It is far more likely that some tracks whose angle of scattering is somewhat less than 85° have been recorded. Since the angle cannot be measured accurately to within a few degrees and the general tendency of the observer is to reject as little data as possible, the fact that the scattering intensity rises very rapidly with decreasing angle could account for the apparent excess at the rather uncertain lower angular limit.

No inelastic collisions of fast β-particles with nitrogen nuclei were recorded with this arrangement, which however, was unsuited to a satisfactory examination of inelastic scattering for two reasons. First, the remaining energy of the electron after collision might be insufficient to penetrate the counter wall, and secondly, the radius of curvature of the track would be reduced after inelastic collision so that it might not traverse the region occupied by the counters. Both these difficulties could be overcome to some extent by using several thin-walled counters distributed over a greater length of arc in the chamber than was used in the present arrangement. However, since such inelastic collisions in nitrogen have been found to be very infrequent it is doubtful if such a straightforward extension of our present experiment would add very much to our knowledge.

Combining these experiments on the large-angle elastic scattering of β-particles of energy up to 1 MeV. by nitrogen nuclei with our previous results on the scattering at smaller angles, we can state that Mott's formula is in good agreement with experiment at all angles of scattering.

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The Penetrating Particles in Cosmic-ray Showers: II. The Lightly-ionizing Penetrating Particles in Penetrating Showers

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ABSTRACT. The momentum spectrum of the penetrating particles in a small sample of penetrating showers has been measured. Most of the particles are positive and have momenta of the order 10^9 ev/c. From a study of the interaction of these particles with nucleons in a lead plate it is concluded that whilst a small number may be μ-mesons most are protons, π-mesons, or heavier mesons.

§ 1. INTRODUCTION

An account is given of the lightly-ionizing, penetrating particles occurring in a small group of penetrating showers selected from a larger group of cosmic-ray showers. For the purpose of this analysis a penetrating shower is defined as a shower containing two or more ionizing penetrating particles. Penetrating showers containing single penetrating particles in the cloud chamber have been excluded because of the difficulty of distinguishing them from knock-on showers. A selection has been made, therefore, which is much more rigid than in counter work on penetrating showers.

Broadbent and Jánossy (1947) have suggested that penetrating showers are of two types, namely, local and extensive. A local penetrating shower is one created in the layer of absorber immediately above the counter set while an extensive penetrating shower is one associated with an air shower. It seems probable that the local showers are produced by fast nucleons (Jánossy and Rochester 1943), and it is to this type of shower that the results in this paper mainly refer.

The nature of the penetrating particles in penetrating showers is not yet known but there is much evidence that the local showers contain mesons and protons (Hazen 1944, Daudin 1944, W. M. Powell 1946, Rochester 1946, Rochester, Butler and Runcorn 1947, Rochester and Butler 1947, Fretter 1948). The results presented in this paper, while supporting this conclusion, indicate that only a small fraction of the mesons are μ-mesons.

§ 2. THE EXPERIMENTAL ARRANGEMENT AND THE MEASUREMENT OF MOMENTUM

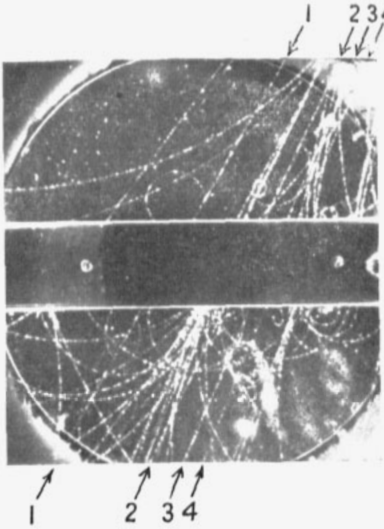
The experimental arrangement was described in an earlier paper (Rochester and Butler 1948, to be referred to as I). All the showers described in the present paper were taken with counter arrangement P, figure 2 of paper I. The thickness of lead in contact with the wall of the chamber and the total thickness of lead above the chamber are given in table 1. There was no lead below the chamber.

As described in I the curvatures of the tracks were measured on the Blackett curvature-compensating machine. Showers were selected with tracks free from

Table 1. Penetrating particles in penetrating showers

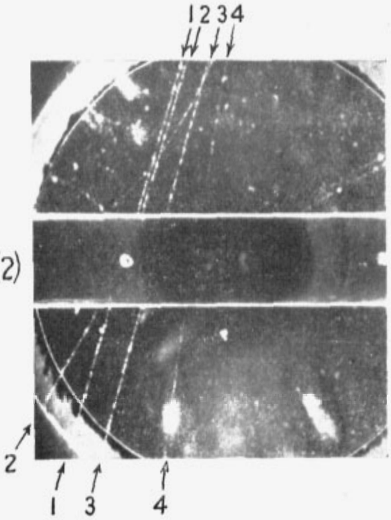
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
A(1)	1·8	16·8	7200	1	Positive	1·3	0·1	1·4
				2	Positive	1·1	0·1	1·7
				3	Positive	1·4	0·5	1·3
				4	Positive	0·65	0·8	2·9
B(2)	1·8	16·8	7250	1	Positive	3·3	0·6	0·6
				2	Positive	0·91	12·8	2·1
				3	Positive	1·0	0·8	1·9
				4	Too faint to measure			
C	1·8	16·8	7100	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(3)	5·0	10·0	6900	1	Too faint to measure			
				2	Negative	1·1	12·0	1·7
				3	Positive (above)	4·5	28·0	—
					(below)	0·3	—	—
F(4)	5·0	10·0	7300	1	Positive	0·63	3·0	3·0

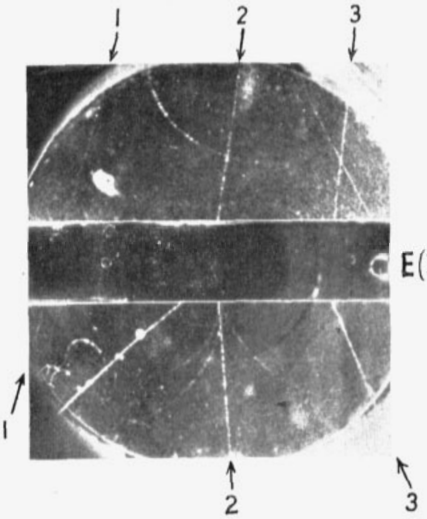
(1) Shower (No. of photograph on Plate). (2) Lead in contact with wall of chamber (cm.). (3) Total thickness of lead above chamber (cm.) (4) Magnetic field (gauss). (5) Number of particle. (6) Sign of particle. (7) Momentum ($\times 10^9$ ev/c.) (8) Angle of scatter (deg.) observed. (9) Angle of scatter (deg.) calculated.



A(1)

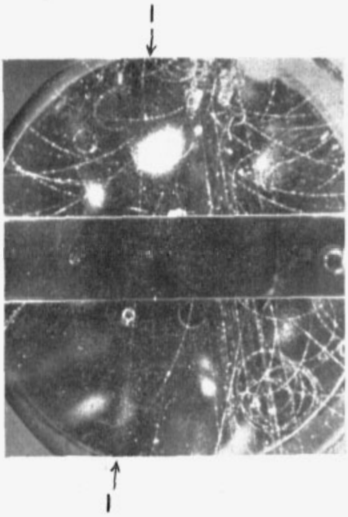
B(2)

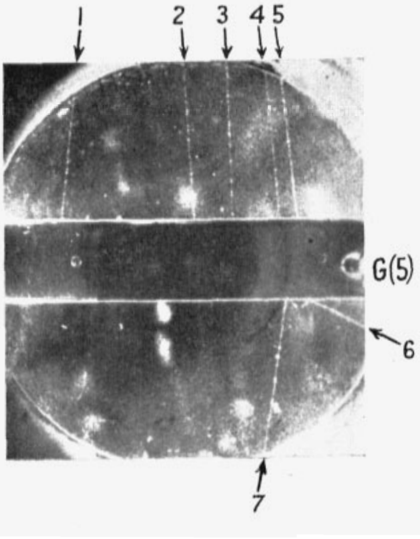




E(3)

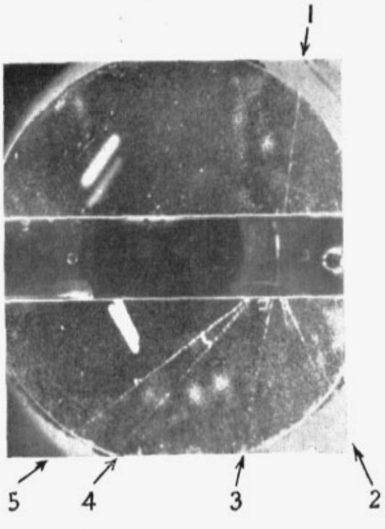
F(4)





G(5)

H(6)



PLATE

For all photographs except (3) a positive particle coming down is curved in a clockwise direction

Photograph (1) : 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 $0·65 \times 10^9$ ev/c

$H = 7200$ gauss.

Photograph (2) : An example of a simple type of local penetrating shower consisting of four positive penetrating particles whose momenta range from 3·3 to $0·91 \times 10^9$ ev/c. Particle 2 is anomalously scattered through 12·8° in the lead plate. $H = 7250$ gauss

Photograph (3) A penetrating shower consisting of three penetrating particles 1, 2 and 3 Particle 2 is a negative particle of momentum $1·1 \times 10^9$ ev/c and is anomalously scattered through 12·0° in the lead plate Particle 3 is positive with a momentum of $4·5 \times 10^9$ ev/c above the plate and $3·0 \times 10^8$ 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 $1·6 \times 10^8$ ev/c. A proton of this momentum ionizes 15 × minimum whereas the ionization is estimated as 7 × minimum. The difference may be due to fluctuation or indicate a particle of intermediate mass $H = 6900$ gauss

Photograph (4) : A complex penetrating shower associated with an extensive shower Only particle 1 is clearly penetrating but at least three other particles in the wide core seem to pass through the plate without multiplication. The shower is coming forward in the chamber at a rather steep angle. Accurate measurement of the tracks is difficult because of the confusion and the rather low technical quality Most of the particles seem to be positive and some are lightly ionizing with momenta approximately 5×10^8 ev/c. suggesting that they are not protons. The wide-angle pair of tracks at the lower right-hand side of the photograph seem to be those of protons.

$H = 7300$ gauss.

Photograph (5) · 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.

Photograph (6) : An example of a high-energy star induced by particle 1 Particles 4 and 5 have momenta of approximately 10^9 ev/c and are positive and negative respectively. This photograph would appear to indicate the creation of mesons or protons $H = 6600$ gauss obvious distortion and no track was measured unless its length in the chamber was greater than 6 cm. A check on the performance of the cloud chamber was made in two ways, firstly, by measuring up 87 meson tracks photographed without magnetic field, and secondly, by measuring up 90 meson tracks in the magnetic field. All these tracks were taken under chamber conditions identical with the showers. The lead above the chamber was, however, removed. It was found that a fairly good Gaussian curve could be fitted by the method of least squares to the no-field curvature measurements. The half-width of the Gaussian corresponded to a momentum of $8{\cdot}4 \times 10^9$ ev/c. in a magnetic field of 7500 gauss, which may be taken as the maximum detectable momentum (Blackett 1937).

The meson tracks in the magnetic field provided an effective check of the performance of the cloud chamber under conditions identical with those for penetrating showers. The resulting meson spectrum agreed closely with the data given by Wilson (1946). It may therefore be assumed that the performance of the cloud chamber was satisfactory.

§ 3. THE PENETRATING PARTICLES IN PENETRATING SHOWERS

(i) *Photographs and classification of the showers*

Using the criteria outlined in §§ 1 and 2, six penetrating showers containing sixteen penetrating particles have been selected for measurement and the results are given in table 1. The number in brackets after the letters in column (1) of table 1 refer to the photographs on the plate. A photograph of shower D has already been published (shower 2 of Rochester and Butler 1947). With the photograph published by Rochester, Butler and Runcorn (1947) these photographs present the main types of penetrating shower in a magnetic field. It is seen that a broad classification is possible in that some penetrating showers consist only of a few ionizing penetrating particles as, for example, showers B, D and E, while others include a considerable electronic component, as for example, showers A and F. This classification is clearly shown in the investigation made by Rochester (1946) and by Bridge, Hazen and Rossi (1948). Showers of the first type are presumably local penetrating showers, for in each case the penetrating particles can be traced back to a common point of origin in the absorber. Showers of the second type may be associated with extensive showers. Shower F was connected with an extensive air shower but it is not possible to classify shower A because the counter extensive tray was not in operation when this photograph was taken.

(ii) *Positive excess and spectrum*

The data show several interesting features, two of the most striking being the large positive excess and the relative abundance of particles with momenta below 2×10^9 ev/c. It will be noticed that of the 16 penetrating particles, 14 are positive and only 2 negative. This large positive excess suggests that some of the penetrating particles are protons. However, with such a small sample

Table 2. Spectrum of penetrating particles

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

the result should be taken with caution. Nevertheless it is interesting to see how many of the particles are probably *not* protons. We may assume that the negative particles are not protons and if we add the particles which are still lightly ionizing when their momenta are less than $0{\cdot}66 \times 10^9$ ev/c.—a proton of this momentum would ionize twice minimum—we find five out of the sixteen particles.

(iii) *Anomalous scattering*

Another striking feature is the anomalous scattering of three of the penetrating particles in the lead plate. These particles are: particle 2 of shower B, which is scattered through 12·8°, and particles 2 and 3 of shower E, which are scattered through 12·0° and 28·0° respectively. The probable angle of scatter for any one of these particles, calculated from Williams' formula, is not greater than 2°. There is little doubt that this result is significant especially when taken in conjunction with previous work on penetrating showers. Thus, Rochester (1946) found two cases of particles scattered through 10·2° and 18·0° respectively out of 32 penetrating particles in penetrating showers. Although the momenta of the particles were not known, the type of shower was so similar that it may be assumed that these were also cases of anomalous scattering. In all, five cases of scattering have been found in 48 penetrating particles or, in terms of the thickness of lead traversed, one particle per 25 cm. lead. This value is in sharp contrast with the scattering of ordinary mesons. Thus Wilson (1940) found one case of anomalous scattering per 40 m. of lead traversed, and Shutt (1946) and Code (1941) have obtained similar results. Where the sign could be determined almost all of the anomalously scattered particles were positive. It has therefore been suggested that the observed cases of anomalous scattering are due to protons and that the observed scattering cross-section does not represent the true cross-section for mesons. The results presented here support this conclusion; indeed, particle 3 of shower E can be unambiguously identified below the plate as a proton. It is not, however, valid to assume that the particles above and below the plate are necessarily the same, nor even that they are all protons. They could, for example, be protons or π-mesons which produce stars in the plate with secondary particles of such short ranges that all are absorbed except one. It is improbable that the scatterings represent examples of the spontaneous disintegration observed by Rochester and Butler (1947) in shower D, because only one such event has been found in the gas of the chamber, whereas at least five times as many events should have been observed in the gas as in the lead plate. Thus, it must be concluded that the scatterings are due to a collision process and not to any type of spontaneous process.

The minimum momenta of a meson of mass 200 m_e and a proton to penetrate the lead plate are $1{\cdot}4 \times 10^8$ ev/c. and $5{\cdot}7 \times 10^8$ ev/c. respectively. A proton of this momentum would ionize 2·4 times minimum.

§ 4. SHOWERS G AND H

In this paragraph a description will be given of two unusual showers which are shown in photographs 5 and 6 of the plate. The data for these showers are given in table 3. The positions of the ends of the tracks with respect to the front of the chamber, which is 9 cm. in depth, are given in columns (8) and (9), so that some idea of the space-orientation of the tracks can be obtained. The lengths of the tracks vary from 6 cm. to 12 cm. in the chamber.

(i) *Shower G*

This shower was connected with an extensive air shower and like showers F and E consists mainly of a collimated group of positive particles. The tracks are, however, not quite parallel, but project back to a common point of origin in the lead absorber above the counter set (see figure 2, paper I). 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 (1942) 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 penetrating particles discussed in § 3. 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 inclinations and positions at the plate do not suggest that they would have gone out of the illuminated region. Just as in the case of the large-angle scattering it is not known what type of collision process will account for this phenomenon. A large star, could however, be produced in the plate and no visible particle appear.

Table 3. Showers G and H

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
G(5)	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
H(6)	5·0	10·0	6600	1	Positive	5·2	3·3	3·3
				2	—	—	2·8	2·8
				3	—	—	2·8	2·8
				4	Positive	1·5	2·1	1·3
				5	Negative	1·1	4·0	6·2

(1) Shower (No. of photograph on Plate.) (2) Lead in contact with wall of chamber (cm.). (3) Total thickness of lead above chamber (cm.). (4) Magnetic field (gauss). (5) Number of particle. (6) Sign of particle. (7) Momentum ($\times 10^9$ ev/c.). (8) Position of track at plate (cm.) (9) Position of other end of track (cm.).

This shower and several of the others, for example, showers B, E and F also show another 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 centre 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 immediately above the cloud chamber. Thus the showers presented here are quite consistent with the star-like penetrating showers found by Hazen, Fretter and others. Moreover, they are also consistent with production by incident particles whose ranges are from 5 to 10 cm. of lead. In order to account for showers like E, F and G, however, where particles emerge from a block of lead 5 cm. in thickness and are then absorbed in a further 3 cm. lead plate, we require that many of the secondary particles are, like the primary particles, catastrophically absorbed with a range of from 5 to 10 cm. lead.

(ii) *Shower H*

This shower is of especial interest because it is an explosive-type shower in which high-energy particles are emitted at large angles to the direction of the incident particle. It will be seen from table 3 that the incident particle 1 has a very high energy. The particles which emerge below the plate come from a point 1 cm. from the bottom of the plate. The quality of tracks 2 and 3 is not high and they are so short that no measurement of their energies has been attempted. Tracks 4 and 5 are of better quality and are sufficiently long to permit of fairly accurate momentum measurements. The results of these measurements are surprising. They show that these particles are of opposite sign and have almost the same momenta (i.e. 10^9 ev/c.). These particles make angles of 35° and 46° respectively with the direction of the incident particle. Clearly, they are not electrons since two electrons of such high momenta are unlikely to emerge singly after traversing such a large thickness of lead. Again, the particles are unlikely to be heavier than protons. Thus, for each of the particles the ionization is typical of a fast particle and therefore the rest energies must be equal to or less than the momenta. Since the momenta are approximately 10^9 ev/c. the rest masses must be approximately equal to or less than the mass of the proton. If the particles are protons one is a negative proton. They may, however, be particles of intermediate mass. The large angle of emission does not help in deciding what kind of heavy particle, however, for with a suitable model a wide range of particles can be emitted at large angles to the direction of the incident particle. This shower raises many interesting questions, for example, what is the mechanism of the transfer of such a large amount of momentum, why are there so few low-energy particles emitted, and why are there so few mesons emitted? The answers to these questions await a fuller understanding of the interaction of fast nucleons.

§ 5. CONCLUSION

The following are the main results which follow from the analysis of the small sample of penetrating showers described in this paper. (i) A large fraction of the ionizing particles consists of particles which are different from ordinary 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 ionizing particle. (ii) A number of the positive particles are likely to be protons. This conclusion is suggested by the positive bias of the spectrum and by the presence of identifiable protons in the showers (for example, in shower 2 of Rochester and Butler 1947). (iii) The remaining penetrating particles may be either π-mesons (Lattes, Occhialini and Powell 1947) or heavier mesons (Rochester and Butler 1947). (iv) Some of the showers are very complex. There are complex showers which consist mainly of electrons and penetrating particles, and others which consist of large collimated groups of positively charged penetrating particles.

ACKNOWLEDGMENTS

It gives us great pleasure to express our sincere thanks to Professor P. M. S. Blackett, F.R.S. for the excellent facilities which he has given us and for the keen interest he has taken in this investigation. We are indebted also to Dr. S. M. Mitra and Mr. W. G. Rosser who operated the cloud chamber during part of the experiment and took several of the photographs described in this paper.

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A few Remarks about Spectroscopy at Low Frequencies

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BEING the man who has just failed to make the important discoveries in radio- and microwave spectroscopy and having little to report about recent researches (Dr. Bloembergen will speak for himself) I shall say a few words about the reasons I had about twelve years ago to expect that it was possible to start spectroscopy at low frequencies.

It was clear that electric dipole lines would be broadened enormously by interaction and, moreover, often would not be allowed by the selection rules. So I came to consider the magnetic dipole transitions between the Zeeman levels of paramagnetic ions and between the nuclear Zeeman levels, and arrived at the following result.

If the absorption in the centre of the absorption band is described by the imaginary part χ'' of the magnetic volume susceptibility, we have $\chi'' \simeq \chi_0 \nu/\Delta\nu$, where $\Delta\nu$ denotes the width of the band and χ_0 the susceptibility connected with it. Often χ_0 is the static susceptibility, $\chi_0 = NM^2/3\boldsymbol{k}T$, where N is the number of magnetic moments M per unit of volume. In relaxation bands $\Delta\nu \simeq \nu$, but in