for approaching the problem is given instead by the study of the other components of the extensive showers, which, however, are unfortunately only a few percent of the total number of particles in the showers.

II. THE PENETRATING COMPONENT

The penetrating component of the extensive showers is selected when the recording devices are arranged as for detecting the soft component, but shielded by a screen of material thick enough to stop all the electrons. Because of the large energies and the overwhelming number of the electrons and photons in the showers, no less than 18–20 cm of Pb, at sea level, is necessary, as well as a very careful arrangement of the screens on *all* sides of the recording devices. The more significant results thus far obtained are the following.

a. Correlation Between Soft and Penetrating Components. "All extensive air showers contain penetrating particles and all extensive penetrating showers are accompanied by extensive electron showers." This conclusion was reached by Cocconi, Loverdo, and Tongiorgi[9] and confirmed by Treat and Greisen[10] and by Fretter.[11] The first two groups of experimenters showed this correlation between soft and penetrating extensive showers by using unshielded and shielded counters in coincidence, whereas Fretter observed the two kinds of components in a cloud chamber triggered by extensive showers.

This result demonstrates that the development of the extensive showers involves the multiple production not only of electrons, but also of penetrating particles and rules out the possibility of describing *all* processes in the extensive showers in terms of cascade theory.

b. Relative Intensities of the Soft and Penetrating Components. From the experiments mentioned in *a* and from similar ones, indications may be drawn about the relative number of penetrating particles and electrons in the extensive showers, if we assume that the ratio of penetrating particles to electrons is constant throughout the showers. The experiments performed at sea level,[12] have indicated that the penetrating particles are about 2 percent of the electrons; the same figure was found at 2200 m,[9] while 3 percent and 4 percent have been obtained at 3200 m and 4300 m.[10] The accuracy of all these experiments is not good enough to make reliable the altitude variation of the relative intensities of the two components. Furthermore, the ratio in question strongly depends on the amount of lead screening the apparatus, i.e., on the energy of the recorded penetrating particles.

Besides that, it is necessary to remember that the assumption of the constancy of the ratio of penetrating particles to electrons in every region of the shower is a very crude one. It is more likely in fact that electrons and penetrating particles, owing to different angular spread in the production processes, have different relative distributions inside the showers.

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[8] R. Maze, A. Fréon, and P. Auger, Phys. Rev. **73**, 418 (1948).

* *Note added in proof:* Recent experiments (G. Cocconi and V. Tongiorgi, to appear in the Phys. Rev.) have shown that the exponential law for the density spectrum given in *b* does not hold when Δ varies by a factor larger than 100. The exponent γ slightly increases with Δ. For medium densities ($\sim$100 m^{-2}) γ slightly decreases with altitude, while for large densities it shows the opposite behavior.

[9] G. Cocconi, A. Loverdo, and V. Tongiorgi, Phys. Rev. **70**, 852 (1946).

[10] J. E. Treat and K. I. Greisen, Phys. Rev. **74**, 414 (1948).

[11] W. B. Fretter, Phys. Rev. **73**, 41 (1948).

[12] D. Broadbent and L. Janossy, Proc. Roy. Soc. **192**, 364 (1948).

The study of the distribution of the particles in the showers may probably throw some light on the mechanism of production of the extensive showers. The extreme possibilities are the existence of a single core (i.e., a distribution of particles with a single density and energy maximum), as the cascade theory predicts for the electrons, and the existence of several cores as predicted by the Lewis, Oppenheimer, and Wouthuysen's theory of multiple production of penetrating particles.[13] Experiments of Williams[14] with ionization chambers seem to indicate the presence of a single core of electrons, but since the experiments were limited to distances not bigger than 12 meters, no definite conclusions may be drawn.**

c. Penetrating Power of the Hard Component. Information about the penetrating power of the hard component of the extensive showers has been till now very scanty, so that conclusions cannot be drawn.

In our opinion the selection of penetrating particles in the extensive showers has often been carried on without shielding carefully enough the detecting apparatus, hence recording, besides penetrating particles, either energetic electrons or photons, when the shields were not thick enough, or scattered electrons, when the detecting apparatus was not shielded on all sides.***

d. Origin of the Penetrating Particles. It has been found by Cocconi and Festa[15] that the frequencies of the penetrating showers associated with extensive showers do not depend on the atomic number of the material used for shielding the counters (the comparison was made between lead and concrete). The same conclusion has been reached by Janossy[12] and Salvini and Tagliaferri[16] from the comparison of the frequencies under lead and iron; however, we have to note that their arrangements for selecting the extensive showers do not fully satisfy the requirements we think necessary for ruling out phenomena different from extensive showers.

As Ferretti has shown,[17] the independence of the frequencies of the penetrating showers of the atomic number Z implies that, if the penetrating showers are locally created in the material above the detecting apparatus by a single electron or photon, the cross section of the process depends on Z^2, which is quite hard to understand.

The experimental result is instead easily understandable if the penetrating particles are mostly pre-existing in the showers before reaching the counters, because in this case the absorption is mass-proportional. A strong support in favor of this assumption has been obtained in recent works performed at Cornell.[10,18] Looking at penetrating showers accompanied by extensive showers, no difference has been found between the frequencies of narrow and large penetrating showers, i.e., of showers recorded with the counters under lead, once 15 cm apart, once 2 m apart. In the case of local multiple production of penetrating particles, a much higher rate should have been recorded when the counters were closer.

Different conclusions have been reached by Janossy[12] and by Salvini and Tagliaferri.[16] But as said before, their experiments may have been invalidated by spurious phenomena.

We insist on the necessity of the selection of the extensive showers satisfying the requirements stated at the beginning of this paper, because there exists another kind of penetrating shower,[10,12,18] namely, penetrating showers not accompanied by extensive showers. Strong experimental evidence has been obtained that these showers behave in a completely different manner than the extensive penetrating showers, i.e., they are locally produced in the material surrounding the apparatus, their frequencies depend on the

[13] H. V. Lewis, J. B. Oppenheimer, and S. A. Wouthuysen, Phys. Rev. **73**, 127 (1948).

[14] R. W. Williams, Bull. Am. Phys. Soc. **23**N, 21 (1948).

** *Note added in proof:* A recent experiment (G. Cocconi, V. T. Cocconi, and K. Greisen, to appear in the Phys. Rev.) has shown that this conclusion holds also for showers covering distances up to 200 m, and that the ratio penetrating particles/electrons is not a constant throughout a shower, but increases with the distance from the core.

*** *Note added in proof:* In a recent experiment (G. Cocconi, V. T. Cocconi, and K. Greisen, to appear in the Phys. Rev.) it has been found that the penetration in lead of photons in extensive showers is larger than previously thought. Only under more than 19 cm Pb the recorded particles are surely not electrons. They show a very small absorption coefficient and their number increases with height *less* than the number of the electrons. This strongly supports the assumption that they are μ-mesons.

[15] G. Cocconi and C. Festa, Nuovo Cimento **3**, 293 (1946).

[16] G. Salvini and G. Tagliaferri, Phys. Rev. **73**, 261 (1948).

[17] B. Ferretti, Nuovo Cimento **3**, 301 (1946).

[18] G. Cocconi and K. I. Greisen, Phys. Rev. **74**, 62 (1948).

atomic number of the material in which their production takes place and their primaries are probably nucleonic particles.

The main conclusion which may be drawn from the experimental results listed in *a*, *b*, *c*, and *d* is the strong correlation between soft and penetrating components in the extensive showers. This phenomenon seems to be characteristic of the high energy processes responsible for the origin of the showers.

A tentative hypothesis is that the primary protons coming from outside the atmosphere are the particles giving rise to all the components of the extensive showers, which later develop throughout the atmosphere. If this is true, the same phenomenon may be produced by high energy protons also in condensed materials. Actually there is evidence of local simultaneous production in lead of showers consisting of both penetrating and soft particles generated by a nucleonic component of the cosmic radiation.[11,19,20] Further checks on this point are very important. Greisen[21] has pointed out that local and extensive penetrating showers, though appearing differently in the experimental investigation, might be not different phenomena but only different stages in development of the same kind of showers. The same phenomena occurring in the air might occur also under lead, though on a smaller scale owing to the lower energy of the particles originating the showers. The probability that a particle of very high energy will fall on the absorbers shielding the recording devices is in fact extremely small, while the probability of recording an air shower originated by a particle of the same energy is much bigger because of the large spread of the shower in the air.

Reasonable mechanisms of simultaneous production of soft and penetrating particles have been tentatively suggested.[21]

III. THE NEUTRON COMPONENT

Evidence of the existence of neutrons associated with extensive showers has been obtained.[22]

Neutrons have been detected with proportional BF_3 counters imbedded in paraffin and put in delayed coincidences with G.-M. counters selecting extensive showers. Such a delay allowed the removal of the background due to spurious events and, on the other hand, did not imply a sensible loss of neutrons because of their long lifetime in paraffin.

The following conclusion has been reached: At sea level neutrons in the extensive showers, with energies not bigger than 15 Mev, are nearly as frequent as penetrating particles, i.e., they constitute about 1–2 percent of all particles.

Further experiments[23] have been carried on, in an attempt to face the problem of the origin of the neutron in the showers. Though till now only preliminary results are available, we think that a good evidence has been obtained that neutrons are produced by a penetrating component of the extensive showers with small, if any, contribution from the soft component.

This result enhances the assumption that a substantial fraction of the penetrating component of the extensive showers may consist of nucleons.****

[19] E. P. George and P. T. Trent, Nature **161**, 248 (1948).
[20] H. Bridge, W. E. Hazen, and B. Rossi, Phys. Rev. **73**, 179 (1948).
[21] K. I. Greisen, Phys. Rev. **73**, 521 (1948).

[22] V. Tongiorgi, Phys. Rev. **73**, 923 (1948).
[23] V. Tongiorgi, Phys. Rev. **74**, 226 (1948).
**** *Note added in proof:* This assumption is strongly supported by other experiments by the same author, which show that the neutron-producing component generates in lead showers of $\sim$30 neutrons of energies between 3 and 15 Mev.