CECIL F. POWELL

The cosmic radiation*

Nobel Lecture, December 11, 1950

Coming out of space and incident on the high atmosphere, there is a thin rain of charged particles known as the primary cosmic radiation. As a result of investigations extending over more than 30 years, we now know the nature of the incoming particles, and some, at least, of the most important physical processes which occur as a result of their passage through the atmosphere.

Today the study of the cosmic radiation is, in essence, the study of nuclear physics of the extreme high-energy region. Although the number of incoming particles is very small in comparison with those which are produced by the great machines, most of them are much more energetic than any which we can yet generate artificially; and in nuclear collisions they produce effects which cannot be simulated in the laboratory. The study of the resulting transmutations is therefore complementary to that which can be made at lower energies with the aid of the cyclotrons and synchrotrons.

For the investigation of the cosmic radiation, it is necessary to solve two principal technical problems: First, to detect the radiation, to determine the masses, energy and transformation properties of the particles of which it is composed, and to study the nuclear transmutations which they produce. Second, to develop methods of making such observations throughout the atmosphere and at depths underground.

For the detection of the radiations, the same devices are available as in the general field of nuclear physics, and two main classes can be distinguished.

In the first class are found the trigger mechanisms such as the Geiger counter and the scintillation counter. Such devices record the instants of passage of individual particles through the apparatus. Their most important advantages are (a) that they allow observations to be made of great statistical weight; and (b) that the relationship in time of the instants of passage of associated particles can be established. With modern instruments of this type, the time interval between the arrival of two charged particles can be

* The lecture was illustrated by lantern slides and a film of the construction and launching of balloons.

measured even although this is as small as one or two hundredths of a micro-second. These devices have made possible contributions of the greatest importance to our knowledge of the subject, and they have proved especially valuable when the nature of the physical processes being studied has been well understood.

In the second class of detectors are the devices for making manifest the tracks of particles; namely, the Wilson expansion chamber and the photographic plate. These instruments have the particular advantage, amongst others, that they allow a direct and detailed insight into the physical processes which accompany the passage of charged particles through matter. On the other hand, it is arduous to employ them to obtain observations of great statistical weight. The two classes of instruments thus provide complementary information, and each has made a decisive contribution.

The second principal technical problem to be solved is that of making experiments at great altitudes. Some information has been obtained by means of V-2 rockets which pass almost completely out of the earth's atmosphere, but their time of flight is restricted to only a few minutes. Alternatively, balloons can be made to ascend to great altitudes and to give level flights for many hours. The simplicity of the photographic method of recording the tracks of charged particles makes it very suitable as a detector in such experiments.

Today the most suitable types of balloons for experiments on the cosmic radiation are those made of thin sheets of a plastic material, « polyethylene ». Although rubber balloons can sometimes be made to ascend higher into the atmosphere, their performance is erratic. The rubber, whether natural or synthetic, appears to perish rapidly under the action of the solar radiation high above the clouds: it is therefore difficult, even when employing many rubber balloons in a single experiment, to secure the sustained level flight which is desirable. On the other hand, polyethylene is chemically inert, and the fabric of the balloon can remain for many hours at high altitudes without any serious effect on its mechanical strength.

In Bristol, we construct balloons of polyethylene by methods similar in principle to those developed in the U.S.A. by the General Mills Corporation. We employ polyethylene sheet 1½ thousandths of an inch thick, the shaped pieces of which are « heat-sealed » together to form an envelope which, when fully inflated, is nearly spherical in form. Unlike those of rubber, these balloons are open at the lower end; and just before launching, the envelope is very slack and contains only a small fraction of its total volume filled with

hydrogen (see Fig. 1). As the balloon ascends, the pressure falls and the balloon inflates. Near maximum altitude its envelope becomes tensed and hydrogen escapes from the bottom aperture. Balloons of this type, 20 m in diameter, give - with light loads of about 20 kg - level flights at altitudes of the order of 95,000 ft. It is anticipated that a similar balloon 50 m in diameter should reach about 120,000 ft.

By observations at great altitudes we now know that the primary cosmic radiation is made up of atomic nuclei moving at speeds closely approaching that of light (Freier *et al.* [1]; Bradt and Peters[2]). It is possible to record the tracks of the incoming particles (see Fig. 2) and to determine their charge; and thence the relative abundance of the different chemical elements. Recent experiments prove that hydrogen and helium occur most frequently, and the distribution in mass of the heavier nuclei appears to be similar to that of the matter of the universe. Thus elements more massive than iron or nickel occur, if at all, very infrequently.

The detailed study of the « mass spectrum » of the incoming nuclei has an important bearing on the problem of the origin of the primary particles; but it is complicated by the fact that, because of their large charge, the particles rapidly lose energy in the atmosphere by making atomic and nuclear collisions. They therefore rarely penetrate to altitudes less than 70,000 ft. It is for this reason that exposures at high altitudes are of particular interest.

A second reason for making experiments at extreme altitudes is that the primary nuclei commonly suffer fragmentation in making nuclear collisions (see Fig. 3). A primary nucleus of magnesium or aluminium. for example, may decompose into lighter nuclei such as lithium, α-particles and protons. The mass spectrum at a given depth is therefore different from that of the primary radiation, and such effects are appreciable at 90,000ft., where the mass of overlying air is about 20 g per cm^2. They would be much reduced at 12,000 ft. (6 g per cm^2), an altitude which, we have seen, appears to be accessible with very large balloons.

The primary protons and α-particles, because of their smaller charge, penetrate to much lower altitudes. In collisions they disintegrate the nuclei which they strike (see Fig. 4) and, in the process, lead to the creation of new forms of matter, the π-mesons of mass 274 m_e (Lattes *et al.*[3]; Piccioni[4]; Fowler[5]). These particles are usually ejected with great speed and proceed downwards towards the earth.

The π-mesons are now known to have an average lifetime of about 2 x 10^{-8}sec (Richardson[6]). This period is so short that, when moving in a
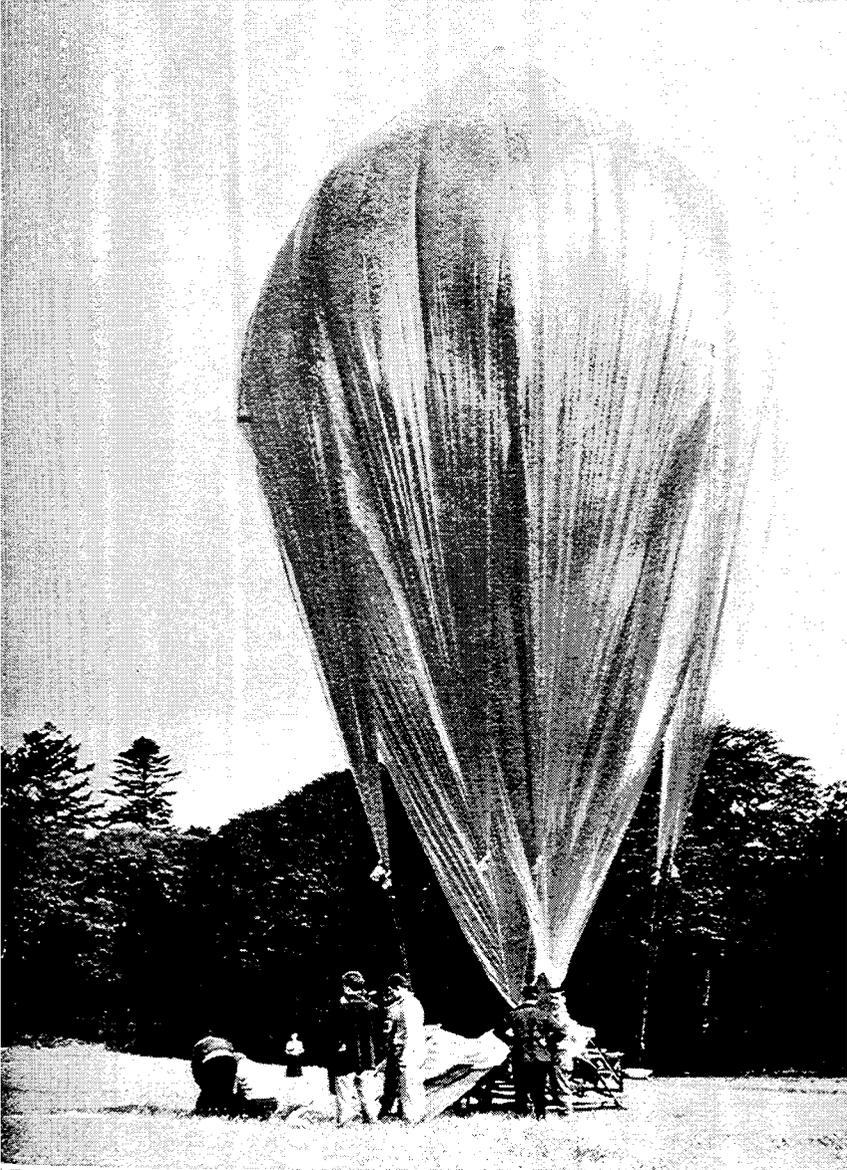
Fig. 1. Inflation of balloon of polyethylene just after dawn. The balloon has a total length of about 120 ft. and most of the fabric is on the ground. Such a balloon can in favourable conditions give level flight at about 90,000 ft. for many hours with a load of 40 kg.

| B. | C. | N. | O. | Ne. | Na. | Ca. |
| Z=5. | Z=6. | Z=7 | Z=8. | Z=10. | Z=11. | Z=20. |
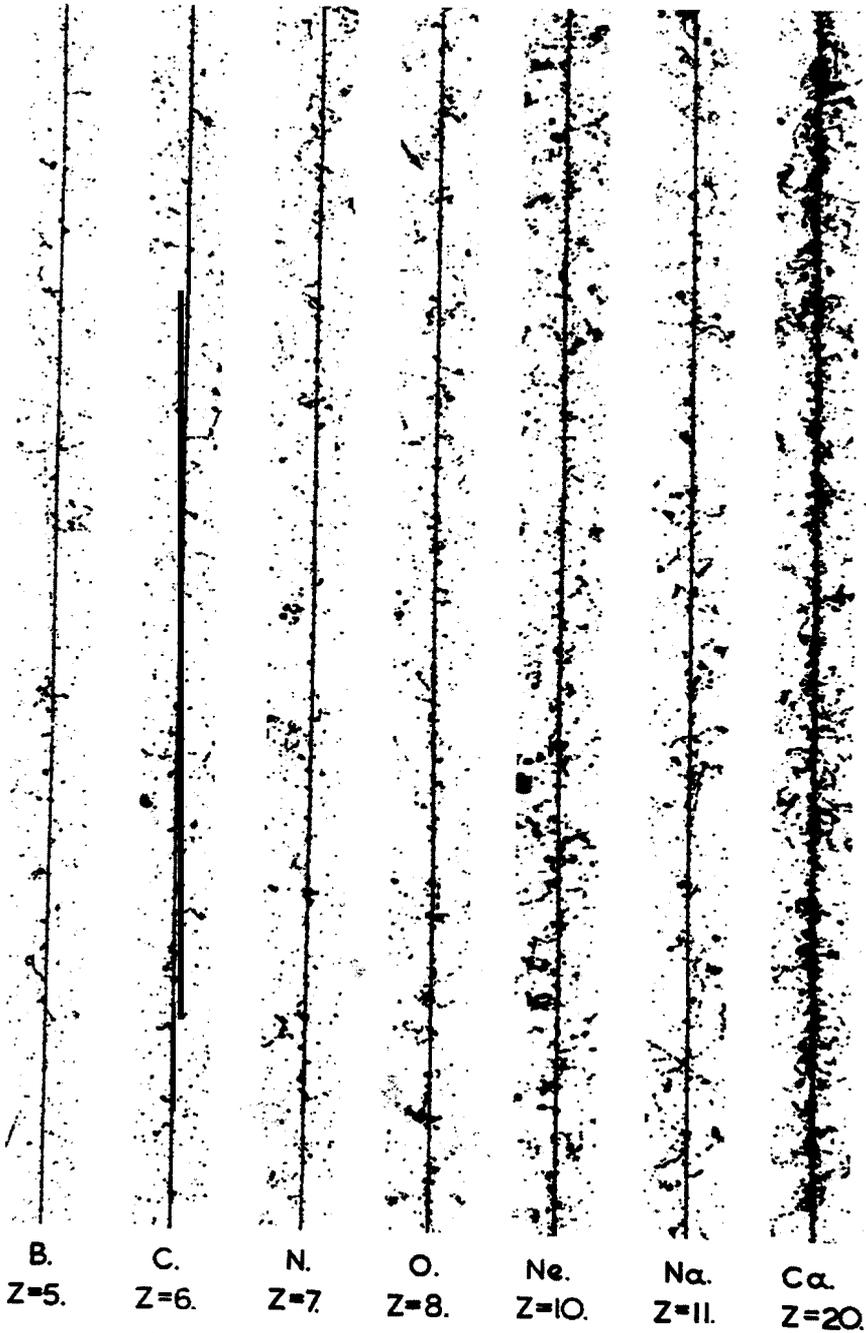
Fig. 2. Examples of the tracks in photographic emulsions of primary nuclei of the cosmic radiation moving at relativistic velocities.
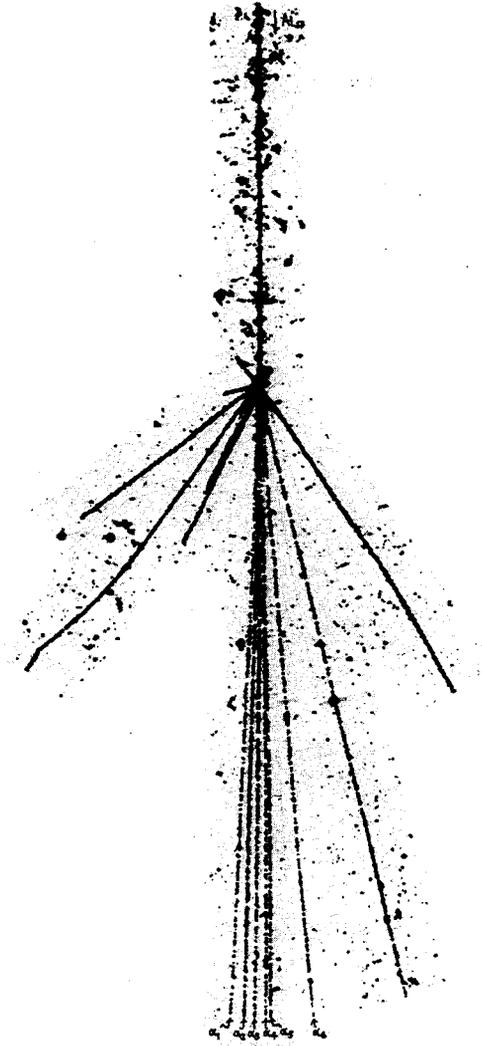
Fig. 3. A nucleus of magnesium or aluminium moving with great velocity, collides with another nucleus in a photographic emulsion. The incident nucleus splits up into six α–particles of the same speed and the struck nucleus is shattered.
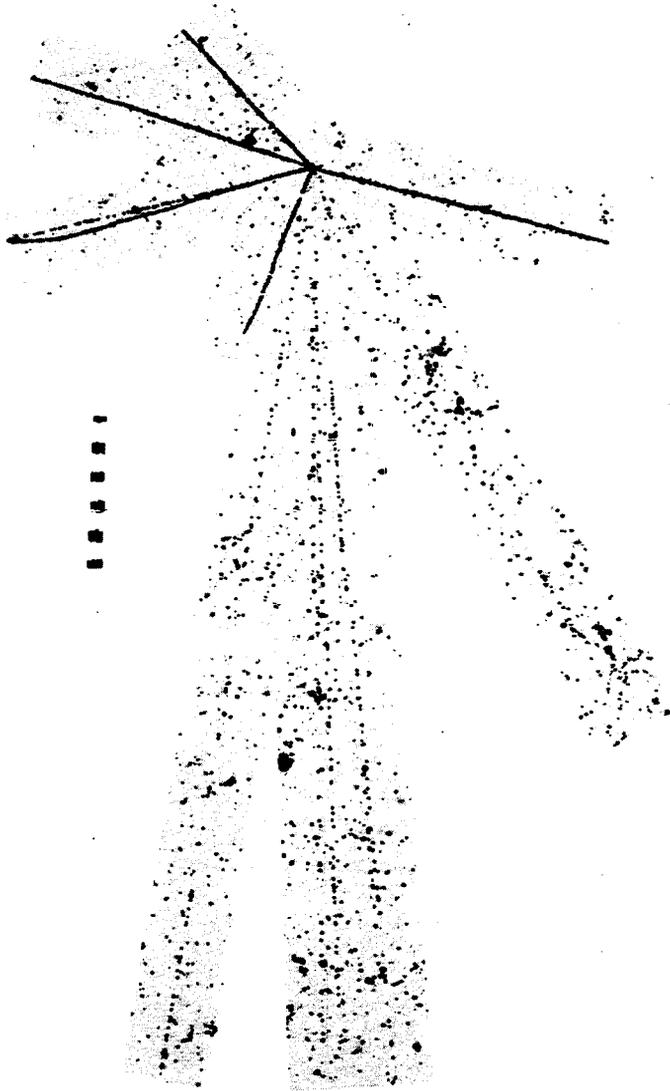
Fig. 4. A disintegration caused by a fast neutron of the cosmic radiation. The «thin tracks» of the fast-moving shower particles can be distinguished. Most of these are due to π-particles. A γ-ray, produced by the decay of a neutral π-meson, gives rise to a pair of electrons near the «star».

Fig. 5. Photo-micrographs of four examples of the successive decay π-μ-e as recorded in photographic emulsions.

gas - in which their velocity is reduced, by loss of energy through ioniza-
tion, at a relatively slow rate - they commonly decay in flight. In a solid
material, however, they can be arrested before they have had time to decay.
This was the most important of the factors which prevented the identifica-
tion of the particles until after the development of the photographic method
of recording the tracks.

When brought to rest in a photographic emulsion, the positive π-par-
ticles decay with the emission of a μ-meson of mass 212 m_e (see Fig. 5). This
particle commonly emerges with a constant velocity, so that its range varies
only within the narrow limits due to straggling. It follows that in the trans-
mutation of the π-meson, the μ-meson is accompanied by the emission of a
single neutral particle. It has now been shown that this neutral particle is of
small rest-mass and that it is not a photon. It is therefore reasonable to as-
sume, tentatively, that it is a neutrino, the particle emitted in the process of
nuclear β–decay.

When a negative π-meson is arrested in a solid material, it is captured by
an atom, interacts with a nucleus and disintegrates it (Perkins[7]; Occhialini
and Powell[8]). It follows that the particle has a strong interaction with nu-
cleons, and in this respect its properties are similar to those predicted for the
«heavy quanta» of Yukawa.

When the π-mesons are created in nuclear collisions occurring in the at-
mosphere, they commonly transform, whilst in flight, into μ-mesons and
neutrinos. It is these μ-particles which form the «hard» or «penetrating»
component of the cosmic radiation and they are responsible for most of the
residual ionization in air at sea level. The μ-mesons are penetrating because,
unlike the π-mesons, they are able to traverse the nuclei with which they
collide without interacting with them, and some of them reach great depths
underground.

The production of mesons by protons and α-particles of great energy in
nuclear encounters appears to be a result of interactions between nucleons.
Accordingly, the heavy nuclei of the primary radiation - if of sufficient en-
ergy - also produce similar effects when they collide with other nuclei (see
Fig. 6). Because of the large numbers of nucleons involved in such an en-
counter, the number of mesons produced may be very great.

In addition to producing the charged π-mesons, the primary protons in
making nuclear collisions also produce neutral π-particles (Bjorklund *et al.*[9])
The neutral π-mesons are very short-lived and each transforms sponta-
neously into two quanta of radiation (see Fig. 7). Such a quantum, when it
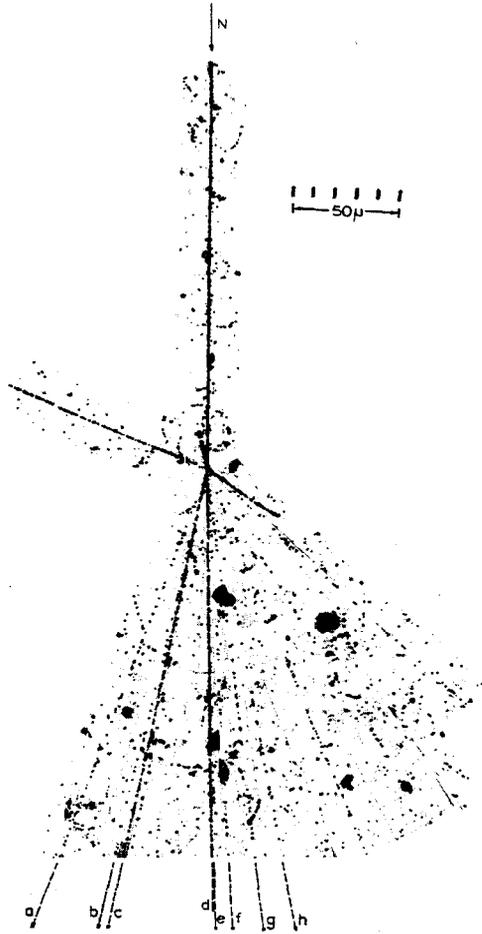
Fig. 6. A nitrogen nucleus of the primary cosmic radiation collides with a nucleus, and splits up into a lithium nucleus, a deuteron, and a number of protons. Some π-mesons are created in the collision. The event is very exceptional in that, by chance, the tracks in the emulsion of many of the particles are long so that they can be identified and their energy determined. *Top: N, $\overline{\alpha}$ = 0.0061 ~ 16%, 28,000* MeV. Bottom: (a) α-particle, $\overline{\alpha}$ = 0.109 ± 12%, 220 MeV; (b) π-particle, $\overline{\alpha}$ = 0.035 ± 25%, 800 MeV; (c) ^1_1H, $\overline{\alpha}$ = 0.206 ± 20%, 81 MeV; (d) Li, $\overline{\alpha}$ = 0.0075 ± 30%, ~ 10,000 MeV; (e) ^1_1H, $\overline{\alpha}$ = 0.012 ± 30%. 2000 MeV; (f) ^2_1D, $\overline{\alpha}$ = 0.0053 ± 16%, 4800 MeV; (g) π-particle, $\overline{\alpha}$ = 0.029 ± 20%, 1000 MeV; *(k) π-*particle, $\overline{\alpha}$ = 0.025 ± 30%, 1200 MeV.

happens to pass near an atomic nucleus, can in turn transform into a pair of electrons, one positive and one negative; and the electrons can generate new photons in further collisions. A succession of such processes results in the production of the well-known cascades of electrons and photons which form the «soft» or easily absorbed component of the cosmic radiation (Carlson *et al.*[10]).

Although much longer-lived than the π-mesons, some of the μ-mesons also decay in flight to produce electrons and neutrinos. The electrons contribute to the soft component, whilst the neutrinos join the similar particles arising from the decay of the π-mesons to produce a flux of neutral radiation which has a very weak interaction with matter, and of which the fate is at present unknown.

In addition to the π- and μ-mesons, recent experiments at Manchester (Rochester and Butler[11]) and Bristol (Brown *et al.*[12]), and in other laboratories, have shown that more massive types of mesons exist (Fig. 8). Although they occur much less frequently than the π-mesons, the elucidation of their properties appears to be of great importance for the development of nuclear physics.

We are only at the beginning of our penetration into what appears to be a rich field of discovery. Already, however, it seems certain that our present theoretical approach has been limited by lack of essential information; and that the world of the mesons is far more complex than has hitherto been visualized in the most brilliant theoretical speculations. The fast protons and α-particles generated by the cyclotrons are not sufficiently energetic to produce these more massive mesons, but this may become possible when the proton synchrotrons now under construction come into operation.

Only about twenty-five years have passed since it was generally recognized that part of the residual conductivity of a gas at sea level is due to the arrival from out of space of a radiation of great penetrating power. In the 1928 edition of *Conduction of Electricity through Gases,* J. J. Thomson and G. P. Thomson, commenting on this conclusion, remark that «It would be one of the romances of science if these obscure and prosaic minute leakages of electricity from well-insulated bodies should be the means by which the most fundamental problems in the evolution of the cosmos came to be investigated.»

In the years which have passed, the study of what might, in the early days, have been regarded as a trivial phenomenon has, in fact, led us to the discovery of many new forms on matter and many new processes of funda-
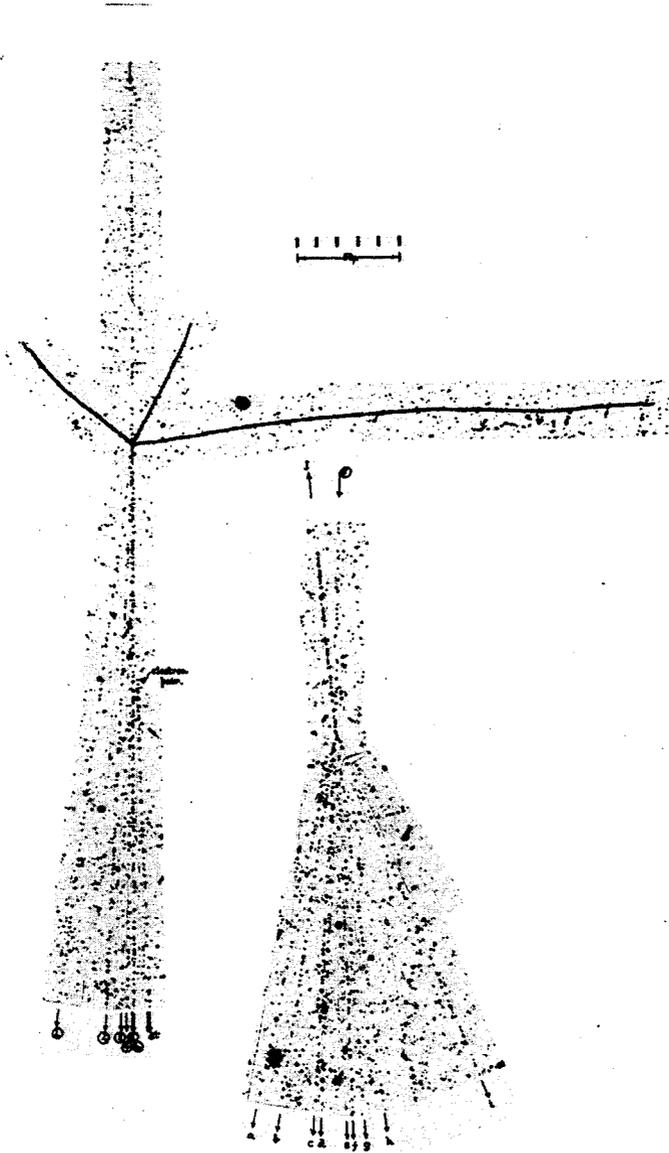
Fig. 7. A fast proton produces a disintegration (*see the left-hand picture).* One of the emerging «shower» particles (No. 5) after passing some millimeters in the emulsion, makes a second disintegration *(see right-hand «star»).*
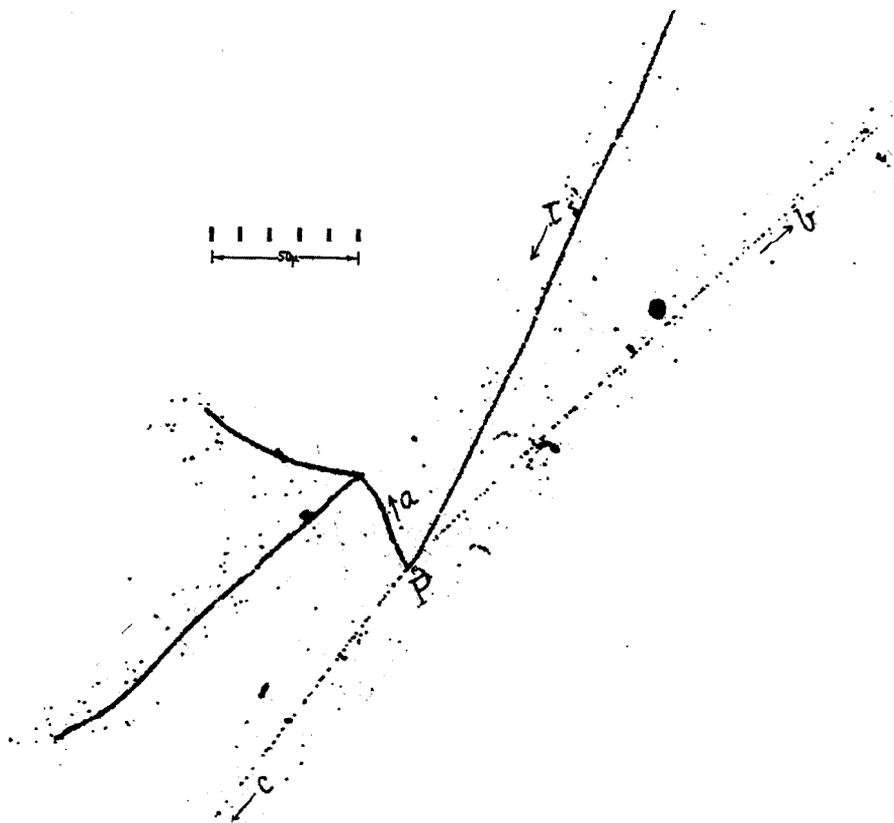
Fig. 8. The particle τ coming to rest in the emulsion at the point P disintegrates into three particles, a, b, and c, of which the initial directions of motion are co-planar. Particle a is almost certainly a negative π-meson. Tracks b and c are long enough to allow the velocity of the corresponding particles to be determined. Particle τ can be proved to be lighter than a proton, but heavier than a π-meson. With the assumption that b and c are also π-mesons, the momenta of a, b, and c are in balance, without any neutral particle. The τ-particle would then have a mass of about 970 m_e.

mental physical importance. It has contributed to the development of a picture of the material universe as a system in a state of perpetual change and flux; a picture which stands in great contrast with that of our predecessors with their fixed and eternal atoms. At the present time a number of widely divergent hypotheses, none of which is generally accepted, have been advanced to account for the origin of the cosmic radiation. It will indeed be of great interest if the contemporary studies of the primary radiation lead us - as the Thomsons suggested, and as present tendencies seem to indicate - to the study of some of the most fundamental problems in the evolution of the cosmos.

1. P. Freier, E. J. Lofgren, E. P. Ney, F. Oppenheimer, H. L. Bradt, and B. Peters, *Phys. Rev.*, *74* (1948) 213.
2. H. L. Bradt and B. Peters, *Phys. Rev.*, *74* (1948) 1828.
3. C. M. G. Lattes, H. Muirhead, G. P. S. Occhialini, and C. F. Powell, *Nature*, *159* (1947) 694.
4. O. Piccioni, *Phys. Rev.*, *77* (1950) 1, 6.
5. P. H. Fowler, *Phil. Mag.*, 41 (1950) 169.
6. J. R. Richardson, *Phys. Rev.*, *74* (1948) 1720.
7. D. H. Perkins, *Nature*, 159 (1947) 126.
5. G. P. S. Occhialini and C. F. Powell, *Nature*, 159 (1947) 186.
9. R. Bjorklund, W. E. Crandall, B. J. Moyer, and H. F. York, *Phys. Rev.*, *77* (1950) 213.
10. A. G. Carison, J. E. Hooper, and D. T. King, *Phil. Mag.*, *41* (1950) 701.
11. G. D. Rochester and C. C. Butler, *Nature*, *160* (1947) 855.
12. R. Brown, U. Camerini, P. H. FowIer, H. Muirhead, C. F. Powell, and D. M. Ritson, *Nature*, *163* (1949) 47, 82.