P ATRICK M. S. BLACKETT

Cloud chamber researches in nuclear physics and cosmic radiation

Nobel Lecture, December 13, 1948

The experimental researches with which I have been occupied during the 24 years of my career as a physicist have been mainly concerned with the use of Wilson's cloud chamber for the purpose of learning more about the intimate processes of interaction of the sub-atomic particles. On 12th December, 1926, C. T. R. Wilson gave his Nobel Lecture entitled « On the cloud method of making visible ions and the tracks of ionizing particles », and described in it how, after a long series of researches starting in 1895, he developed in 1912 this exquisite physical method. Some here will probably remember that C. T. R. Wilson was originally drawn to investigate the condensation of water drops in moist air through the experience of watching the « wonderful optical phenomena shown when the sun shone on the clouds)) surrounding his Scottish hilltops. I, like all the other workers with the cloud chamber, the world over, are indebted more than we can express to his shy but enduring genius.

In 1919, Sir Ernest Rutherford made one of his (very numerous) epoch-making discoveries. He found that the nuclei of certain light elements, of which nitrogen was a conspicuous example, could be disintegrated by the impact of fast alpha particles from radioactive sources, and in the process very fast protons were emitted. What actually happened during the collision between the alpha particle and the nitrogen nucleus could not, however, be determined by the scintillation method then in use. What was more natural than for Rutherford to look to the Wilson cloud method to reveal the finer details of this newly discovered process. The research worker chosen to carry out this work was a Japanese physicist Shimizu, then working at the Cavendish Laboratory, Cambridge, to which Rutherford had recently migrated from Manchester. Shimizu built a small cloud chamber and camera to take a large number of photographs of the tracks of alpha particles in nitrogen with the hope of finding some showing the rare disintegration processes. Unfortunately Shimizu had to return unexpectedly to Japan with the work hardly started. Rutherford's choice of someone to continue Shimizu's work fell on me - then in 1921 a newly graduated student of physics. Provided by, Rutherford with so fine a problem, by C. T. R. Wilson with so powerful a method, and by Nature with a liking for mechanical gadgets, I fell with a will to the problem of photographing some half million alpha-ray tracks.

Shimizu's cloud chamber was improved and made fully automatic, taking a photograph every 15 seconds - this rapid rate was only possible because of its small size, 6.0 cm diameter by 1.0 cm deep. The first task was clearly to study the forked tracks due to the normal collisions of alpha particles with oxygen, hydrogen, and helium atoms (Figs.1,2, and 3), so as to verify that the normal collisions were truly elastic - that is, that no energy was lost in the process. If M and m are the masses of the alpha particle and nucleus, φ and θ the angle of deflection of the alpha particle and the angle of projection of the nucleus, then the assumption that energy and momentum are conserved during the collision leads to the relation

$$\frac{M}{m} = \frac{\sin (2\theta + \varphi)}{\sin \varphi}$$

Since θ and φ can be determined from the photograph, the mass ratio can be calculated. If for some track this is found to agree with the known ratio of the masses, then we conclude that the collision is elastic.

The following table shows the results of measurement of collisions with the nuclei ofoxygen, hydrogen and helium, and show that, within the experimental error, the collisions were elastic.

Recoil atom			*calc.*	*r*
Oxygen	*76°6'*	45°12'	**16.72**	**16.00**
Hydrogen	*9°21'*	*65°39'*	*1.024*	1.008
Helium	*45°49'*	*43°56'*	*4.032*	*4.00*

The study of these forked tracks was one of the first quantitative investigations of the dynamics of *single* collisions of sub-atomic particles.

In order to calculate the angles φ and θ from the two photographs taken from directions at right angles, it was necessary to work out a geometrical method, which took into account the fact that a photograph of an object does not represent an orthogonal projection of the object but a conical projection, that is a projection through a point on to a plane. Only by such a method was it possible to obtain the necessary accuracy. An indication of the accuracy of the angular measurements later achieved is shown by some results obtained in collaboration with E. P. Hudson in 1927 and with D. S. Lees in 1932. Measurements of 16 forked tracks due to the collision of alpha par-

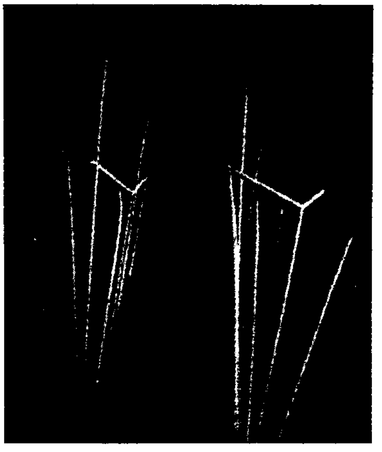

Fig. 1. Elastic collision of alpha particle with an oxygen nucleus.

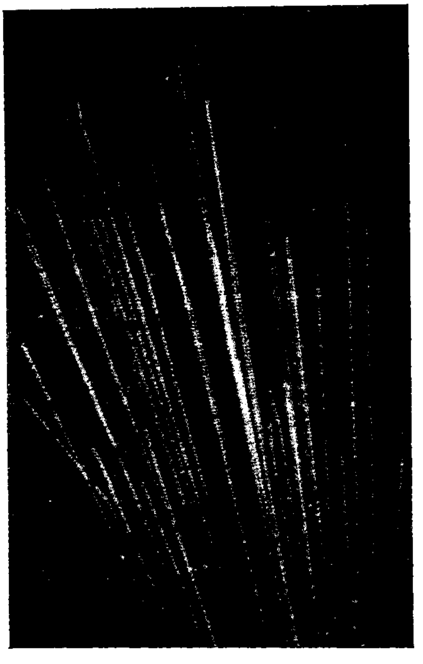

Fig. 2. Elastic collision of alpha particle with a hydrogen nucleus.

titles with hydrogen nuclei were made. The mean value of the mass ratio as calculated from the measured angles was 0.2531 ± 0.011, which differs from the known ratio 0.2517 by only a little more than the probable error. The probable error of a single angle measurement was estimated from these results to be 13′ of arc. The average energy, if any, lost in the collision must have been less than 1%.

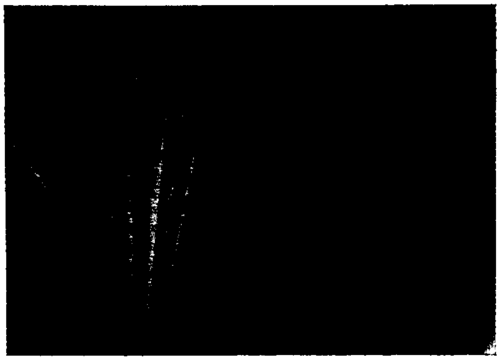

Fig. 3. Elastic collision of alpha particle with a helium nucleus.

Returning to the earlier period (1921-1924), a detailed study was also made of the relation between the range of a recoil nucleus and its velocity, the latter being calculated from the angles of the collision and the initial or final velocity of the alpha particle, assuming the collision to be elastic. The nuclei studied were those of hydrogen, helium, nitrogen, and argon. It was found that the range in air of a nucleus of mass m and atomic number z was approximately of the form

$$R \text{ cc m } z^{-1/2} \text{ f(V)}$$

where f(u) was roughly proportional to $v^{3/2}$. This relation was of importance in order to aid the identification of the recoil particles emerging from abnormal collisions.

This preliminary work done, production was started in earnest in 1924 and 23,000 photographs were taken within a few months. With an average of 18 tracks a photograph these gave over 400,000 tracks, each of which had to be scrutinized for anomalous behaviour. On some days when the apparatus worked well, as many as 1,200 photographs were taken. Eight forked tracks were found which had a quite different appearance from those showing normal elastic collision, and these were readily identified as the sought for transmutation of nitrogen. Typical photographs are shown in Figs. 4 and 5.

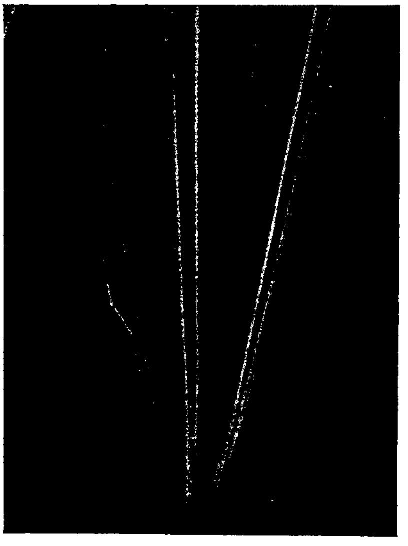

Fig. 4. Transmutation of nitrogen. One of the first photographs showing the capture of an alpha particle by a nitrogen nucleus with emission of a proton. The thin track moving to the right is the proton, and the short thick track to the left is due to the newly created ^{17}O nucleus. The alpha rays are from Thorium B + C (1925).

Rutherford's original experiments, using the scintillation technique, were only capable of proving that when an alpha particle struck a nitrogen nucleus a fast proton occasionally was ejected, but they were not able to reveal what happened to the alpha particle after the collision. There were two possibilities. The alpha particle might leave the nucleus again as a free particle, or it might be captured, so forming a heavier nucleus. In the former case, one would expect to find a forked track showing the track of the incident alpha particle, with three emergent tracks due to the alpha particle, the ejected proton, and the recoil nucleus. In the latter case one would find only two tracks, that of the proton and the recoil nucleus. The eight anomalous tracks all showed only two emergent particles, so proving that the assumed "disintegration" of nitrogen by alpha particles was in reality an "integration" process. Applying the principle of conservations of charge and mass, it was immediately deduced that the new nucleus formed must be a heavy isotope of oxygen $^{17}_{8}O$; the nuclear reaction being

$$^{4}_{2}He + ^{14}_{7}N \rightarrow ^{1}_{1}H + ^{17}_{8}O$$

At the time of these experiments this isotope of oxygen was not known, but shortly afterwards it was discovered by the analysis of band spectra.

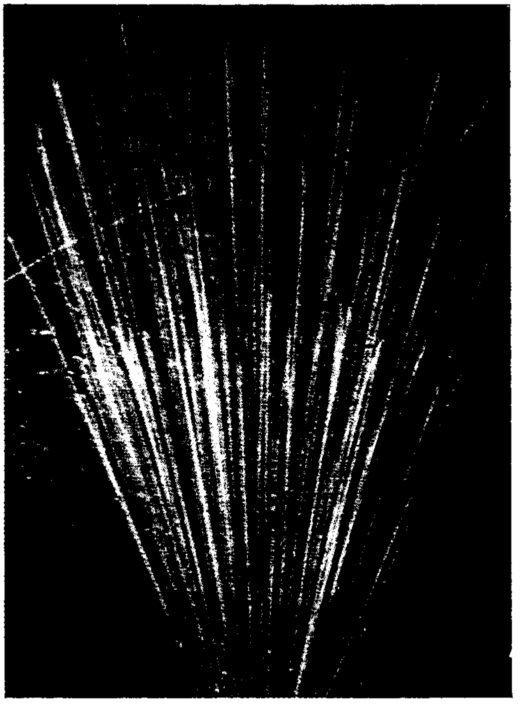

Fig. 5. Transmutation of nitrogen. The range of the alpha particle before the collision is only 3.4 cm and the range of the ejected proton, moving to the left and slightly backward, is only about 3.5 cm. The end of the 4.8 cm alpha particles from Thorium B + C can be seen near the middle of the photograph. (Blackett and Lees, 1932)

Since the ranges of the ejected protons were in all cases much larger than the size of the cloud chamber, it was not possible to determine directly their range or energy. However, the lengths of the tracks of the recoiling 170 nucleus were readily measurable, and could be compared with that expected from the momenta of the particles, calculated on the assumption that momentum but not energy were conserved during the collision. The relation between the range and the momentum of an ^{17}O nucleus was not, of course, known directly, but could be estimated by interpolation, using the data for other common nuclei H, He, C, N, ^{16}O, and A, which, as has already been explained, had previously obtained from the analysis of elastic collisions. In this way it was shown that the range of the recoil tracks was in good agreement with the calculated value for a mass of 17 and an atomic number of 8. Again, assuming the conservation of momentum, the sum of the energies of the two particles after the collision could be calculated, and was found to be on the average about 20% less than the energy of the incident alpha particle. The collision process was therefore an endothermic one - that is energy was absorbed in the process - so that the sum of the masses of the final products, $^{1}_{1}H$ and $^{17}_{8}O$, was somewhat larger than the sum of the masses of the original particles $^{4}_{2}He$ and $^{16}_{8}O$.

These experiments gave for the first time detailed knowledge of what is now known to be a typical nuclear transformation process. Owing to the laborious nature of the task of photographing the collisions of natural alpha particles with nuclei, not very much subsequent work has been carried out with this method. But with the discovery in 1932 of the neutron by Chadwick and of the disintegration of nuclei by artificially accelerated particles by Cockcroft and Walton, very many nuclear transformations have been studied in many laboratories by the use of the cloud chamber. In recent years the use of special photographic emulsions to record the tracks of nuclear particles, first used successfully by Blau and Wambacher, and later most fertilely exploited particularly at Bristol by Powell, Occhialini and their co-workers, has made possible the study of many types of nuclear collision processes with much greater facility than can be achieved with the cloud chamber.

After the work was completed, a larger automatic chamber of 16 cm in diameter was constructed and an attempt was made with D. S. Lees to photograph the disintegration of argon; 750,000 tracks were photographed on some 1,200 photographs, but no case of an argon disintegration was found. A further 350,000 tracks in nitrogen gave four more nitrogen disintegration processes, one of which was striking in that it was caused by an alpha particle of relatively low range (2.4 cm in air) and produced a proton track of only about 3.5 cm range (Fig. 5).

In 1930 Mott had predicted by means of wave mechanics that the scattering of identical nuclear particles should differ markedly from that given by the inverse-square law. Theory showed that interference effects should occur somewhat analogous to the scattering of light by small particles. Chadwick had verified Mott's conclusion using fast alpha particles detected by scintillations. In collaboration with F. C. Champion, the scattering of slow alpha particles with helium nuclei was studied using the automatic cloud chamber and a striking verification of Mott's theory was achieved.

In the autumn of 1931 in collaboration with G. P. S. Occhialini, I started to study the energetic particles found in cosmic rays by means of the cloud method. About 4 years previously Skobeltzyn in Leningrad had investigated the beta rays from radioactive sources using a cloud chamber in a magnetic field of 1,500 gauss. On some of the photographs he noticed a few tracks with very little curvature, indicating an energy over 20 MeV, that is much higher than any known beta ray. He identified these tracks with the particles responsible for the « Ultrastrahlung » or « cosmic rays », whose origin outside the earth's atmosphere had first been demonstrated in 1912 by the balloon flights of Hess and which had subsequently been much studied with ionization chambers by Millikan, Kolhörster, Regener, Hoffman, and others.

Skobeltzyn noticed also that these energetic particles occasionally occurred in small groups of 2 , 3, or 4 rays, apparently diverging from a point somewhere near the chamber.

Skobeltzyn's work was followed up by Kunze in Kiel, and by Anderson in Pasadena. By using much larger magnetic fields up to 18,000 gauss, the energy spectrum of the particles was shown by these workers to extend to at least 5,000 MeV, and it was found that roughly half the particles were positively, and half negatively charged. The occasional association of particles was again noticed, particularly by Anderson.

The method used, that of making an expansion of a cloud chamber at a random time and taking the chance that one of the rare cosmic rays would cross the chamber during the short time of sensitivity - generally less than ¼ second - was much consuming of time and photographic film, since in a small chamber only some 2% to 5% of photographs showed cosmic ray tracks.

Occhialini and I set about, therefore, the devising of a method of making cosmic rays take their own photographs, using the recently developed « Geiger-Miiller counters » as detectors of the rays.

Bothe and Rossi had shown that two Geiger counters placed near each other gave a considerable number of simultaneous discharges, called coincidences, which indicated in general the passage of a single cosmic ray through both counters. Rossi devised a neat valve circuit by which such coincidences could easily be recorded.

Occhialini and I decided to place Geiger counters above and below a vertical cloud chamber, so that any ray passing through the two counters would also pass through the chamber. By a relay mechanism, the electric impulse from the coincident discharge of the counter was made to actuate the expansion of the cloud chamber, which was made so rapid that the ions produced by the ray had no time to diffuse much before the expansion was complete. The chamber was placed in a water-cooled solenoid giving 3,000 gauss. Having made the apparatus ready, one waited for a cosmic ray to arrive and take its own photograph. Instead of a small fraction ofphotograph showing a cosmic ray track, as when using the method of random expansion, the counter-controlled chamber yielded a cosmic ray track on 80% of the photographs. The first photographs by this new method were made in the early summer of 1932.

In the autumn of the same year, Anderson working with a normal chamber taking photographs at random, reported the finding of a track which he interpreted as showing the existence of a new particle - the positive electron.

The track described by Anderson traversed a lead plate in the centre of the chamber and revealed the direction of motion of the particle by the difference of curvature on the two sides. From the direction of motion and the direction of the magnetic field, the charge was proved positive. From the range and ionization, the mass could be proved to be much less than that of a proton. Anderson thus identified it as a new particle, the positive electron or positron.

During the late autumn of 1932, Occhialini and I, using our new counter-controlled cloud method, accumulated some 700 photographs of cosmic rays, among which groups of associated rays were so striking a feature as to constitute a new phenomenon and to deserve a name. From their appearance they came to be known as « showers » of cosmic ray particles. As many as 23 particles were found on a single photograph, diverging from a region over the chamber. Roughly half the rays were due to positively charged and half to negatively charged particles. From their ionization and range, the masses of the positive particles was evidently not much different from that of negative electrons. So not only was Anderson's discovery of the positive electron further confirmed by a wealth of evidence, but it was proved that the newly discovered particles occurred mainly in showers along with approximately an equal number of negative electrons. This fact of the rough equality of numbers of positive and negative electrons, and the certainty that the former do not exist as a normal constituent of matter on the earth, led us inevitably to conclude that the positive electrons were born together

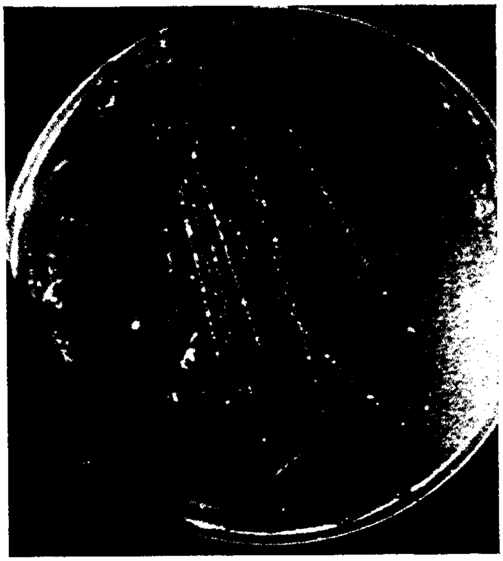

Fig. 6. Cosmic ray shower. One of the first photographs of a large shower of cosmic ray particles. Some 16 particles, about half positive and half negative, diverge from a region over the chamber. This shower was interpreted as showing the birth of a number of pairs of positive and negative electrons. The counter-controlled cloud chamber was in a field of 3,000 gauss. (Blackett and Occhialini, 1933)

in collision processes initiated by high-energy cosmic rays. The energy required to produce such a pair is found from Einstein's famous equation to be $2\ mc^2 \cong 1$ MeV. So was demonstrated experimentally for the first time the transformation of radiation into matter.

The fate of the positrons was discussed in relation to Dirac's theory of holes. On this theory a positive electron was envisaged as a "hole" in a sea consisting of an infinite number of negative electrons in states of negative kinetic energy. Dirac's theory predicted that a positive electron would disappear by uniting with a negative electron to form one or more quanta. Occhialini and I suggested that the anomalous absorption of hard gamma rays by nuclei might be a result of the process of pair production, and that the observed re-emission of softer radiation might represent the emission of two 0.5 MeV quanta resulting from the annihilation of a positive and negative electron. Subsequent work has confirmed this suggestion.

This work was described in a paper which appeared in March 1933. Some of the photographs from the paper are reproduced here (Figs. 6-8). These represent the first published photographs showing positive electrons, as An-

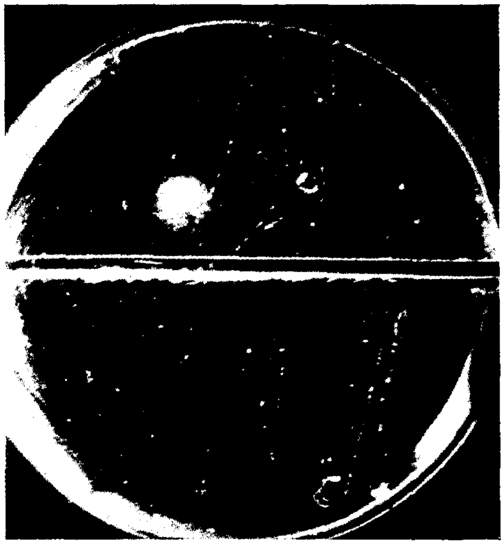

Fig. 7. Cosmic ray shower. Some 23 particles cross the chamber. Several radiant points can be detected above the chamber and also in the lead plate. H = 2,000 gauss. (Blackett and Occhialini, 1933)

derson's very beautiful photograph, though taken six months earlier, was not published till shortly afterwards.

The photographs showed clearly that some form of non-ionizing radiation must play an essential part in the formation of the showers, and that the mean range in lead of these radiations, which were assumed to be either photons or neutrons, must be quite small. Subsequent theoretical work by Heitler, Bethe, Bhabha and others gave a full account of these showers as due to a cascade process, consisting of the alternate emission of collision radiation by fast electrons and positrons, and the subsequent absorption of the latter by pair production.

As soon as the presence of positive electrons in cosmic rays was fully established, experiments were undertaken in collaboration with Occhialini and Chadwick to see if they were formed when hard gamma rays from radioactive sources were absorbed by matter. This was found to be the case when the energy of the rays was considerably above 1 MeV. One of the photographs of pair production by gamma rays is shown in Fig. 9.

It is interesting to note that the development of the counter-controlled cloud chamber method, not only attained the original objective of achieving much economy in both time and film, but proved to have the quite unex-

Fig. 8. Nuclear explosion produced by cosmic rays. Three heavily ionizing particles, probably alpha particles, together with two electronic in character, emerging from a point near the surface of the piston (1934).

pected advantage of greatly enhancing the number of associated rays photographed. This was so because the greater the number of rays in a shower of cosmic ray particles, the greater the chance that the counter system controlling the chamber would be set off. As a result the larger showers appeared in the photographs far more frequently relative to single rays than they actually occur in nature. This property of bias towards complex and so interesting phenomena has proved one of the most important advantages of the counter-controlled method.

In a subsequent paper I sketched in detail the formation of tracks by the counter-controlled method and calculated the expected breadth of a track as a function of the coefficient of diffusion of the gaseous ions and of the time elapsing between the passage of the rays and the completion of the expansion. The experimentally measured breadths in hydrogen and oxygen agreed well with the theory.

One serious disadvantage of the counter-controlled method lay in the necessity to maintain the magnetic field for deflecting the particles during the whole period when the apparatus was awaiting the arrival of a ray; in contrast when using the random method, the magnetic field could be flashed up momentarily at the moment of the expansion, so avoiding overheating the coils. This demand for a large magnetic field over a large volume, but using only a relatively small expenditure of electric power, led to the design of a special magnet illustrated in Fig. 10. Weighing some 10,000 kg it gave a field up to 14,000 gauss between pole pieces 25 cm in diameter and 15 cm apart, for a power consumption of 25 kW. Cooling was by an air stream from a fan. A shower of high energy taken with the new chamber is shown in Fig. 11, and a single ray of very high momentum traversing a lead plate in Fig. 12.

The first work undertaken with the new apparatus was the measurement of the momentum spectrum of the cosmic ray particles. The earlier measurements by Kunze and by Anderson using the random method had shown the approximate equality of positive and negative momenta up to values of

Fig. g. Pair of positive and negative electrons produced by gamma rays. (Chadwick, Hackett, and Occhialini, 1934)

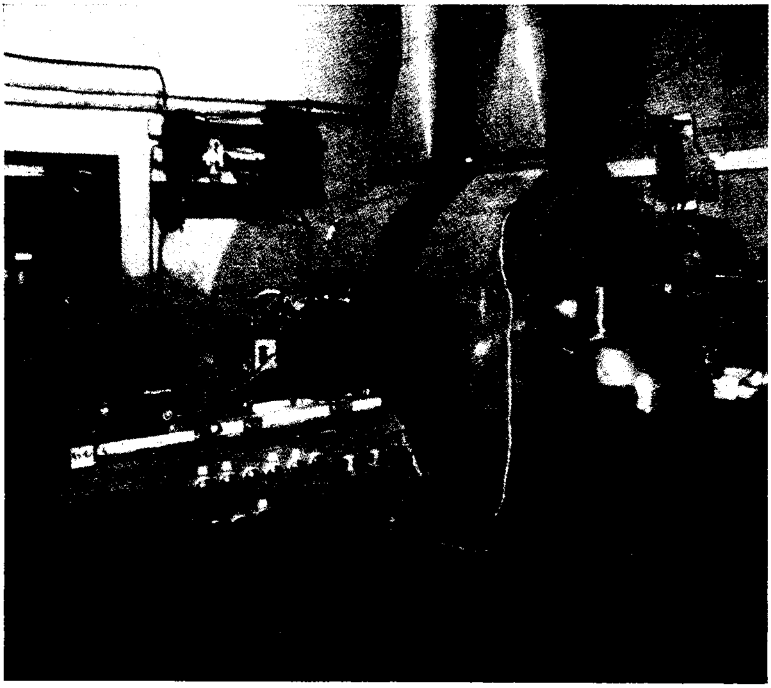

Fig. 10. Magnet and cloud chamber. Ten-ton air-cooled magnet. A 30-cm cloud chamber, slides on rails between the poles of the magnet. On the left of the slide can be seen the automatic release and resetting mechanisms (1935). Figures No. 11 to 19 are all made with this magnet and chamber, though the depth of the chamber and the counter arrangement are different in the later work.

5×10^9 eV/c. With a specially constructed chamber in the field of the new magnet the spectrum was extended in collaboration with R. B. Brode up to about 2×10^{10} eV/c, and it was shown that the differential energy spectrum above 10^9 eV/c could be represented by $g(E)dE \propto E^{-2}dE$.

To attain such a high precision of measurement entailed detecting the curvature of a track of 20 cm length when its radius of curvature was 70 metres. Moreover a careful study had to be made of the distortions in the tracks, produced on the one hand by the optical system used, and on the other by the motion of the gas in the interval between the passage of the ray and the instant of the photograph. The great importance of attaining thermal equilibrium in the chamber prior to the expansion came to be recognized.

An optical method of measuring small curvatures was devised by which the curvature of the image of a reprojected track was compensated by the curvature introduced optically by means of a prism of small angle.

When adequate number of tracks were available it was found that the number of positive tracks was about 13% in excess of the number negatives but the probable error of the determination was rather large, of the order of 6%. Other workers (Hughes and Jones)subsequently found a rather larger positive excess of the order of 25%.

The next task was to measure accurately the loss of energy of the rays in passing through metal plates placed in the chamber, a study initiated by Anderson. This was of special importance in relation to the identification of the penetrating component, which comprised 80% of the rays at sea level and which were far less absorbed than the electronic component. The energy loss of most rays of momentum over 200 MeV/c were found to be quite small, whereas most of the rays of lower momentum were found to be absorbed very rapidly, as was expected from the theory of collision radiation if they were electrons. This result led me to what turned out to be the quite erroneous conclusion that the particles of high momentum were electrons, but with a much smaller energy, less than that given by the quantum theory of radiation. These results were therefore held by me to confirm the views held at that time by many theorists (Nordheim, Williams, and others) that a breakdown of the radiation formulae could be expected at high energies.

Fig. 11. Cosmic ray shower. Nineteen tracks diverging nearly horizontally from a point to one side of the chamber (H = 14,000 gauss). Total energy of visible particles is 5×10^9 eV. Some of the individual particles have an energy of over 10^9 eV (1935).

Subsequent experimental work, particularly by Anderson showed, however, that electrons of high energy did in fact show the large energy loss expected from quantum mechanics, and so proved that the penetrating rays could not be electrons at all, but must be a new type of particle, now called the "meson" and known to have a mass about 200 *m*. On the theoretical side, Williams and Weiszacker independently proved by an ingenious application of Fermi's impact parameter method that no breakdown of the radiation formula was to be expected. Final identification of the meson came from the photographs of Street and of Anderson.

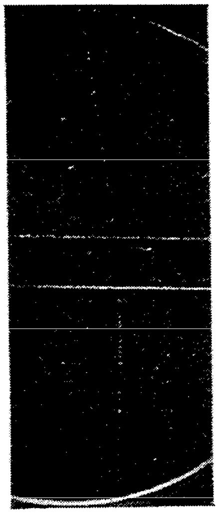

Fig. 12. Mu-meson traversing a 2-cm gold plate. Appreciable energy loss and scattering occurs.

A detailed study in collaboration with J. G. Wilson was made of the scattering of penetrating cosmic rays particles in metal plates and it was shown that the observed scattering agreed closely with that calculated by Williams. A few particles (mainly with a positive charge), were found which showed both abnormally large scattering, and some others which showed abnormally large energy loss. These were thought then to be possibly protons, but the subsequent discovery by Powell and Occhialini using the photographic emulsion technique of the π-meson of mass about 300 *m* has made other alternative explanations possible.

In parallel with these developments of the counter-controlled cloud chamber as a precision method for measuring the momentum and energy loss of single cosmic ray particles, a number of investigations were made by many different workers in many different countries of the rarer types of cosmic ray showers, utilizing the selective property of the counter-controlled method to reveal them in numbers far above that of their actual occurrence in nature.

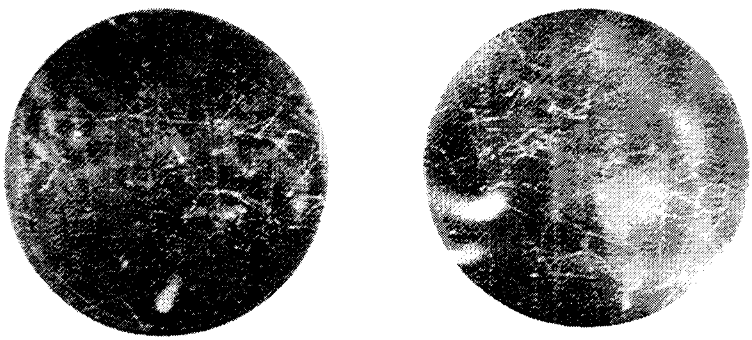

Fig. 13. Extensive shower. Two cloud chambers several metres apart record an extensive air shower. (Wilson and Lovell, 1939)

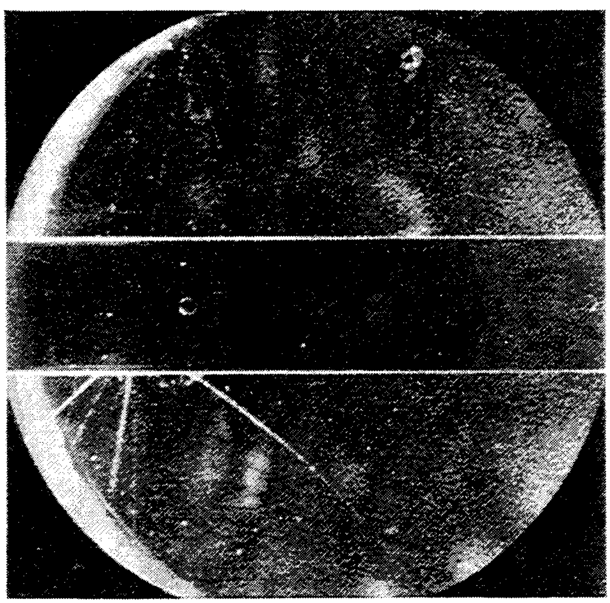

Fig. 14. Explosion showers. Two high-energy incident particles strike a 3.5-cm lead plate: one penetrates without much scattering or energy loss while the other initiates nuclear explosion. Two heavily ionizing protons are ejected with a few faster particles, which cannot be identified. The markedly curved and heavily ionizing track on the right is identified as a meson. (Rochester, Butler, and Runcom, 1947)

Particularly beautiful examples of such photographs were made by Anderson, Street, Hazen, Leprince-Ringuet and others and allowed the details of the cascade theory of shower formation to be followed. The extensive air showers, discovered by Auger and his collaborators, were investigated by Lovell and Wilson in my laboratory using two cloud chambers separated by a distance of several metres (Fig. 13). The knock-on showers produced by mesons in lead plates were investigated by Lovell.

In 1939, a counter-controlled cloud chamber was operated by Braddick and Hensby in the Holborn Tube Station in London at a depth of 30 metres underground. Amongst the photographs taken were a few which showed the simultaneous occurrence of two associated penetrating particles.

By delaying the expansion for a fraction of a second after the passage of a ray, the ions diffuse a short distance from their places of formation, so producing a broad track in which the separate droplets condensed on each ion

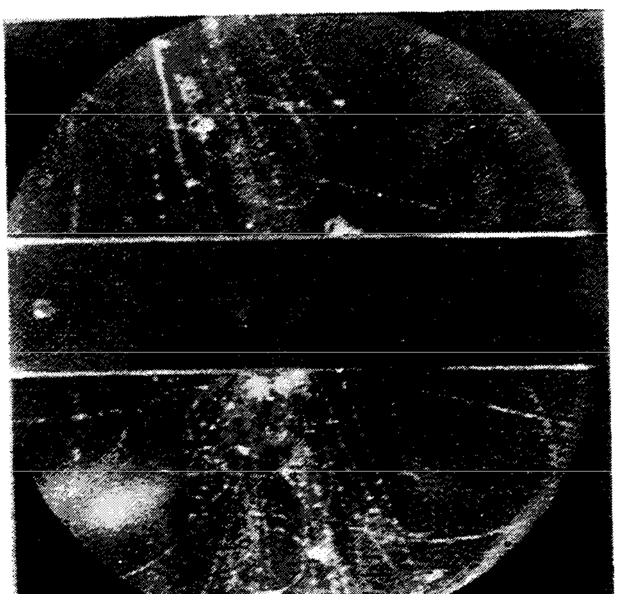

Fig. 15. Penetrating shower with anomalous forked track. A typical, but rare, type of penetrating shower showing several particles penetrating a g-cm lead plate together with some soft electronic component. On the right below the plate is a peculiar forked track, which for reasons given in the text, is considered to represent the spontaneous disintegration of a new type of neutral particle (π-meson) of mass about 900 m into a positive and negative particle of lower mass. H = 3,500 gauss. (Rochester and Butler, 1947)

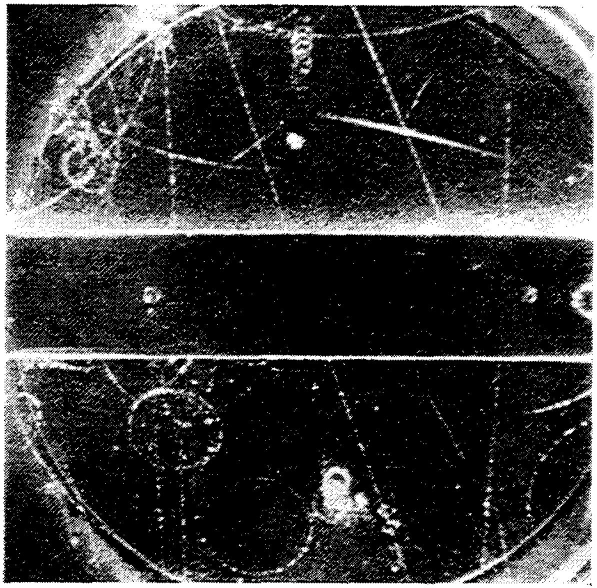

Fig. 16. Penetrating shower with anomalous bent track. A few penetrating particles pass through the plate. One of them, at the top right-hand comer of the photograph, makes an 18° deflection in the gas and then passes through the plate with little further deflection. This is interpreted as the spontaneous disintegration of a new type of positive particle (τ-meson) of mass about 900 *m* into a positive particle of lower mass together with a neutral unobserved particle. H = 7,000 gauss. (Rochester and Butler, 1947)

can be counted. By this technique it is possible to count the number of ions produced by rays of given momentum. Theoretical considerations by Bethe and by Williams had shown that this ionization should increase slowly with the momentum of the particle when this was much greater than *mc*. As shown by Williams, this increase arises in a very simple ray from the principle of relativity. Corson and Brode in 1938 in Berkeley succeeded in showing that the predicted increase of ionization does occur with electrons. Sen Gupta in 1940 investigated this phenomenon using the cloud chamber in he big magnet and verified that for electrons the increase of ionization agreed closely with the production up to energies of some 800 MeV at which energy the ionization is some 70% above the minimum.

The counter experiments of Jánossy and Wataghin at sea level showed hat a rare type of shower existed consisting of a few associated penetrating rays. These penetrating showers were studied by Rochester during the War

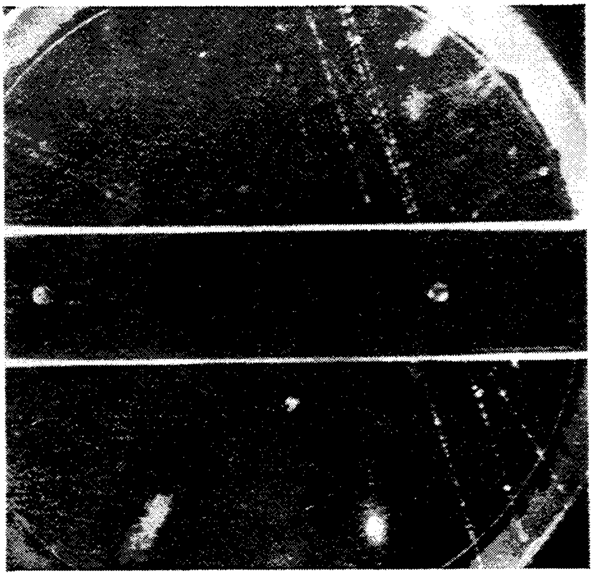

Fig. 17. Penetrating showers with no electronic component. Four associated positive particles traverse a 3.5 cm lead plate. The momenta of three of them are 3.3, 0.9 and 1.0×10^9 eV/c. One is anomalously scattered through 13°. The nature of the particles in such showers is not yet certain, but they may consist of a mixture of protons and positive π– mesons. H = 7,000 gauss (Rochester and Butler, 1947)

of these showers consisted of narrow groups of nearly parallel-penetrating particles. In some experiments, the counter system used to control the chamber was so rigidly defined as to be actuated only once every 24 hours or so. By this means it was possible to set a chamber so that it would wait a whole day to be activated by the particular type of shower which it was desired to photograph.

As soon as the end of the War made it possible to resume work with the large magnet, a detailed study was commenced by Rochester and Butler of the penetrating showers. Jánossy had deduced from his counter experiment that these showers were probably produced by a primary proton component, but the exact nature of the particles in the showers and of the processes by which they are produced remained, and still remain, very obscure. It is generally agreed, however, that the quantum-mechanical treatment of the collision of energetic nucleons with nuclei would be expected to lead to the emission of numbers of ejected protons and mesons. Detailed calculation have been made by Hamilton, Heitler, and Peng, and by Jánossy.

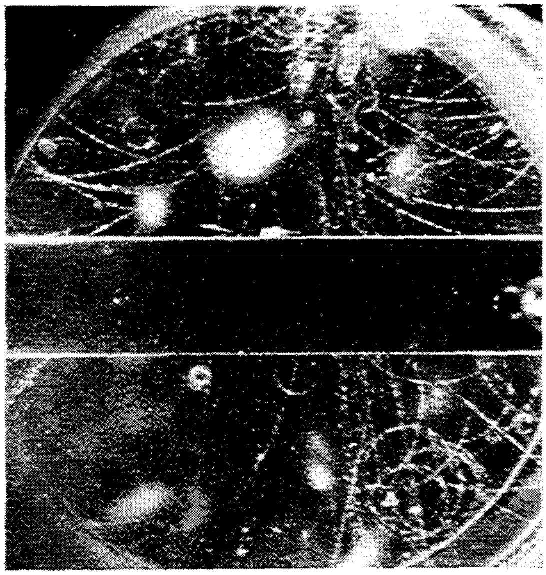

Fig. 18. Penetrating shower with electronic component. Some 8 penetrating particles traverse the plate. Most of them appear to be positive, but this is not certain. A considerable electronic component is present. $H \approx 7{,}000$ gauss. (Rochester and Butler, 1947)

Among the many thousand photographs taken by Rochester and Butler many interesting phenomena were observed, the details of which are still being elucidated. Of particular importance was the discovery that the large majority of penetrating particles in penetrating showers have a positive charge. Some few of them appear to be protons, but some are certainly not. Since many of these particles appear to be rather highly scattered in a lead plate, it is probable that those that are not protons may be $\pi-$ or $\tau-$ mesons, rather than $\mu-$ mesons, which are known to be very little scattered. Certain photographs showed explosive showers in which a number of extremely energetic rays are emitted at rather wide angles, while in others the rays are nearly parallel. It is not yet certain whether these represent two distinct types of showers or whether they represent different aspects of essentially the same phenomenon.

Two photographs taken by Rochester and Butler were of exceptional interest in that they seemed to suggest the existence of two new types of particles, one uncharged and one with a positive charge, and both of mass about 900 *m*. In one, Fig. 15, a forked track was observed in the gas, due to two particles, one positive and one negative with momenta of a few hundred

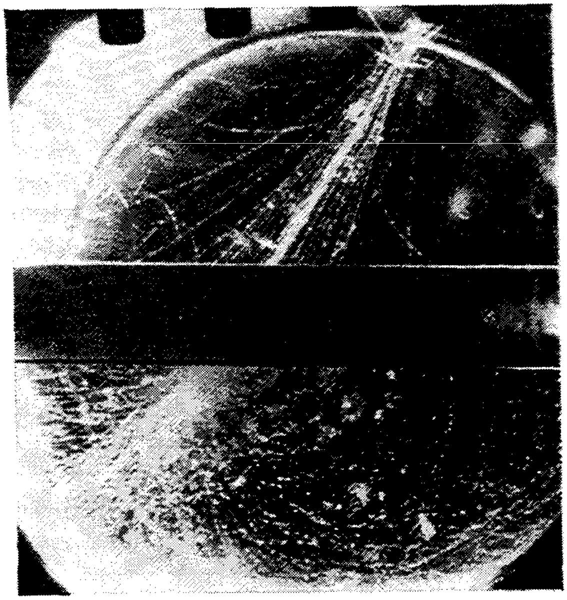

Fig. 10. Cascade shower initiated by meson. This unusual photograph is interpreted as initiated by a meson of very high energy (10^{11} eV/c) emitting a collision radiation, or knocking on an electron, in a lead block above the chamber. Some 40 rays, half positive and half negative, with a total energy of over 10^{10} eV are seen in the top of the chamber and a very large number, perhaps 500 or so, appear below the lead plate. Their number and energies are consistant with a cascade shower of total energy 10^{11} eV, having been initiated a few cascade units back in the lead block over the chamber. A surprising feature is the occurrence of a g-pronged star of protons, etc. with a total energy of 10^{9} eV originating in the central core of the shower. The explanation of the occurrence is not yet clear, as it would not be expected if the shower is a pure cascade. (Butler, 1948; unpublished.)

MeV/c. The simplest explanation was that a neutral particle had collided with a nucleus and ejected two mesons, but this was rejected since one would expect to find very many more of such cases occurring in the lead plate in the gas. As these were not found, it was concluded that the forked track did not represent a collision process at all, but a case of spontaneous integration of an unstable particle. From the momenta of the ejected particles the mass of the neutral particle was estimated as probably about 870 $\pm$ 200.

A second photograph (Fig. 16) showed a positive particle which seemed to undergo a deflection of 18° in the gas, and then to pass through the 3-cm lead plate without appreciable further deflection or energy loss. Similar argu-

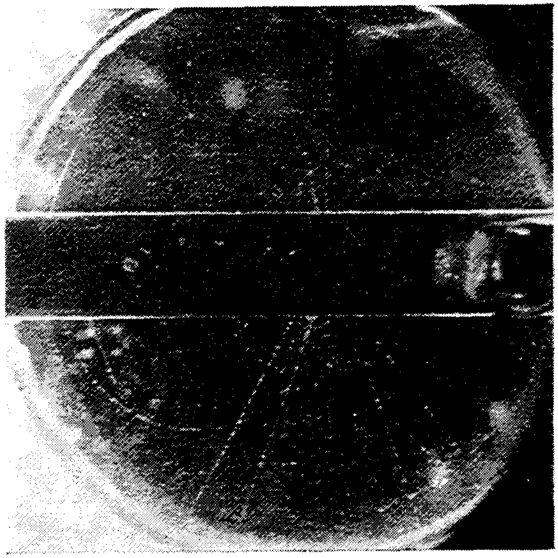

Fig. 20. Wide-angle explosive shower. At least seven particles of momenta about 10^9 eV/c are emitted over a wide solid angle. Two are protons; the rest may be some type of meson. (Butler and Rosser, 1948)

ments to those used for the first photograph led to the interpretation that an unstable positive particle of mass about 1080 ± 100 had spontaneously transformed itself into a positive particle, probably a μ-meson, and into an unobserved neutral particle.

Though an extensive search has been made for further events of this kind, none have been found. However, recent work by Powell in Bristol has given one track which seems must be interpreted as due to a meson of mass about 900. A single track photographed by Leprince-Ringuet in 1940 had been interpreted as indicating a particle of about the same mass. These are now called τ-mesons, and their life is estimated as of the order of 10^{-8} to 10^{-7} seconds.

Although a careful search has been made, no case of a negative proton has yet been found.