tions of extensive showers becomes much smaller than that of their highly absorbable parts.

(4) The very penetrating parts of extensive showers (beyond 20 cm of lead) produce in the lead numerous secondary electrons.

(5) In the study of coincidences between near counters, under thick lead shields (10 cm to 20 cm), a local phenomenon produced in the lead is substituted for the local atmospheric phenomenon, and it is uncertain whether it has the same cause. The absorption coefficient of this local secondary phenomenon is of the order of 100 to 200 g cm^{-2}, that is to say, of same order as the decrement of extensive showers in the atmosphere and also of local showers above 3000 m.

An explanation of this set of observations cannot be found in the hypothesis that in cosmic radiation only mesons and electrons are present. It is impossible to attribute to mesons either the important secondary effects observed even under 20 cm of lead in the penetrating parts of extensive showers, or without doubt the "explosive" effects observed for penetrating particles which are not parts of extensive showers. The absorption of extensive shower particles between 5 cm and 15 cm of lead does not correspond either to electrons or to mesons.

REVIEWS OF MODERN PHYSICS VOLUME 21, NUMBER 1 JANUARY, 1949

The Penetrating Particles in Cosmic-Ray Showers

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I. INTRODUCTION

During the past two years the Blackett electromagnet has been used in the study of cosmic-ray showers, and a summary of the main results is given in this paper.* Two aspects of showers are considered; firstly, the nature of the heavily-ionizing particles occurring in showers, and secondly, the lightly-ionizing particles in penetrating showers.

Two counter arrangements (Rochester and Butler[1]) were used to trigger the cloud chamber. Neither arrangement was rigidly selective for any particular kind of shower and even though the counters were connected in fivefold coincidence to reduce the rate of random coincidences, the cloud chamber could be set off by a shower consisting of two particles. In order to identify the showers in the cloud chamber connected with extensive showers, a tray of 14 counters connected in parallel, effective area 1700 cm^2, was placed 1 m from the chamber. An indicator lamp at the cloud chamber showed whether one or more ionizing particles crossed the extension tray within 2 μsec. of the fivefold master pulse. For most of the showers described in this paper the counter trays above the chamber were covered by a layer of lead 5 cm in thickness. There was, moreover, a layer of lead immediately in contact with the chamber wall. The thickness of this lead is indicated in the tables.

The cloud chamber was 30 cm in diameter and 9 cm in depth and was filled to a pressure of 1.5 atmospheres with a gas mixture consisting of 80 percent argon and 20 percent oxygen. Across the chamber was a lead plate 30.5 mm in thickness faced above and below with brass reflecting plates 1.8 mm in thickness.

II. MEASUREMENT OF CURVATURE AND ACCURACY OF MOMENTUM DETERMINATION

The curvatures of most of the low energy tracks were determined by direct measurement on a travelling microscope fitted with a Zeiss micrometer eyepiece. The results for good tracks

* This work has been carried out in collaboration with Dr. C. C. Butler, Dr. S. M. Mitra, and Mr. W. G. V. Rosser.

[1] G. D. Rochester and C. C. Butler, Proc. Phys. Soc. London 61, 307 (1948).

measured by different observers agreed to within 10 percent. A good track is defined as one free from obvious distortion and longer than 6 cm in the chamber.

The curvatures of the high energy tracks were measured on the Blackett curvature-compensating machine.[2] A check on the performance of the cloud chamber was made in two ways: firstly, by measuring up 87 meson tracks photographed without a magnetic field, and secondly, by measuring up 90 meson tracks in a magnetic field. These tracks were taken under chamber conditions identical with the showers, except that the lead above the chamber was removed. It was found that a fairly good Gaussian could be fitted to the no-field measurements. The half-width of the Gaussian corresponded to a momentum of 8.4×10^9 ev/c in a magnetic field of 7500 gauss, and this was taken as the maximum detectable momentum.

The meson tracks photographed in the magnetic field gave a spectrum which agreed closely with that obtained by Wilson.[3] It was therefore assumed that the performance of the cloud chamber was satisfactory.

III. THE HEAVILY IONIZING PARTICLES

The different types of heavily ionizing particles have been identified by the measurement of their momenta and the visual estimation of the density of ionization along their tracks. The proton tracks have been used as a reference scale. The data are plotted in Fig. 1, following a procedure used by Leprince-Ringuet, Léhritier, and Richard-Foy.[4] The estimated error in the ionization is taken as the range of several independent estimates by two observers. Arrows at the ends of the error lines indicate ionizations greater than fifteen times the minimum. The theoretical curves calculated for masses of $200m_e$, $320m_e$, and $1837m_e$ are also shown from which it is apparent that the data fall into two main groups, around the proton and meson curves. Data for the slow mesons are given in Table I, and photographs of two of these particles are shown in Fig. 2. The sign of the particle has been determined by making a reasonable choice as to the direction of the particle, and confirmation has been obtained in several cases from knock-on electrons. All the slow mesons make large angles with the vertical and in three cases they arise from explosions in the lead plate. Because of the large magnetic field the error in curvature due to scattering is relatively small.

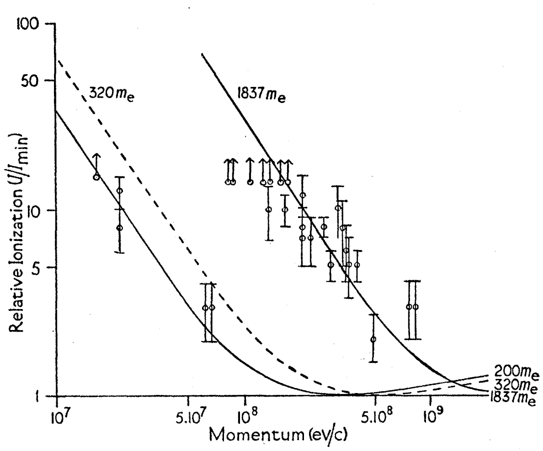

FIG. 1. Relative ionization for particles of different mass.

TABLE I. Slow mesons.

1. Photograph	1	2	3	4	5
2. Sign	negative	positive		negative	negative
3. Magnetic field (gauss)	3400	7100	7100	7250	6500
4. Momentum (ev/c)	2.2×10^7	6.9×10^7	1.7×10^7	6.3×10^7	2.2×10^7
5. Kinetic energy (ev)	2.4×10^6	2.4×10^7	1.4×10^6	2.0×10^7	2.4×10^6
6. Estimated $I/I_{\text{min.}}$	6–10	2–4	15	2–4	10–15
7. Calculated $I/I_{\text{min.}}$					
Electron (m_e)	1.4	1.5	1.4	1.3	1.4
Meson ($100m_e$)	3.8	1.2	5.8	1.2	3.8
Meson ($200m_e$)	10.9	2.1	16.2	2.3	10.9
Meson ($320m_e$)	22.3	3.9	32.4	4.5	22.3

The estimated ionization is given in line 6 of Table I and in line 7 are given the calculated relative ionizations for particles of different mass. It is seen that in most cases reasonable agreement is obtained by assuming a mass of $200m_e$. In four out of the five cases, however, *viz.*, particles (2), (3), (4), and (5), a mass of $320m_e$ would be quite consistent with the measurements. Even in the fifth case a mass of $320m_e$ cannot be excluded. The assignment of mass $200m_e$ also gives a rather better fit with the measured energies of the knock-on electrons observed with particles (1) and (5). The electron knocked on by meson (5) is indicated by the letter '*k*' in Fig. 2.

These results have a bearing on the important problem of the creation of the meson. In the first place they give support to the view that

[2] P. M. S. Blackett, Proc. Roy. Soc. **A159**, 1 (1937).
[3] J. G. Wilson, Nature **158**, 414 (1946).
[4] L. Leprince-Ringuet, C. Léhritier, and R. Richard-Foy. J. de phys. et rad. Sér. 8, **7**, 69 (1946).

mesons are created mainly in explosive-type showers and not in electron-cascade showers, a view which is consistent with the work of W. M. Powell[5] and Hazen[6] and with the recent discovery of the artificial production of mesons in the Berkeley cyclotron. In the second place they suggest that μ-mesons may be created directly in nucleon collisions, and are not necessarily always the disintegration products of the π-mesons as suggested by Marshak and Bethe.[7]

The meson (m) of Fig. 2b is of interest because it is connected with an extensive air shower. There was no lead above the chamber for this photograph. Stereoscopic examination of the photographs shows that this meson comes from the piston at the back of the chamber. It is not possible to determine, therefore, whether it has been created locally or was part of the extensive air shower incident on the apparatus.

IV. THE LIGHTLY IONIZING PENETRATING PARTICLES

In this section an account will be given of the lightly ionizing particles which occur in the penetrating showers selected from the main group of showers. A penetrating shower is defined for this purpose as a shower containing two or more ionizing particles which can penetrate the 3-cm lead plate in the cloud chamber. This very rigid selection has been made in order to exclude knock-on showers. It is presumed that these penetrating showers are mainly of the 'local' type, that is, showers created near the chamber.

Six penetrating showers containing sixteen penetrating particles have been selected and the results are given in Table II. Photographs of the showers A, D, and E are shown in Fig. 3. The thickness of the lead above the chamber is given in columns (2) and (3) of the table and the observed and calculated scattering of the particles in columns (8) and (9). Shower F was connected with an extensive air shower.

The data show three striking features, namely: (1) a large positive excess, (2) a relative abundance of particles with momenta below 2×10^9 ev/c (see Table III), and (3) three cases of anomalous

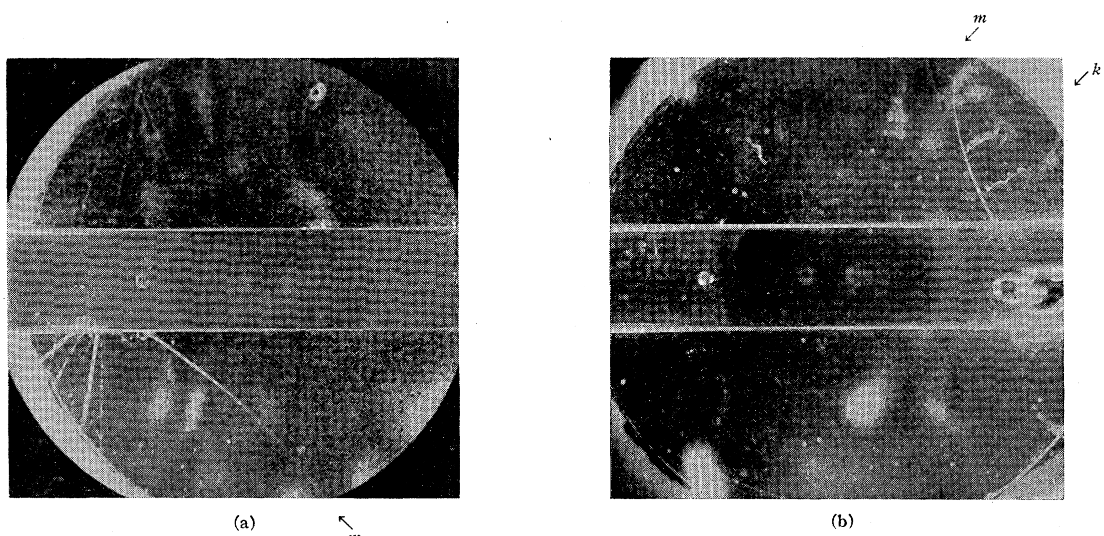

FIG. 2(a). (*Particle (1) Table I.*) A slow meson associated with a penetrating shower. This meson (m), which is interpreted as a μ-meson, has a momentum of 2.2×10^7 ev/c and a kinetic energy 2.4×10^6 ev. It is negative if coming downwards. The track at the point where the meson emerges from the plate is interpreted as due to a knock-on electron. $H=3400$ gauss.

FIG. 2(b). (*Particle (5) Table I.*) A slow meson (m) associated with an extensive air shower. This meson, which is interpreted as a μ-meson, has a momentum of 2.2×10^7 ev/c (kinetic energy 2.4×10^6 ev) and is negative if coming downwards. It comes across the chamber out of the piston and may therefore have been created locally. The direction and identification are confirmed by the knock-on electron (k). The other electron, which is not a knock-on, can be seen stereoscopically to cross the meson track towards the front of the chamber. $H=6500$ gauss.

[5] W. M. Powell, Phys. Rev. 69, 385 (1946).
[6] W. E. Hazen, Phys. Rev. 65, 67 (1944).
[7] R. E. Marshak and H. A. Bethe, Phys. Rev. **72**, 506 (1947).

TABLE II. Penetrating particles in penetrating showers.

Shower	Lead in contact with wall of chamber (cm)	Total thickness of lead above chamber	Magnetic field (gauss)	No. of particle	Sign of particle	Momentum ($\times 10^9$ ev/c)	Angle of scatter (deg.) Obsd.	Calcd.*
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
A	1.8	16.8	7200	1	Positive	1.3	0.1	1.4
				2	Positive	1.1	0.1	1.7
				3	Positive	1.4	0.5	1.3
				4	Positive	0.65	0.8	2.9
B	1.8	16.8	7250	1	Positive	3.3	0.6	0.6
				2	Positive	0.91	12.8	2.1
				3	Positive	1.0	0.8	1.9
				4		Too faint to measure.		
C	1.8	16.8	7100	1	Positive	0.66	0.5	2.9
				2	Negative	0.85	2.2	2.2
D	1.8	6.8	7200	1	Positive	1.2	2.4	1.6
				2	Positive	1.1	0.0	1.7
				3	Positive	1.0	0.0	1.9
				4	Positive	0.77	2.4	2.4
E	5.0	10.0	6900	1		Too faint to measure.		
				2	Negative	1.1	12.0	1.7
				3	Positive	(Above 4.5) (Below 0.3)	28.0	—
F	5.0	10.0	7300	1	Positive	0.63	3.0	3.0
			This shower was part of an extensive shower.					

* E. J. Williams, Proc. Roy. Soc. **A169**, 531 (1939).

scattering. These results will be considered in turn.

The large positive excess of 14 positive to two negative particles suggests that the ionizing penetrating particles in penetrating showers are mainly protons. With such a small sample of particles, however, this result should be taken with some caution. If we assume that the negative particles are mesons and add the particles which are still lightly ionizing when their momenta are $<0.66\times10^9$ ev/c, we find that five of the sixteen particles could be mesons. The ionization of a proton of momentum 0.66×10^9 ev/c is twice minimum.

The relative abundance of particles of approximately 10^9 ev/c seems to indicate a spectrum which is very different from the ordinary meson spectrum at sea level. This result, also, must be taken with some caution in view of the small numbers. Nevertheless, the bias in the spectrum is somewhat similar to the positive 'excess' found by Adams, Anderson, Lloyd, Rau, and Saxena[8] at an altitude of 30,000 feet. Anderson and his co-workers suggested that the 'excess' positive particles were probably protons. It is not suggested, however, that the particles reported in this paper are necessarily protons. If, for example, they were mesons created near the chamber, the spectrum would clearly be different from the meson spectrum at sea level.

Finally, out of sixteen penetrating particles, three are anomalously scattered. There is little doubt that this result is significant especially when taken in conjunction with previous work on penetrating showers. Rochester[9] found two cases of ionizing penetrating particles scattered through 10.2° and 18.0°, respectively, in a 2.3-cm lead plate out of 32 penetrating particles in penetrating showers. Although the momenta of the particles were not known, the type of shower

TABLE III. Spectrum of penetrating particles.

No. of penetrating particles	0	8 ± 3	6 ± 2	2 ± 1
Momentum range (10^8 ev/c)	1–5	6–10	11–20	21–∞

[8] Adams, Anderson, Lloyd, Rau, and Saxena, Rev. Mod. Phys. **20**, 334 (1948).

[9] G. D. Rochester, Proc. Roy. Soc. **A187**, 464 (1946).

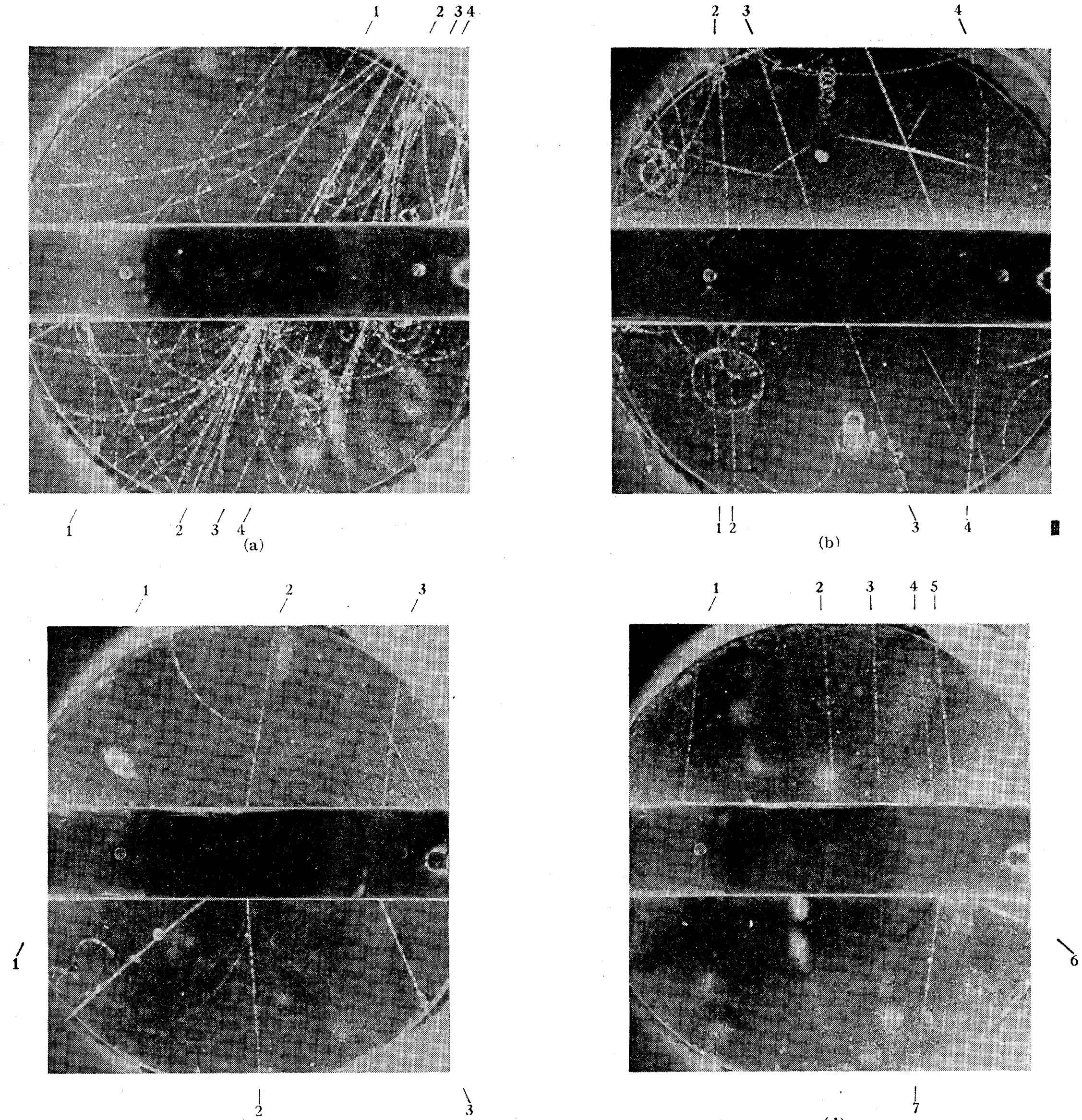

FIG. 3. For all photographs except (*c*) a positive particle coming down is curved in a clockwise direction. *Figure 3*(*a*) (*Shower A*, *Table II*) shows a complex penetrating shower consisting of four lightly-ionizing penetrating particles and a large electronic shower. The penetrating particles are indicated by numbers. They are positively charged and have momenta ranging from 1.4 to 0.65×10^9 ev/c. $H=7200$ gauss. *Figure 3*(*b*) (*Shower D*, *Table II*) is an example of a locally-produced penetrating shower consisting of several penetrating particles, two identifiable protons, and a small number of electrons. The interpretation of the deflection in track (4) has been discussed by Rochester & Butler (Nature **160**, 855, 1947). *Figure 3*(*c*) (*Shower E*, *Table II*) shows a penetrating shower consisting of three penetrating particles (1), (2), and (3). Particle (2) is a negative particle of momentum 1.1×10^9 ev/c and is anomalously scattered through 12.0° in the lead plate. Particle (3) is positive with a momentum of 4.5×10^9 ev/c above the plate and 3.0×10^8 ev/c below the plate and is scattered through 28.0°. The particle below the plate is a proton. The heavily ionizing particle which appears to come from the same region in the lead plate as the lower part of (2) is actually in a plane 1.8 cm behind it. Thus, if the heavily ionizing particle is connected with particle (2), it must be via an intermediate link. The heavily ionizing particle is positive and has a momentum of 1.6×10^8 ev/c. A proton of this momentum ionizes $15\times$minimum whereas the ionization is estimated as $7\times$minimum. The difference may be due to fluctuation or indicate a particle of intermediate mass. $H=6900$ gauss. *Figure 3*(*d*) (*Shower G*, *Table IV*) shows an unusual shower consisting of several high energy particles which stop in the lead plate without producing visible particles. All the particles except (3) are well in the illuminated region of the chamber and nearly all have momenta much above 10^9 ev/c. $H=7100$ gauss.

TABLE IV. Shower G.

Shower	Lead in contact with wall of chamber (cm)	Total thickness of lead above the chamber (cm)	Magnetic field (gauss)	No. of particles	Sign of particle	Momentum ($\times 10^9$ ev/c)	Posn. of track at plate (cm)	Posn. of other end of track (cm)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
G	5.0	10.0	7100	1	Positive	0.75	4.9	3.8
				2	Positive	7.0	4.0	2.9
				3	Positive	8.5	6.0	4.0
				4	Positive	2.3	2.8	2.8
				5	Positive	1.7	4.0	4.0
				6	—	—	3.5	3.5
				7	—	—	4.5	4.5

was so similar that it may be assumed that these were also cases of anomalous scattering. Thus, in all, five cases of anomalous scatterings have been observed in 48 penetrating particles in penetrating showers, or, in terms of the thickness of lead traversed, one particle per 25 cm lead. Wilson[10] found one *meson* scattered per 40 m lead and Shutt[11] and Code[12] have obtained similar results. Where the sign could be determined almost all of the anomalously scattered particles were positive. It is therefore unlikely that these particles are ordinary mesons not only because of the large excess of positive particles, but also because the interaction of these particles with the nucleons is clearly much greater than the interaction of ordinary mesons. The particles must therefore be protons or a type of meson different from the ordinary cosmic-ray meson. On one shower (E) one of the scattered particles (3) can be unambiguously recognized as a proton below the plate. Many of the reported cases of anomalous scattering may be examples of proton-neutron exchange, i.e., nuclear explosions in which a fast proton enters a nucleus and a fast neutron and a proton emerge. The scatterings might, however, be due to protons, π-mesons, or heavier mesons which produce stars in the lead plate with secondary particles of such short range that nearly all are absorbed.

It may be noted that the minimum momenta of a meson of mass $200m_e$ and a proton to penetrate the lead plate are 1.4×10^8 ev/c and 5.7×10^8 ev/c, respectively. A proton of this momentum would ionize 2.4 times the minimum.

[10] J. G. Wilson, Proc. Roy. Soc. **A174**, 73 (1940).
[11] R. P. Shutt, Phys. Rev. **69**, 261 (1946).
[12] F. L. Code, Phys. Rev. **59**, 229 (1941).

Another shower which also shows similar features but could not be definitely classified as a penetrating shower is shown in Fig. 3d. The data for this shower (G) are given in Table IV. The positions of the ends of the tracks with respect to the front of the chamber are given in columns (8) and (9) so that some idea of their space orientation can be obtained.

This shower was connected with an extensive air shower and like showers F and E consists mainly of a collimated group of positive particles. It is clear that these particles are not electrons for most have momenta greater than 10^9 ev/c and yet do not produce showers in the lead absorbers either above or in the cloud chamber. According to Chakrabarty[13] an electron of momentum 10^9 ev/c produces on the average a shower of 10 particles in a lead plate of 3 cm thickness and an electron of 5×10^9 ev/c a shower of 50 particles. The particles seem to be similar to the anomalously scattered penetrating particles which have just been discussed. Particle (5) is scattered in the plate and emerges as particle (6); particle (7) is probably associated with the same collision process. The other particles are remarkable in that they are apparently completely absorbed in the lead plate without producing other charged particles. Although some are moving slightly backwards, their inclination and positions at the plate do not suggest that they would have gone out of the illuminated region. Here again there is evidence of particles with strong interaction with nucleons.

This shower and several of the others, for example, showers B, E, and F, also show another

[13] S. K. Chakrabarty, Proc. Ind. Acad. Sci. **XV**, 472 (1942).

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).

REVIEWS OF MODERN PHYSICS VOLUME 21, NUMBER 1 JANUARY, 1949

Results and Problems Concerning the Extensive Air Showers

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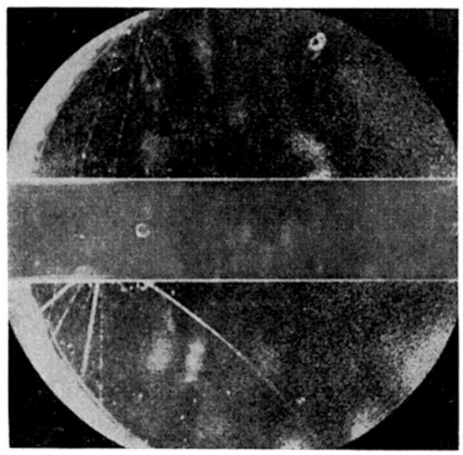
THE extensive air showers constitute the only known phenomena in which energies as large as 10^{15}–10^{18} ev are involved; this is the reason why at present and surely at least in the near future the deepest interest is attached to them. After ten years of research in the extensive showers, experimental 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

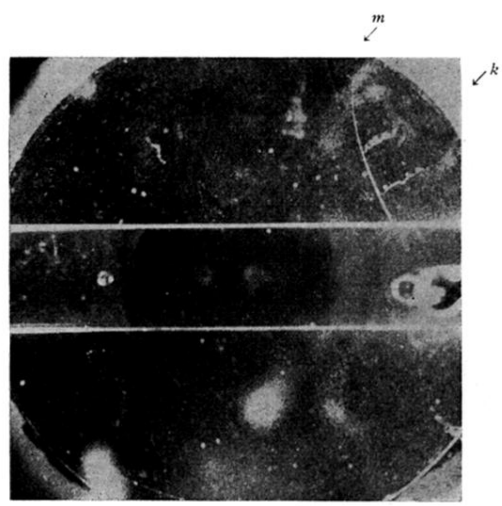
† On leave from the University of Catania, Italy.



(a)

m

FIG. 2(a). (*Particle (1) Table I.*) A slow meson associated with a penetrating shower. This meson (m), which is interpreted as a μ-meson, has a momentum of 2.2×10^7 ev/c and a kinetic energy 2.4×10^6 ev. It is negative if coming downwards. The track at the point where the meson emerges from the plate is interpreted as due to a knock-on electron. $H=3400$ gauss.



(b)

FIG. 2(b). (*Particle* (5) *Table I.*) A slow meson (m) associated with an extensive air shower. This meson, which is interpreted as a μ-meson, has a momentum of 2.2×10^7 ev/c (kinetic energy 2.4×10^6 ev) and is negative if coming downwards. It comes across the chamber out of the piston and may therefore have been created locally. The direction and identification are confirmed by the knock-on electron (k). The other electron, which is not a knock-on, can be seen stereoscopically to cross the meson track towards the front of the chamber. $H=6500$ gauss.

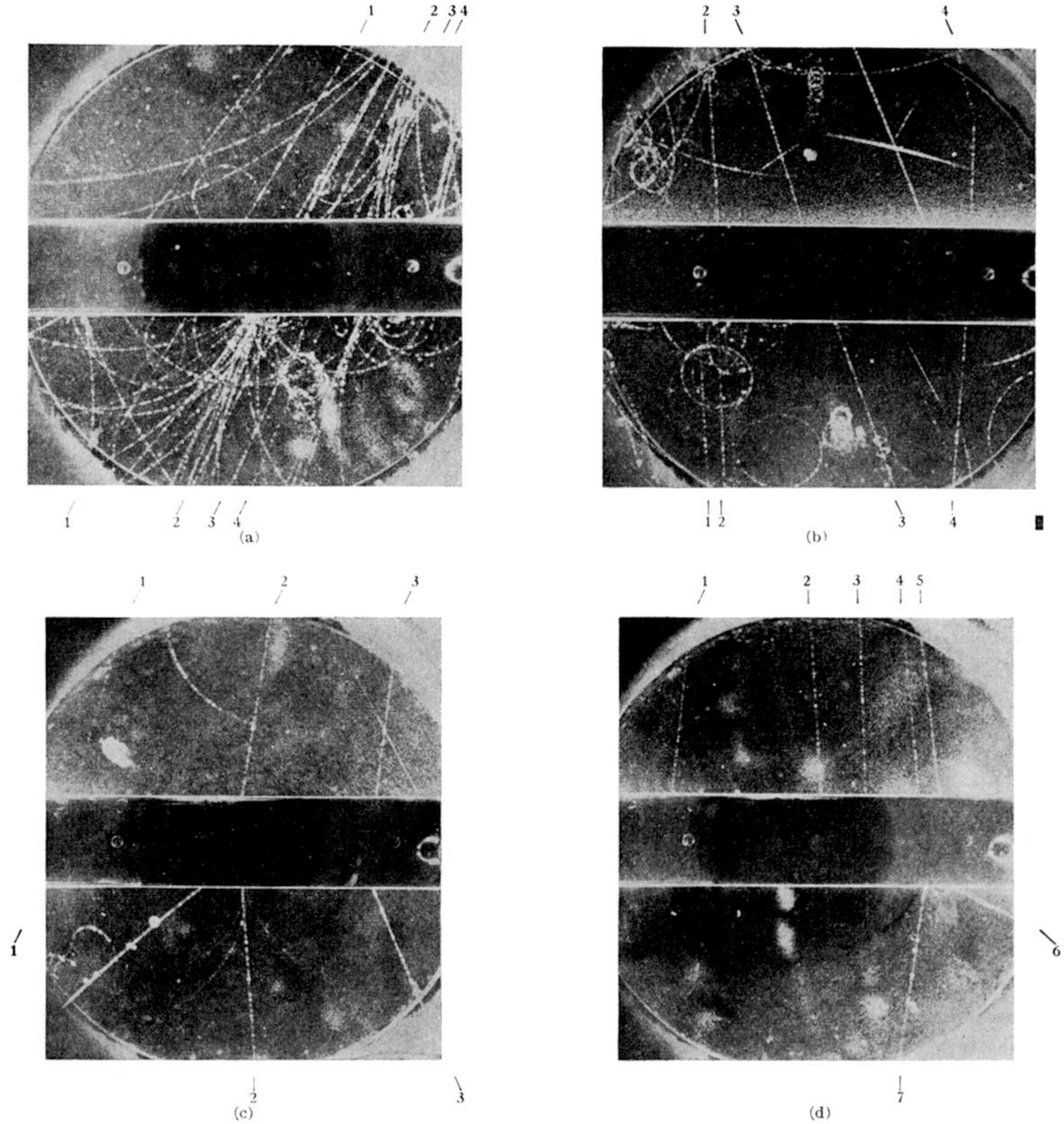


FIG. 3. For all photographs except (c) a positive particle coming down is curved in a clockwise direction. *Figure 3*(a) (*Shower A*, *Table II*) shows a complex penetrating shower consisting of four lightly-ionizing penetrating particles and a large electronic shower. The penetrating particles are indicated by numbers. They are positively charged and have momenta ranging from 1.4 to 0.65×10^9 ev/c. $H=7200$ gauss. *Figure 3*(b) (*Shower D*, *Table II*) is an example of a locally-produced penetrating shower consisting of several penetrating particles, two identifiable protons, and a small number of electrons. The interpretation of the deflection in track (4) has been discussed by Rochester & Butler (Nature **160**, 855, 1947). *Figure 3*(c) (*Shower E*, *Table II*) shows a penetrating shower consisting of three penetrating particles (1), (2), and (3). Particle (2) is a negative particle of momentum 1.1×10^9 ev/c and is anomalously scattered through 12.0° in the lead plate. Particle (3) is positive with a momentum of 4.5×10^9 ev/c above the plate and 3.0×10^8 ev/c below the plate and is scattered through 28.0°. The particle below the plate is a proton. The heavily ionizing particle which appears to come from the same region in the lead plate as the lower part of (2) is actually in a plane 1.8 cm behind it. Thus, if the heavily ionizing particle is connected with particle (2), it must be via an intermediate link. The heavily ionizing particle is positive and has a momentum of 1.6×10^8 ev/c. A proton of this momentum ionizes $15\times$minimum whereas the ionization is estimated as $7\times$minimum. The difference may be due to fluctuation or indicate a particle of intermediate mass. $H=6900$ gauss. *Figure 3*(d) (*Shower G*, *Table IV*) shows an unusual shower consisting of several high energy particles which stop in the lead plate without producing visible particles. All the particles except (3) are well in the illuminated region of the chamber and nearly all have momenta much above 10^9 ev/c. $H=7100$ gauss.