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# Mesons

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## (1) *Historical survey*

(*a*) *Introduction. Early history of the meson problem.*—Our ideas concerning the structure of matter have undergone great changes since the days of DEMOCRITUS and LUCRETIUS, and the present century has witnessed an enormous extension of our knowledge. In the years immediately following 1900 RUTHERFORD established the concept of the nucleus, which existed at the centre of every atom. For many years it was thought that the nucleus itself consisted of protons and electrons. The discovery of the neutron (1932) caused the abandonment of this theory and its replacement by the hypothesis that the nucleus consisted only of protons and neutrons.

The problem of the stability of such an arrangement of charged and uncharged particles then arose. Several theories of nuclear binding, including that of YUKAWA[2] were put forward following the discovery of the neutron. It was known that the forces concerned were extremely powerful and that they operated only over short distances. YUKAWA postulated that a special kind of interaction occurred between the protons and neutrons contained within the nucleus. A necessary consequence of this theory was the assumption of the existence of particles with a rest mass about 150 times that of an electron ($m_e$).

YUKAWA visualised a process whereby the protons and neutrons continually exchanged charge by means of a *meson field*; the quanta of this field were the new particles called *mesons*[3]. When freed from a nucleus the mesons were unstable and decayed in a calculated time of approximately $10^{-7}$ sec, giving an electron and a neutrino. The latter hypothesis was introduced in order to account for the radioactive $\beta$-decay of certain elements.

Since 1938 many types of meson have been found to exist in nature, and considerable information about their properties has been acquired. Most of our knowledge in this respect has been obtained from a study of the cosmic radiation, which enters the atmosphere of the earth from outer space[4]. All the known types of meson occur in this radiation, those most commonly encountered being designated by the symbols $\mu$, $\pi$, and $\pi^0$; the first two possess either positive or negative electrostatic charge of the same magnitude as that of an electron, while the third is electrically neutral. These mesons have recently been created artificially by the bombardment of nuclei by fast protons from the synchrocyclotrons now operating in the United States. The energy of the protons, about 345 MeV, represents the maximum at present available in the physics laboratory. In the cosmic radiation, however, protons are found with energies up to $10^6$ MeV. It can thus be seen that the cosmic radiation provides a convenient source of high energy particles with which to bombard nuclei; the mesons so created may then be studied in detail.

(*b*) *The discovery of the $\mu$-meson.*—Prior to the predictions of YUKAWA it had been found that the cosmic radiation could be conveniently divided into two components, a *soft* component and a *hard* component. The former component was easily absorbed in lead or other material of high atomic number, and had been shown to consist mainly of electrons and photons. On the other hand, the hard component could penetrate great thicknesses of absorbing materials without appreciable diminution in intensity. Experiments at sea level, and at mountain altitudes, on the nature of the latter component, showed that the particles comprising it could carry either positive or negative electric charge. Further they did not appear to possess the mass or the properties of either electrons or protons. It was therefore suggested by ANDERSON and NEDDERMEYER[1] that these experiments offered evidence for the existence of particles with a mass intermediate between that of an electron and that of a proton. This idea was subsequently confirmed by a photograph, which they obtained in 1938, showing a particle stopping in the gas of a cloud chamber. The mass of the particle was estimated to be about 220 $m_e$. Later work has shown that the majority of the particles comprising the hard component at sea level are mesons.

This result appeared to be in accord with the theory of YUKAWA. His prediction that the new particle was radioactive also seemed to be correct. Evidence was obtained which indicated that a large number of particles in the hard component were unstable. The

[1] H. H. Wills Physical Laboratory, University of Bristol.

[2] H. YUKAWA, Proc. Phys. Math. Soc. Japan. *17*, 48 (1935).

[3] The term *meson* was introduced at a later date, but it is convenient to use it when referring to the early work. A *meson* may be defined as any particle with a rest mass intermediate between that of an electron and that of a proton.

[4] For an elementary account of the nature of the cosmic radiation reference should be made to the article by H.L. BRADT, *Why are we studying Cosmic Rays?*, Exper. *4*, 41 (1948).

[1] C. D. ANDERSON and S. H. NEDDERMEYER, Phys. Rev. *51*, 884 (1937); *54*, 88 (1938).

reduction in intensity of a given flux of these particles after traversing an absorber was found to be not only dependent on the amount of the absorber, but also on the distance travelled by the particles. This effect, called the *absorption anomaly*, could be interpreted by assuming that the particles were removed from the flux by radioactive decay as well as by energy loss through ionisation.

The first photograph of the decay of a meson was not obtained until 1940, when Williams and Roberts[1] obtained a picture in which a particle with a mass of the order of 200 $m_e$ was observed to come to rest in the gas of a cloud chamber, and from its end point the track of a lightly ionising particle emerged. This photograph was interpreted as showing the spontaneous decay of the meson into an electron and some neutral particle. Many similar photographs have since been obtained.

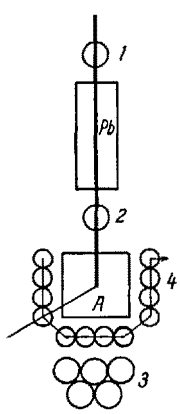


Fig. 1.—A schematic drawing of the apparatus used by Rossi and Nereson to determine the lifetime of the $\mu$-meson.

Thus by 1940 the existence of an unstable particle with a rest mass about 200 $m_e$ had been established. This particle was subsequently given the name $\mu$-meson and was thought for some years to be the particle required by the theory of Yukawa.

(c) *The lifetime of the $\mu$-meson.*—Experiments on the absorption anomaly of the hard component gave a value for the mean lifetime of the $\mu$-meson of the order of $2 \cdot 10^{-6}$ sec. The method, however, was dependent upon the value assumed for its mass, which was believed to be about 200 $m_e$. This assumption was avoided by a later method which measured directly the time interval between the stopping of a meson in an absorber and the appearance of a decay electron. An early determination by Rasetti[2] yielded a value of $1{\cdot}5 \times 10^{-6}$ sec; a more accurate determination by Rossi and Nereson[3] gave $2{\cdot}15 \times 10^{-6}$ sec. Their apparatus is shown schematically in figure 1. A thick block of lead was used to filter out the soft component, and some of the mesons which passed through the lead stopped in the brass absorber $A$. The arrival of such mesons was signified by the simultaneous discharge of the counter banks 1 and 2 together with an anticoincidence from the counter bank 3. This is usually written as (1, 2, −3). If the decay electron from the $\mu$-meson was emitted in a favourable direction it discharged one of the delayed coincidence countres 4. The time interval between (1, 2, −3,) and the discharge 4 was measured electronically. The distribution in the observed values of the delay time was found to obey the exponential law characteristic of a radioactive substance, viz.:

$$N_\mu = N_o \exp\,(-t/t_o),$$

where $N_o$ = number of mesons present initially,
$N_\mu$ = number of mesons present after a time $t$,
$t_o$ = mean life of the mesons.

Both Rasetti, and Rossi and Nereson, noticed that only about half of the mesons which stopped in the absorber $A$ appeared to decay. Rasetti used iron and aluminium absorbers whilst Rossi and Nereson used brass. This result seemed to be explained by a theory put forward by Tomonaga and Araki[1]. These workers predicted that positive and negative $\mu$-mesons should behave differently when brought to rest in solid materials. According to this theory a positive meson would be repelled from the positively charged nucleus by the relatively long range Coulomb forces, and would be unable to make a sufficiently close approach to the nucleus for the short range nuclear forces to operate. It would therefore decay freely irrespective of the atomic number of the material in which it stopped. A negative meason, on the other hand, would be attracted into the nucleus of an atom, first by the Coulomb forces and then by the nuclear forces. It would thus be absorbed before it had time to decay. Since it was known that positive and negative mesons occured with approximately equal frequency in the cosmic radiation, the experimental results appeared to confirm this theory.

In 1947 the theory was put to a more direct test by Conversi, Pancini, and Piccioni[2]. They separated the positive mesons from the negative mesons by means of a magnetic field, and brought the particles to rest in iron and graphite absorbers. In accordance with theoretical predictions, it was found that only positive mesons decayed when brought to rest in iron ($z = 26$). When graphite ($z = 6$) was used as the absorber, however, both positive and negative mesons were found to decay freely with a mean lifetime of $2 \times 10^{-6}$ sec.

[1] E. J. Williams and G. E. Roberts, Nature *145*, 202 (1940).
[2] F. Rasetti, Phys. Rev. *59*, 613 (1941); *60*, 198 (1941).
[3] B. Rossi and N. Nereson, Phys. Rev. *62*, 417 (1942); *64*, 199 (1943).

[1] S. Tomonaga and G. Araki, Phys. Rev. *58*, 90 (1940).
[2] M. Conversi, E. Pancini, and O. Piccioni, Phys. Rev. *71*, 209 (1947).

*Table I*
Mean lives in microseconds of negative $\mu$-mesons in various substances

| Substance | $Z$ | $\tau^-$ | $\tau/\tau^+$ | $f$* | Author |
|---|---|---|---|---|---|
| 0 | 8 | $1{\cdot}89 \pm 0{\cdot}15$ | $0{\cdot}87 \pm 0{\cdot}08$ | $0{\cdot}83 \pm 0{\cdot}08$ | Ticho |
| NaF | 9–11 | $1{\cdot}23 \pm 0{\cdot}12$ | $0{\cdot}57 \pm 0{\cdot}06$ | $0{\cdot}60 \pm 0{\cdot}065$ | Ticho and Schein |
| Mg | 12 | $0{\cdot}96 \pm 0{\cdot}06$ | $0{\cdot}45 \pm 0{\cdot}04$ | $0{\cdot}52 \pm 0{\cdot}04$ | Ticho |
| Mg | 12 | $1{\cdot}1 \pm 0{\cdot}2$ | | | Valley |
| Al | 13 | $0{\cdot}75 \pm 0{\cdot}07$ | $0{\cdot}35 \pm 0{\cdot}04$ | $0{\cdot}40 \pm 0{\cdot}04$ | Ticho |
| Al | 13 | $0{\cdot}70 \pm 0{\cdot}06$ | $0{\cdot}35 \pm 0{\cdot}035$ | $0{\cdot}47 \pm 0{\cdot}05$ | Valley |
| S | 16 | $0{\cdot}54 \pm 0{\cdot}12$ | $0{\cdot}25 \pm 0{\cdot}03$ | $0{\cdot}27 \pm 0{\cdot}03$ | Ticho |

* Here $f$ refers to the fraction of negative mesons which undergo decay.

Subsequent experiments by other workers confirmed this result (see Sigurgeirsson and Yamakawa[1], Valley[2], Ticho and Schein[3], and Valley and Rossi[4]). Positive mesons were found to decay freely in all absorbers irrespective of their atomic number. Negative mesons decayed with the same lifetime as positive mesons in very light elements, but as the atomic number of the absorber increased the number of mesons decaying decreased, and the lifetime of those which did decay appeared to decrease also. These results are illustrated by the figures given in Table I (Rossi[5]).

These results were not expected. Accordingly new calculations of the capture time of a meson by a nucleus were made. Fermi, Teller, and Weisskopf[6] showed that in a solid absorber the atomic capture of a meson to the lowest orbit about the nucleus ($K$ orbit) took place in less than $10^{-12}$ sec. The subsequent nuclear capture of the meson by the short range nuclear forces was calculated to take place in about $10^{-18}$ sec in carbon and $10^{-20}$ sec in iron.

But for carbon the time for the two stages of capture appeared to be greater than the mean lifetime of the meson, $2 \times 10^{-6}$ sec. It thus appeared that the $\mu$-meson, which had previously been identified with the meson postulated by Yukawa, possessed too weak an interaction with nucleons for it to be absorbed by a carbon nucleus. Doubts therefore arose about the correctness of the identification of the $\mu$-meson with the Yukawa particle.

(*d*) *The discovery of the $\pi$-meson.*—It is well known that progress in experimental science has been closedly associated with the available instruments and apparatus. This is clearly illustrated by the discovery of the $\pi$-meson.

1 T. Sigurgeirsson and A. Yamakawa, Phys. Rev. *71*, 318 (1947).
2 G. E. Valley, Phys. Rev. *72*, 772 (1947).
3 H. K. Ticho and M. Schein, Phys. Rev. *73*, 81 (1948).
4 G. E. Valley and B. Rossi, Phys. Rev. *73*, 177 (1948).
5 B. Rossi, *Cosmic Radiation* (Colston Papers, 1949), p. 55.
6 E. Fermi, E. Teller, and V. Weisskopf, Phys. Rev. *71*, 314 (1947).

In 1946, Ilford Ltd. of Great Britain produced a new photographic emulsion which was capable of recording the tracks of slow moving $\alpha$-particles, protons, and mesons[1]. The production of these emulsions represented an important technical advance; an account of their uses and applications has recently been published in Experientia[2]. A strip of emulsion one square centimetre in area and 100 $\mu$ in thickness is roughly equivalent in stopping power to a cloud chamber of dimensions $2000 \times 2000 \times 20$ cm. The photographic emulsion possesses the further advantages that it is extremely portable and continuously sensitive.

In the early part of 1947 such emulsions were exposed to the cosmic radiation at mountain altitudes and in aircraft. It was observed by Perkins[3] of London University, and by Occhialini and Powell[4] of Bristol University, that some of the particles brought to rest in the emulsion produced nuclear disintegrations at the end of their range. From a study of their behaviour in traversing the emulsion these particles were shown to be mesons, and they were called $\sigma$-mesons to distinguish them from the normal $\mu$-meson. It was also observed by Lattes, Muirhead, Occhialini, and Powell[5] that some of the mesons brought to rest in the emulsion did not cause a nuclear disintegration, but produced a second meson. Figure 2 shows an example of a disintegration produced by a $\sigma$-meson, whilst figure 3 shows one of the first double meson processes observed.

Measurements on the tracks of the secondary particles of the double meson process showed that their range, and hence their kinetic energy, was constant. This result indicated that the process concerned was a fundamental one. It was therefore postulated that the primary meson, designated $\pi$, decayed whilst at rest to a lighter meson, designated $\mu$, and some neutral particle.

1 C. F. Powell, G. P. S. Occhialini, D. L. Livesey, and L. V. Chilton, J. Sci. Instr. *23*, 102 (1946).
2 H. K. Heitler and D. T. King, Exper. *4*, 281 (1950).
3 D. H. Perkins, Nature *159*, 126 (1947).
4 G. P. S. Occhialini and C. F. Powell, Nature *159*, 186 (1947).
5 C. M. G. Lattes, H. Muirhead, G. P. S. Occhialini, and C. F. Powell, Nature *159*, 694 (1947).

After suitable geometrical corrections had been applied, the number of $\sigma$-mesons observed in a given volume of emulsion was found to be approximately

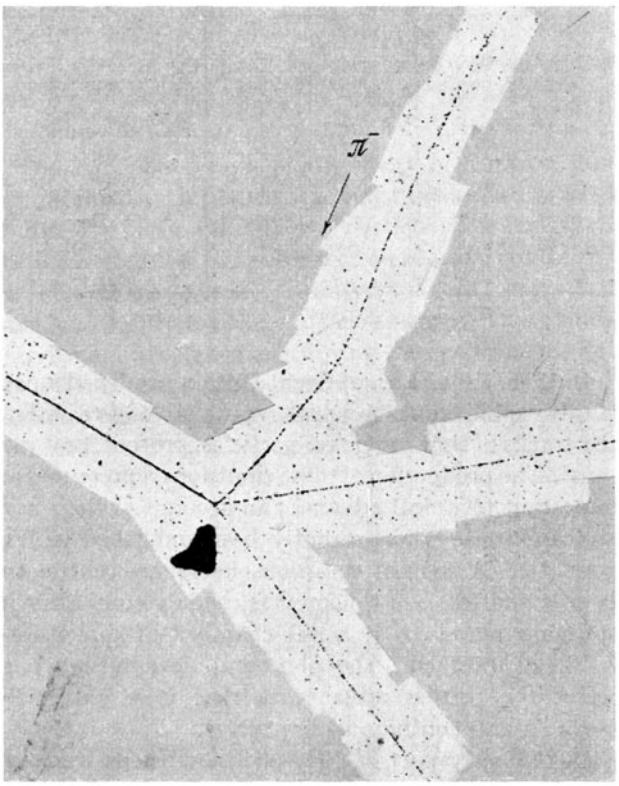


Fig. 2.—A nuclear disintegration caused by a slow $\pi^-$-meson.

equal to the number of $\pi$-$\mu$ decays observed. It was therefore suggested by Lattes, Occhialini, and Powell[1] that there existed in the cosmic radiation a new fundamental particle, the $\pi$-meson. They proposed that the meson responsible for the double meson process was the positive $\pi$-meson, which was repelled by positive nuclei and thus able to decay freely, whilst the $\sigma$-meson was to be identified as its negatively charged counterpart.

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

At the same time as these experimental results were published Bethe and Marshak[1] in the United States, and Sakata and Inoue[2] in Japan, put forward a theory to explain the apparent discrepancy between the results of the experiments on the lifetime of negative $\mu$-mesons, and the concept of a strong interaction between mesons and nucleons. They proposed that there existed in the cosmic radiation strongly interacting mesons, which were produced directly in the disintegration of nuclei. It was postulated that these mesons decayed, in a short period of time, to mesons possessing a weak interaction with nuclei. The latter were the particles normally observed in the hard component. Thus the strongly interacting mesons were to be identified as $\pi$-mesons and the weakly interacting particles as $\mu$-mesons.

Subsequent work has shown the correctness of this hypothesis. The mass of the $\mu$-particle observed in the double meson process has been shown to be identical with that of the mesons of the hard component[3]. Furthermore, it has recently been shown that the majority of the charged mesons produced in nuclear disintegrations are $\pi$-particles[4].

So far we have dealt with the charged mesons of the cosmic radiation. It has recently been established that large numbers of uncharged mesons can also be produced in nuclear explosions. This work, however, is closely connected with the production and properties of the charged $\pi$-mesons and so a description of their discovery will be left to a later section.

### (2) *The masses of the $\pi$- and $\mu$-mesons*

Many methods have been employed for the measurement of the masses of the charged $\pi$- and $\mu$-mesons;

[1] H. A. Bethe and R. E. Marshak, Phys. Rev. *72*, 506 (1947).

[2] S. Sakata and T. Inoue, Prog. Theor. Phys. Japan. *1*, 143 (1946).

[3] Y. Goldschmidt-Clermont, D. T. King, H. Muirhead, and D. M. Ritson, Proc. Phys. Soc. *21*, 138 (1948). – R. B. Brode, Rev. Mod. Phys. *21*, 37 (1949).

[4] O. Piccioni, Phys. Rev. *77*, 1, 6 (1950). – P. H. Fowler, Phil. Mag. *41*, 169 (1950). – U. Camerini, P. H. Fowler, W. O. Lock, and H. Muirhead, Phil. Mag. *41*, 413 (1950).

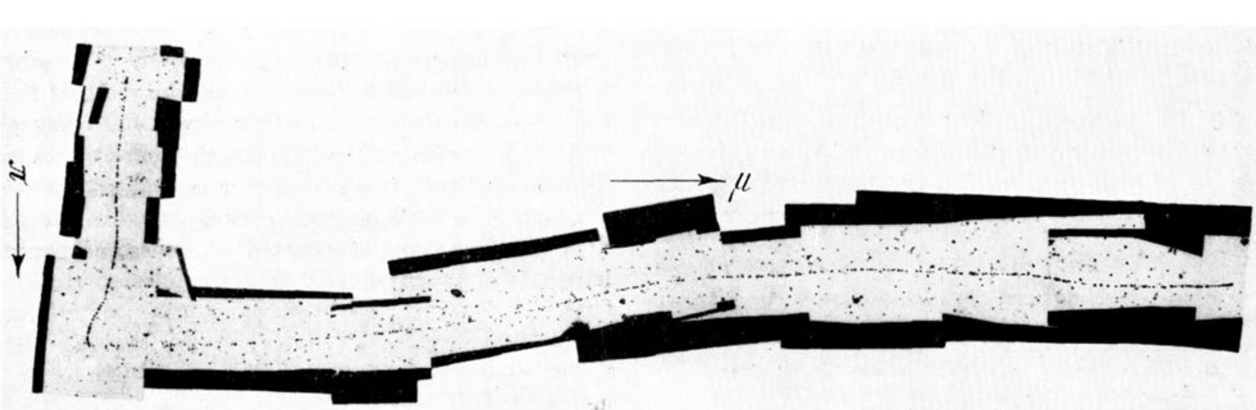


Fig. 3.—The decay of a $\pi$-meson to a $\mu$-meson.

the most successful of these has been applied to both cloud chamber and nuclear emulsion techniques. The method involves the simultaneous measurement of the momentum and of the residual range of a slow meson. The momentum may be determined from the magnitude of the deflection of the particle in a strong magnetic field since

$$P = \frac{m v}{(1 - v^2/c^2)^{1/2}} = \frac{H e \varrho}{c}, \quad (1)$$

where $P$ is the momentum of the meson, $m$ its mass, $v$ its velocity, $e$ its charge, $c$ the velocity of light, and $\varrho$ the radius of curvature of the track of the meson in a magnetic field of strength $H$.

The residual range of a particle, $R$, that is, the distance it travels before it is brought to rest, may be expressed as

$$R = K\, m\, v^x. \quad (2)$$

The constants $K$ and $x$ may be determined experimentally, and thus the only unknown quantities in equations (1) and (2) are the mass and velocity of the meson, which may therefore be calculated.

Accurate measurements of the mass of the $\mu$-meson using two cloud chambers have been made by FRETTER[1], and using three cloud chambers by BRODE and RETALLACK[2]. A schematic diagram of the apparatus used by FRETTER is shown in figure 4. The upper cloud chamber ($CH_1$) was maintained in a strong magnetic field; thus the sign of the charge, and the momentum, of any particle which traversed it could be determined. In the lower cloud chamber ($CH_2$) were placed a series of horizontal lead plates; if a meson stopped in one of these plates then its residual range with respect to the momentum measurement could be determined. Using this method, the mass of the $\mu$-meson in the cosmic radiation has been found to be

$$m_\mu = 212 \pm 5\, m_e.$$

The work of BRODE and RETALLACK gave a value of $215 \pm 2\, m_e$[3].

Measurements of the rest mass of both the $\pi$- and the $\mu$-meson have also been made using photographic emulsions. The method used has been applied both to mesons occurring in the cosmic radiation and to mesons produced with the aid of the BERKELEY synchrocyclotron. In the former case, two emulsions separated by a small air gap were placed face to face in a strong magnetic field[4]. If a meson passed from one emulsion to the other, then the change in direction of the particle from the point it left the one emulsion to the point it entered the second, enabled its charge and momentum to be determined. If the particle stopped in the second emulsion then its residual range could also be found. Using this method FRANZINETTI[1] obtained the following mass values:

$$m_{\pi-} = 281 \pm 7\, m_e,$$
$$m_{\mu+} = 217 \pm 4\, m_e,$$
$$m_{\pi+} = 288 \pm 13\, m_e.$$

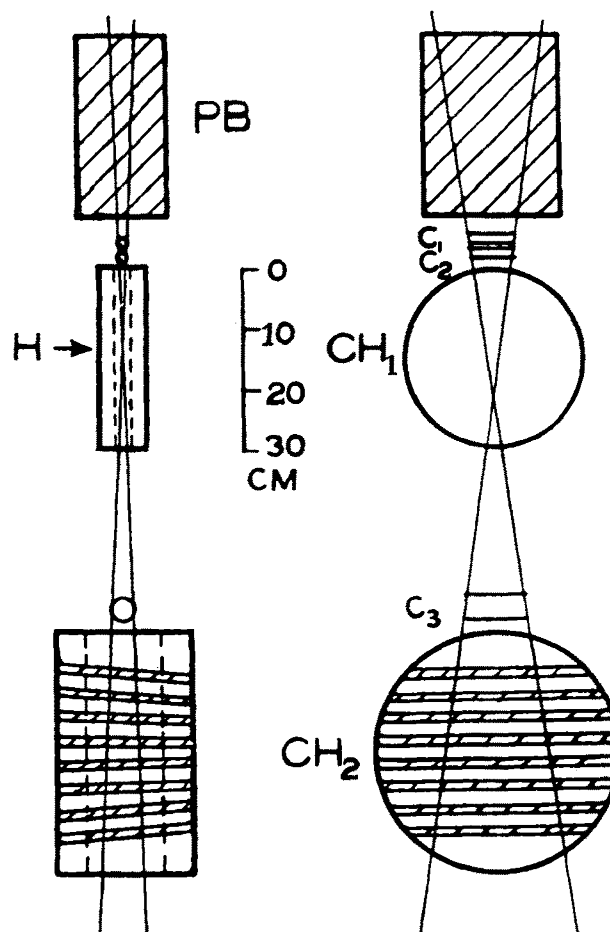


Fig. 4.—A schematic drawing of the apparatus used by FRETTER to determine the mass of the $\mu$-meson observed in the cosmic radiation.

A determination employing a method which is similar in principle has been carried out at the Berkeley radiation laboratory and has yielded $m_{\pi+} = 274 \pm 2 m_e$; $m_{\pi-} = 271{\cdot}4 \pm 2{\cdot}5\, m_e$; and $m_{\mu+} = 208 \pm 2\, m_e$.

### (3) *Properties of $\pi$-mesons*

The $\pi$-meson is a particle with an extremely short lifetime; consequently it decays within a short distance of its point of production. Its detection requires a system of high stopping power such that it is brought to rest before it can decay. Furthermore, the system must be capable of detecting the decay or interaction

[1] W. B. FRETTER, Phys. Rev. *70*, 625 (1946).
[2] R. B. BRODE and J. G. RETALLACK, Phys. Rev. *75*, 1716 (1949).
[3] The latest value given by BRODE is $210 \pm 2\, m_e$ (Oxford Conference, Sept. 1950).
[4] I. BARBOUR, Phys. Rev. *76*, 320 (1949); *77*, 751 (1950); *78*, 518 (1950). – Y. GOLDSCHMIDT-CLERMONT and M. MERLIN, Il Nuovo Cimento *7*, 220 (1950). – C. FRANZINETTI, Phil. Mag. *41*, 86 (1950).

[1] C. FRANZINETTI, Phil. Mag. *41*, 86 (1950).

products of the meson. These requirements are realised in the nuclear emulsion, and it is not surprising that $\pi$-mesons remained undetected until this advance in technique had been made.

(*a*) *The lifetime of the $\pi$-meson.*—The transient life of the $\pi$-meson allows an extremely simple method, using nuclear emulsions, to be employed for its determination. This method merely involves the measurement of the number of $\pi$-mesons present at varying distances from a source of these particles. The distances required are of the order of one or two metres. If the particles travel in air or vacuo between the points of production and detection, their time of flight, $t$, is given by the expression

$$t = \frac{d}{v},$$

where $d$ is the distance travelled by a $\pi$-meson and $v$ is its velocity. If the mesons are detected in photographic plates, the time for them to be brought to rest ($10^{-11}$ sec) is negligible compared with $t$, and we may write

$$N_d = N_o \exp - \frac{t}{t_o} = N_o \exp - \frac{d}{v t_o}, \qquad (3)$$

where $N_d$ = number of mesons at distance $d$ from the source,

$N_o$ = number of mesons emitted from the source,

$t_o$ = mean life of a meson.

An early determination[1] of the quantity $t_o$ for mesons occuring in the cosmic radiation yielded a value of $6 \pm 3 \times 10^{-9}$ sec. A more elaborate experiment[2] performed with mesons produced in the Berkeley synchrocyclotron gave a value of $1{\cdot}97 \pm ^{0{\cdot}14}_{0{\cdot}17} \times 10^{-8}$ sec. It was also shown that the decay of the $\pi$-particle followed an exponential law in common with other radioactive substances. Magnetic fields were used in this experiment in order to obtain mesons of known velocity.

(*b*) *The decay of the $\pi$-meson.*—It has been stated above that in the decay of the $\pi$-meson, a single $\mu$-meson is produced. The latter always has a kinetic energy of 4·1 MeV. An uncharged radiation must also be produced in this process in order to conserve momentum with the $\mu$-meson, and to account for the difference in total energy between the $\pi$- and $\mu$-particles. Since the $\mu$-meson always has the same velocity only one neutral particle can be involved. From a consideration of the difference in mass of the two kinds of meson, and of the kinetic energy of the $\mu$-meson, it may be shown that the rest mass of the neutral particle is very small or even zero (see $P$ equations 4, 5, 6). This particle may thus be either a neutrino or a photon.

[1] U. Camerini, H. Muirhead, C. F. Powell, and D. M. Ritson, Nature *162*, 433 (1948).

[2] E. A. Martinelli and W. K. H. Panofsky, Phys. Rev. *77*, 465 (1950).

The photon hypothesis has been disproved in a recent experiment performed by O'Ceallaigh[1]. As a single neutral particle is produced in the decay process it must travel in an exactly opposite direction to that of the $\mu$-meson. O'Ceallaigh has examined 38 cm of the path of such particles in a nuclear emulsion. In this distance 6 electron pairs should have materialized if the neutral particles were photons. In fact none were observed. The probability of obtaining this result is $4 \times 10^{-3}$. We may therefore conclude that the decay scheme is:

$$\pi \rightarrow \mu^+ + \nu_o$$

where $\nu_o$ represents a neutrino.

(*c*) *The interaction of $\pi$-mesons with nuclei.*—The $\pi$-meson interacts strongly with nucleons and nuclei thus indicating that it is probably the particle largely responsible for the nuclear binding forces. A recent experiment with nuclear emulsions[2] has shown that fast $\pi$-particles cause a nuclear disintegration whenever they encounter a nucleus[3].

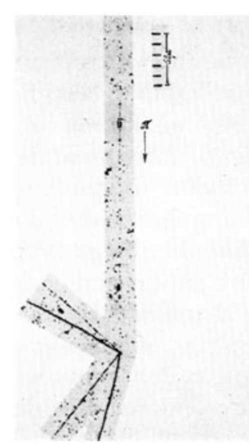


Fig. 5.—A nuclear disintegration caused by a fast $\pi$-meson.

The probability for the occurrence of nuclear reactions is frequently described in terms of cross section; an interaction between particles at each nuclear encounter is said to correspond to geometrical cross section. Figure 5 shows a nuclear disintegration produced by a fast particle which has been identified as a $\pi$-meson.

Due to the general difficulties of identifying fast $\pi$-mesons, little detailed knowledge is as yet available about the processes which occur when they interact with nuclei. In addition the reactions must occur in a suitable system for detection such as a photographic emulsion. However, the nuclei comprising an emulsion,

[1] C. O'Ceallaigh, Phil. Mag. *41*, 838 (1950).

[2] U. Camerini, P. H. Fowler, W. O. Lock, and H. Muirhead, Phil. Mag. *41*, 413 (1950).

[3] Work of W. H. Barkas, B. J. Moyer, and W. K. H. Panofsky, reported by L. W. Alvarez and B. J. Moyer, Harwell Nuclear Physics Conference, Sept. 1950.

which are also the target nuclei, are not necessarily the most suitable for a study of fast $\pi$-meson reactions. Further, the only available source of $\pi$-mesons of great energy is the cosmic radiation, and as the intensity of this component at all altitudes is comparatively weak, the rate of collection of data is very slow.

Considerably more information has been acquired on the interaction of slow negative $\pi$-mesons with nuclei, especially hydrogen nuclei. At Berkeley a search has been made for high energy $\gamma$-rays following the absorption of slow negative $\pi$-mesons by liquid hydrogen. $\gamma$-rays with energies of approximately 70 and 130 MeV were found to be emitted[1]. These values were interpreted by assuming that two alternative reactions could occur. In order to conserve charge and spin angular momentum a neutron must be produced, together with either a $\gamma$-ray or a neutral meson, $\pi^0$, viz,:

$$\pi^- + P \rightarrow N + \gamma, \quad \text{(a)}$$
$$\pi^- + P \rightarrow N + \pi^0. \quad \text{(b)}$$

From reaction (a), a 130 MeV $\gamma$-ray is to be expected from considerations of the conservation of mass-energy and momentum, whilst in reaction (b) the $\pi^0$-meson will almost immediately decay to two $\gamma$-rays of approximately 70 MeV each (see the section on neutral mesons). If the total energy of the two $\gamma$-rays is known, the Einstein relationship between mass and energy will give directly the rest mass of the neutral meson. The value obtained in this manner is $261 \pm 4\ m_e$. Regardless of the exact value, the experiment shows unambiguously that the mass of the neutral meson must be less than that of the negative $\pi$-particle in order that reaction (b) may be energetically possible.

It is of interest to note that the occurrence of reaction (a) proves that the spin quantum number of the $\pi^-$-meson must be either 0 or 1 since that of both the neutron and the proton is known to be one-half whilst that of a $\gamma$-ray is unity. It will be shown later that the spin quantum number of the $\mu$-meson is either $^1/_2$ or $1^1/_2$. The assignment of the value 0 or 1 to the $\pi$-meson then conserves spin in the $\pi$-$\mu$-decay since the spin quantum number of the neutrino is $^1/_2$.

The interaction which results from the absorption of a $\pi^-$-meson by a hydrogen nucleus cannot be directly observed since all the products of the reaction are electrically neutral. When negative $\pi$-particles are brought to rest in nuclear emulsions however, visible disintegrations occur at the arrest points of 72% of the mesons[2].

Owing to the existence of Coulomb forces the meson will first interact with a proton within the nucleus, and so the nuclear charge will be lowered by one unit. The experimental evidence indicates that an entirely different reaction from that found in the case of the free proton then ensues. If either reaction (a) or (b) described above for hydrogen occured within heavier nuclei no visible disintegration would be produced, since most of the rest energy of the $\pi^-$-particles would be carried away by photons and neutral mesons. It has been observed that at least half of the rest energy of the $\pi^-$-particle frequently appears in the visible disintegration of the nucleus. The production of a light particle capable of carrying away most of the available rest energy can rarely, if ever, occur.

BRUNO[1] has proposed that a $\pi^-$-meson interacts in a nucleus in such a manner that its rest energy is shared amongst several particles, and that the volume of the interaction is virtually independent of the nature of the nucleus. Experiments by MENON, MUIRHEAD, and ROCHAT[2] using nuclear emulsions have shown that this hypothesis is essentially correct. In a silver or bromine nucleus the rest energy of the $\pi^-$-particle appears to be shared amongst approximately four nucleons. Each nucleon therefore receives an average energy of about 35 MeV, and in moving through the nucleus these particles undergo collisions. The nucleus becomes excited and subsequently evaporates nucleons and $\alpha$-particles. In light nuclei the volume of interaction occupies a relatively larger part of the nucleus and a more complete disintegration therefore occurs.

### (4) *The properties of $\mu$-mesons*

(*a*) *The decay of the $\mu$-meson.*—Satisfactory knowledge concerning the decay process of the $\mu$-meson has been gained only during the last few years, although the lifetime had been accurately measured by 1942. In order to conserve mass-energy and momentum, when a $\mu$-meson decays some neutral particle or particles must be emitted in addition to the charged decay particle. HINCKS and PONTECORVO[3] have investigated the nature of both the charged and uncharged decay products. Their results show that the charged particle is almost certainly an electron, and that the neutral component does not consist of high energy $\gamma$-rays.

When the decay of the $\mu$-meson was first observed it was assumed that an electron and a neutrino were the sole products of the disintegration, viz.:

$$\mu \rightarrow e + \nu_o.$$

Subsequent work has shown that in actual fact two neutrinos are emitted, viz.:

$$\mu \rightarrow e + \nu_o + \nu_o.$$

This knowledge has been acquired by examining the energy spectrum of the decay electrons. If we consider

[1] W. K. H. PANOFSKY, L. AAMODT, and H. F. YORK, Phys. Rev. *78*, 825 (1950).—W. K. N. PANOFSKY, L. AAMODT and J. HADLEY, *ibid. 8*, 565 (1951).

[2] F. L. ADELMAN and S. B. JONES, Phys. Rev. [A] *75*, 1468 (1949).

[1] B. BRUNO, Ark. Mat. Astro. Fys. A. *36*, 1 (1948); Ark. Fys. *1*, 19 (1949).

[2] M. G. K. MENON, H. MUIRHEAD, and O. ROCHAT, Phil. Mag. *41*, 583 (1950).

[3] E. P. HINCKS and B. PONTECORVO, Phys. Rev. *73*, 256 (1948); *77*, 102 (1950).

the kinetic energy, $E$, the momentum, $P$, and the mass, $m$, of a particle in units of MeV, $\mathrm{MeV}/_c$ and $\mathrm{MeV}/c^2$, respectively, then the following relativistic relation holds between the kinetic energy and the momentum:

$$P^2 = E^2 + 2\,mE\,. \qquad (4)$$

For a meson at rest decaying into an electron and one neutrino, the laws of conservation of energy and momentum show that the energy of the electron is constant. We have

$$m_\mu = E_e + m_e + E_\gamma + m_\gamma \qquad (5)$$

for conservation of energy and

$$P_e = P_\gamma \qquad (6)$$

for conservation of momentum.

Thus we may solve for $E_e$.

Since the mass of the $\mu$-meson is 107 $\mathrm{MeV}/c^2$ and that of the electron is 0·51 $\mathrm{MeV}/c^2$, the electron should be emitted with a kinetic energy of 54 MeV. Early measurements of the momentum of the decay electron gave values which were consistent with this energy (a momentum of 54 $\mathrm{MeV}/c$ is numerically equivalent to an energy of 54 MeV for an electron). Recent experiments using widely different techniques have shown, however, that the electrons are not emitted with a unique energy but in a broad energy spectrum. The three methods employed may be summarized as follows:

(a) Measurement of the residual range of the decay electron[1]. We have shown earlier that the range of a charged particle is a function of its kinetic energy.

(b) Measurement of the momentum[2]. The measurement was carried out in a cloud chamber placed between the pole pieces of a powerful magnet. The resultant deflection of the particle in the magnetic field is inversely proportional to its momentum.

(c) Measurement of the multiple Coulomb scattering of the decay electron in a nuclear emulsion[3]. A charged particle passing through any medium is continually deviated, in a random fashion, by the electromagnetic forces acting between the particle and the nuclei of the atoms of the emulsion. The resultant deviation is termed the multiple coulomb scattering, and for a fast electron the average deviation, $\bar{\alpha}$, is inversely proportional to the energy, $E$, of the particle:

$$\bar{\alpha} = A/E, \text{ where } A \text{ is a constant.}$$

All these experiments yielded substantially the same result. The energies of the decay particles were found to be distributed in a broad energy spectrum which exhibited a peak in the region of 40 MeV. The average energy was about 35 MeV. A reproduction of the spectrum obtained by method (b) is shown in figure 6. All three experiments gave strong evidence that the energy spectrum continued up to 54 MeV and that it had a finite value at this limit. This latter condition can fulfilled only if the total mass of the charged and uncharged decay particles is very small, that is, of the order of one or two electron masses.

[1] J. STEINBERGER, Phys. Rev. *75*, 1136 (1949).
[2] C. D. ANDERSON, R. B. LEIGHTON, and A. J. SERIFF, Phys. Rev. *75*, 1432 (1949).
[3] J. H. DAVIES, W. O. LOCK, and H. MUIRHEAD, Phil. Mag. *40*, 1250 (1949).

The average energy of 35 MeV indicated that two neutral particles of small rest mass were emitted during the decay of the $\mu$-meson, for if an energy of 107 MeV is distributed amongst $n$-particles of very small rest mass, the average energy received by any one particle will be $107/n$ MeV.

Thus the $\mu$-meson decays into an electron and two neutral particles. The work of HINCKS and PONTECORVO has shown that the latter are not photons. It is therefore probable that they are neutrinos, since these particles appear to be present in all cases of natural radioactive $\beta$-decay. The decay scheme is therefore:

$$\mu \rightarrow e + \nu_0 + \nu_0 .$$

Both the electron and the neutrino have spin quantum number of $^1/_2$; accordingly that of the $\mu$-meson must be $^1/_2$ or $1^1/_2$ depending upon the sign of the spin of the decay products.

Theories predicting energy distributions similar to those described above have been satisfactorily developed by several workers[1]. The exact shape of the spectrum remains to be elucidated.

(*b*) *The interaction of slow negative $\mu$-mesons with nuclei.*—It was found in the delayed coincidence experiments that the negatively charged $\mu$-mesons apparently disappeared in elements of high atomic number without the production of a decay electron.

Two alternative explanations were first advanced to explain this phenomenon. VALLEY and ROSSI[2] that proposed the rate of decay of the $\mu$-mesons was accelerated in the intense electro-static fields existing at the periphery of a nucleus. Most of the delayed coincidence circuits used in the experiments alread described accepted electrons from mesons with decay periods between $10^{-5}$ and $10^{-6}$ sec. Since the negatively charged mesons could make a considerably closer approach to the nucleus than their positive counterparts, it was suggested that many of them would decay in a time less than $1\times10^{-6}$ sec and apparently disappear without the production of a decay electron. Ingenious experiments by TICHO and SCHEIN[3], using delayed coincidence apparatus, have disproved this theory. Further, CHANG[4] of Princeton, using a cloud chamber, has examined the absorption of $\mu$-mesons from the cosmic radiation in lead, iron and aluminium. In each absorber approximately half of the mesons observed were found to decay. Since positive and negative $\mu$-mesons occur in

[1] J. TIOMNO, J. A. WHEELER, and R. R. RAU, Rev. Mod. Phys. *21*, 144 (1949).—L. MICHEL, Proc. Phys. Soc. [A] *63*, 514 (1950).
[2] G. E. VALLEY and B. ROSSI, Phys. Rev. *73*, 177 (1948).
[3] H. K. TICHO and M. SCHEIN, Phys. Rev. *73*, 81 (1948).
[4] W. Y. CHANG, Rev. Mod. Phys. *21*, 166 (1949).

approximately equal numbers in the cosmic radiation, it can be seen that result obtained by Chang is consistent with the view that negative $\mu$-mesons disappear without decay in materials of high atomic number.

In a theory put forward by Wheeler[1] it was proposed that nuclear capture of the negative $\mu$-meson could occur, and that the probability for capture competed with the probability for the meson to decay. Wheeler estimated that the probability for nuclear capture varied as the fourth power of the charge of the absorbing nucleus. Thus it follows that capture is far more probable in heavy elements than in light elements. The experimental results confirm this deduction.

When a slow negative $\mu$-meson enters a nucleus very little of its rest energy is conveyed to the latter, and no visible disintegration of the type shown in figure 2 takes place. Chang has shown that no protons are emitted when negative $\mu$-mesons interact with lead nuclei. A similar result has been obtained with photographic emulsions[2].

After entering the nucleus it is to be expected that the negative $\mu$-meson would interact with a proton with consequent neutralisation of charge[3]. In this process the rest mass energy of the meson would be liberated. In addition to the production of a neutron. Tiomno and Wheeler suggested that one other particle was emitted, viz.:

$$\mu^- + P^+ \rightarrow N + X.$$

The particle $X$ must be uncharged and less massive than a $\mu$-meson. Further, since no visible disintegration is produced, it must have a very weak interaction with nucleons. The only known particles with these properties are the photon and the neutrino. Piccioni[4] and others have shown that photons of high energy (greater than 25 MeV) do not accompany the nuclear absorption of $\mu^-$-mesons in iron. It may therefore be concluded that the particle $X$ is a neutrino and that the $\mu$-meson has spin quantum number $^1/_2$ or $1^1/_2$. The latter result agrees with that obtained from the experiments on the decay of the $\mu$-meson.

From considerations of the conservation laws (equations 4, 5, 6), it may be shown that the newly created neutron receives an average kinetic energy of 6 MeV following the interaction of the $\mu$-meson with a proton. The consequent excitation of the nucleus is small and the emission of charged particles is not to be expected.

(c) *The interaction of the fast $\mu$-mesons with nuclei.*— Experiments on the interaction of fast $\mu$-mesons with nuclei have shown conclusively that these particles cannot be responsible for the strong binding forces which exist between nucleons.

At sea level most of the penetrating particles are $\mu$-mesons. Thus experiments on the nuclear interaction of these penetrating particles can give considerable information on the behaviour of $\mu$-mesons. Many experiments have taken the form of a search for a large change in direction of a penetrating particle in passing through a solid medium such as lead. A recent experiment of this type by Amaldi and Fidecaro[1] has yielded a value of less than $10^{-30}$ cm$^2$ per nucleon for the cross-section for nuclear interaction. The cross-sectional area of a nucleon is about $6 \times 10^{-26}$ cm$^2$. If the $\mu$-meson interacted with every nucleon it encountered the meson would be described as having a geometrical cross-section for interaction, namely $6 \times 10^{-26}$ cm$^2$. Thus for a cross-section of $10^{-30}$ cm$^2$ the $\mu$-meson encounters on the average more than $(6 \times 10^{-26}/10^{-30}) = 60{,}000$ nucleons before a nuclear interaction takes place.

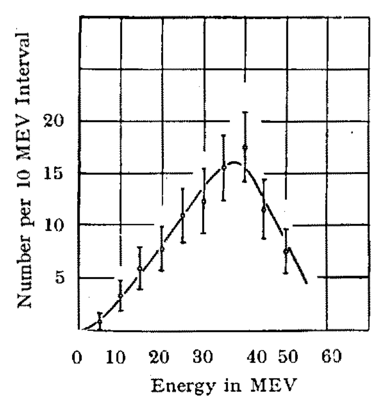


Fig. 6.—The energy spectrum of the decay electrons from $\mu$-mesons as determined by Anderson and his collaborators.

An experiment which has an important bearing on the strength of nuclear interaction of fast $\mu$-mesons has recently been performed by Evans and George[2]. Photographic emulsions were prepared, exposed, and developed, at a depth below ground equivalent to 60 m of water. On examination of the plates a few nuclear disintegrations were observed. Only a small fraction of these could be attributed to $\pi$-mesons and neutrons. It was therefore concluded that the primary particles were $\mu$-mesons. The value for the cross-section for interaction was estimated to be about $10^{-29}$ cm$^2$/nucleon. It has been calculated, however, that the majority of these disintegrations are probably produced by electromagnetic interaction between the $\mu$-meson and the protons and $\pi$-mesons existing within the nucleus, and that nuclear forces play a very small role.

[1] J. A. Wheeler, Phys. Rev. *71*, 320 (1947); Rev. Mod. Phys. *21* 133 (1949).
[2] U. Camerini, H. Muirhead, C. F. Powell, and D. M. Ritson, Nature *162*, 433 (1948).
[3] J. Tiomno and J. A. Wheeler, Rev. Mod. Phys. *21*, 153 (1949).
[4] O. Piccioni, Phys. Rev. *74*, 1236 (1948); *74*, 1754 (1948).

[1] E. Amaldi and G. Fidecaro, Helv. phys. acta *23*, 93 (1950); Il Nuovo Cimento *7*, 535 (1950).
[2] J. Evans and E. P. George, Nature *164*, 20 (1949); Proc. Phys. Soc. *63*, 1235 (1950).

*Table II*

| | $\pi\pm$ | $\mu\pm$ |
|---|---|---|
| Mass | $274 \pm 2 m_e$ | $210 \pm 2 m_e$ |
| Mean lifetime | $1{\cdot}97 \times 10^{-8}$ sec | $2{\cdot}15 \times 10^{-6}$ sec |
| Mode of decay | $\pi \rightarrow \mu + \nu_0$ | $\mu \rightarrow e + \nu_0 + \nu_0$ |
| Spin | Integral | Half integral |
| Interaction of slow particles | Normally produces a visible disintegration | Rarely produces a visible disintegration |
| Interaction of fast particles | "Geometrical" cross-section | $\sim 10^{-5}$ x Geometrical cross-section |

(5) *Summary of the properties of $\pi$- and $\mu$-mesons*

Table II summarizes and compares the main properties of the $\pi$- and $\mu$-mesons.

It can be seen that neither of these mesons resembles the hypothetical particle of YUKAWA in all respects.

(6) *The production of $\pi$-mesons*

(*a*) *The production of slow $\pi$-mesons.*—Within a few weeks of the discovery of the $\pi$-meson examples were found of the ejection of slow $\pi^-$-particles from nuclear disintegrations. The latter were produced in photographic emulsions exposed to the cosmic radiation[1]. The frequency of occurence of such events in the cosmic radiation is low, however, and a detailed study of the process could not be undertaken.

The production of large numbers of slow $\pi$-mesons in the giant synchrocyclotrons[2] has enabled important progress to be made in the study of both the properties of these particles, and of the processes involved in their production. In these machines $\pi$-mesons with kinetic energies up to 150 MeV may be produced by the bombardment of targets of carbon or other elements, by protons, whose maximum kinetic energy is of the order of 345 MeV. The artificial production of $\pi$-mesons was first observed during the bombardment of a carbon target with a beam of 380 MeV $\alpha$-particles.

Outstanding experiments performed with the aid of these machines have already been quoted, viz., the lifetime of the $\pi$-meson and the interaction of slow $\pi^-$-mesons with protons. Many other experiments have been performed, and the absolute cross-section for the production of $\pi$-mesons by 345 MeV protons has been determined[3]. No $\pi$-mesons were produced if protons with a kinetic energy of less than 180 MeV were employed. This result was in good agreement with theoretical predictions[4]. As the energy of the bombarding protons was increased above this value, the meson yield was observed to rise rapidly.

[1] C. M. G. LATTES, G. P. S. OCCHIALINI, and C. F. POWELL, Nature *160*, 453, 486 (1947).

[2] E. GARDNER and C. M. G. LATTES, Science *107*, 270 (1948).

[3] C. RICHMAN and H. A. WILCOX, U.C.R.L. Report No. 510 (1949). – M. WEISSBLUTH, U.C.R.L. Report No. 511 (1949).

[4] W. E. MCMILLAN and E. TELLER, Phys. Rev. *72*, 1 (1947).

More recently, $\gamma$-rays produced in a 340 MeV electron synchrotron have been observed to create $\pi$-mesons on striking carbon targets[1].

(*b*) *The production of fast $\pi$-mesons.*— The maximum proton energy at present available in the physics laboratory is 345 MeV. It has thus only been possible to create $\pi$-mesons singly and with small kinetic energies. However, it has been known for some years that protons occuring in the cosmic radiation sometimes have energies as high as $10^6$ MeV. It is therefore to be expected that when a high energy cosmic ray proton (or neutron) strikes a nucleus an entirely different process will occur. This is strikingly illustrated by the phenomenon of *penetrating showers*. This term derives from the pioneer work of WATAGHIN[2] and of JANOSSY[3], who first detected the occurence in the cosmic radiation of groups of particles which, unlike the soft electron component, could traverse great thicknesses of lead.

Considerable research has been carried out on the production and properties of these showers, employing both counter and cloud chamber techniques. More recently photographic plates have played an important role in the investigation of this phenomenon. A typical penetrating shower, observed in a photographic plate exposed at the Jungfraujoch, is shown in figure 7.

It has recently been shown that the majority of the penetrating shower particles are $\pi$-mesons[4]. If a penetrating shower particle is defined as a particle which emerges from a disintegrating nucleus with a specific ionisation of less than 1·5 times the minimum value, then it has been shown by CAMERINI *et al.*[5] that 82% of them are $\pi$-mesons.

Although the experiments with photographic emulsions show conclusively that many mesons can be produced during the disintegration of a single nucleus,

[1] E. MCMILLAN, J. M. PETERSON, and R. S. WHITE, Science *110*, 575 (1949). – J. STEINBERGER and A. S. BISHOP, Phys. Rev. *78*, 493, 494 (1950).

[2] G. WATAGHIN, M. DE SOUZA SANTOS, and P. A. POMPEIA, Phys. Rev. *57*, 61 (1940).

[3] L. JANOSSY and P. INGLEBY, Nature *145*, 511 (1940). – L. JANOSSY and G. D. ROCHESTER, Proc. Roy. Soc. An. *182*, 180 (1943).

[4] O. PICCIONI, Phys. Rev. *77*, 1, 6 (1950).—P. H. FOWLER, Phil. Mag. *41*, 169 (1950).

[5] U. CAMERINI, P. H. FOWLER, W. O. LOCK, and H. MUIRHEAD, Phil. Mag. *41*, 413 (1950).

considerable controversy exists regarding the nature of the predominant process occuring inside the nucleus. Two main theories of meson production have been advanced—the theory of multiple production (Heisenberg[1], Lewis *et al.*[2]), and the theory of plural production (Heitler and Janossy[3]). The former theory predicts that all the mesons of a penetrating shower can be produced in a single nucleon-nucleon collision, but that the probability for this process to occur is fairly low. The theory of plural production on the other hand, predicts that the most probable number of mesons created in a nucleon-nucleon collision is one, but that the probability for such collisions to occur is quite high. Thus, on this theory, a series of collisions can take place inside a single nucleus and give rise to a large meson shower.

Unfortunately, the present experimental data may be explained on the basis of either theory[4]. A decisive experiment has yet to be performed. One such experiment would be to compare the number of mesons produced in hydrogen and in lead. If the predominant process of meson creation is plural production, then an increase in the average number of mesons produced is to be expected when the hydrogen target is replaced by one of lead. Great technical difficulties attend the carrying out of this experiment.

Rare photographs have been obtained in nuclear emulsions which could be best explained in terms of the collisions of a proton with a hydrogen nucleus in the emulsion, with the consequent production of a shower of mesons. Such photographs indicate that multiple production can occur, but do little to resolve the problem of the nature of the predominant meson production process. It is likely that each approach is partially correct, and that a theory embodying many features of both the multiple and plural production theories may finally be established.

(7) *The production and properties of the neutral meson* $\pi^0$

When photographs of penetrating showers are taken in cloud chambers containing many lead plates it is found that showers of electrons frequently accompany the penetrating particles. An example is shown in figure 8. Fretter has demonstrated in a striking fashion that these electrons are due to $\gamma$-rays[5].

[1] W. Heisenberg, Nature *164*, 55 (1949); Z. Physik. *126*, 569 (1949).

[2] H. W. Lewis, J. R. Oppenheimer, and S. A. Wouthuysen, Phys. Rev. *73*, 127 (1948). - H. W. Lewis, Phys. Rev. *76*, 566 (1949).

[3] W. Heitler and L. Janossy, Proc. Phys. Soc. *62*, 364 (1949); *62*, 669 (1949).

[4] U. Camerini, J. H. Davies, C. Franzinetti, P. H. Fowler, W. O. Lock, H. Muirhead, D. H. Perkins, and G. Yekutieli, Phil. Mag. *42*, in the press (1951).—U. Camerini, C. Franzinetti, W. O. Lock, D. H. Perkins, and G. Yekotieli, Phil. Mag. *42*, in press (1951).

[5] W. B. Fretter, Phys. Rev. *76*, 511 (1949); Echo Lake Conference 1949; Bull. Amer. Phys. Soc. *24*, *f*. 10, 8 (1949).

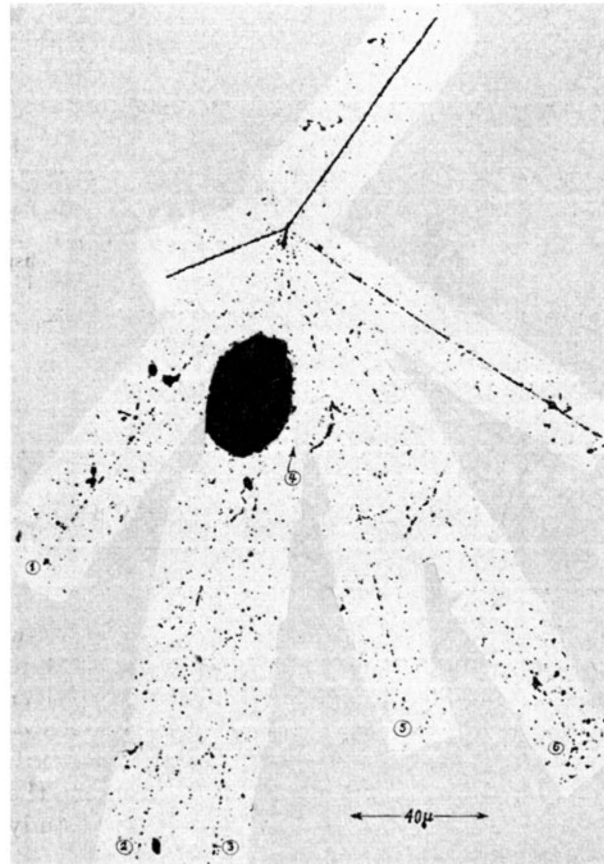


Fig. 7.—A meson shower observed in a nuclear research emulsion exposed at the Jungfraujoch.

Figure 9 shows a penetrating shower produced in a graphite plate of a multi-plate cloud chamber operated at 3,000 m above sea level. The top ten plates were made of graphite whilst the bottom four were of lead. It can be seen that several electron showers are initiated in the lead by an uncharged radiation, which appears to originate from the point of production of the penetrating shower. This uncharged radiation is probably composed of photons, since it appears to behave in accordance with the predictions of the cascade theory for the soft component.

Similar results have been obtained from a study of photographic emulsions exposed at high altitudes. Thus Bradt, Kaplon, and Peters[1] have observed electron-positron pairs materialising in the core of a highly collimated penetrating shower initiated by an $\alpha$-particle. It has also been shown by the Bristol group[2] that high energy electrons are rarely produced directly from the source point of a penetrating shower.

We must now consider the origin of these $\gamma$-rays. Recent work at Bristol[3] has shown that the $\gamma$-rays do

[1] H. L. Bradt, M. F. Kaplon, and B. Peters, Helv. phys. acta *23*, 24 (1950).

[2] U. Camerini, P. H. Fowler, W. O. Lock, and H. Muirhead, Phil. Mag. *41*, 413 (1950).

[3] A. G. Carlson, J. E. Hooper, and D. T. King, Phil. Mag. *41*, 701 (1950).

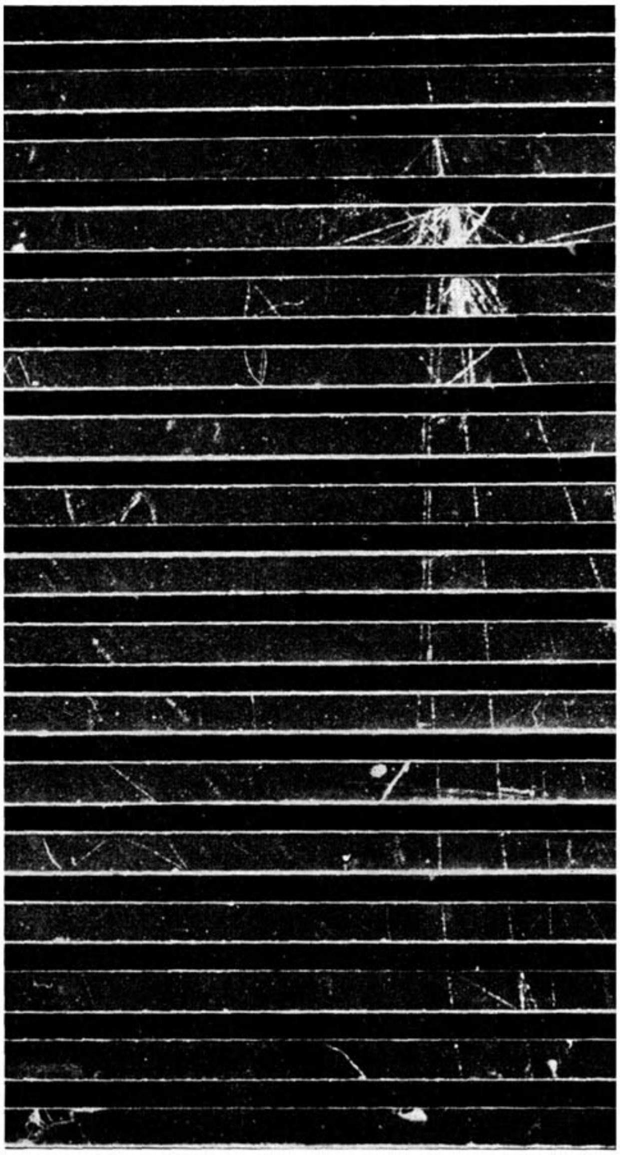

Fig. 8.—A cloud chamber photograph of a penetrating shower in lead. (By courtesy of Prof. W. B. Fretter.)

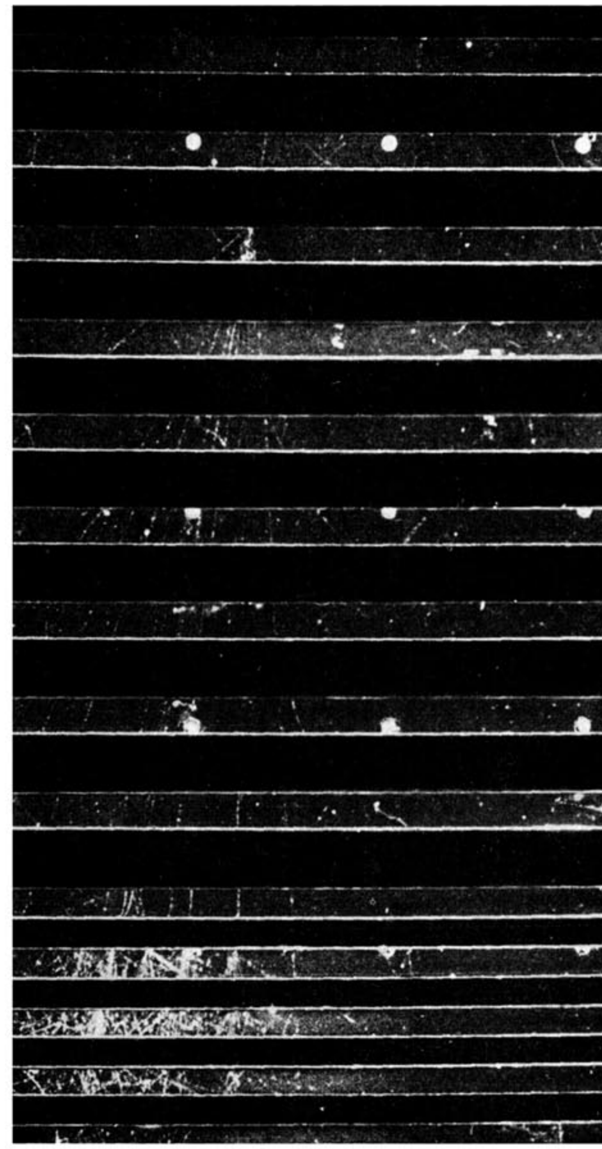

Fig. 9.—A cloud chamber photograph of a penetrating shower commencing in graphite and passing into lead plates. (By courtesy of Prof. W. B. Fretter.)

not arise at the point of the nuclear disintegration. When a high energy $\gamma$-ray materialises into an electron-positron pair the line bisecting the angle between the two particles reproduces the direction of the parent $\gamma$-ray. If this line is traced back, it is found that it normally does not pass directly through the origin of the penetrating shower but a few microns ($10^{-4}$ cm) from it. This result may be explained by assuming the existence of an intermediary neutral particle, which is produced together with the charged $\pi$-particles, and which decays after a very short period of time to give two or more $\gamma$-rays. This is illustrated schematically in figure 10. A statistical examination of the distribution of the projected distances from the point of nuclear disintegration to the line of motion of the $\gamma$-rays has yielded a result which is consistent with the assumption of the radioactive decay of an uncharged particle which has a lifetime less than $5 \times 10^{-14}$ sec. These workers were also able to make a rough estimate of the mass of the particle and obtained a value of $295 \pm 20\ m_e$. The existence of a neutral meson may thus be inferred.

Independent evidence for the existence of such a particle has been obtained at Berkeley[1]. It has been found that when carbon is bombarded with fast protons, the $\gamma$-ray yield increases rapidly in an unexpected fashion as the proton energy is raised above 180 MeV. A detailed examination of the properties of these $\gamma$-rays has revealed that they are produced in pairs, and that their energies and directions of emissions are consistent with the assumption that they are the decay products

[1] R. Bjorklund, W. E. Crandall, B. J. Moyer, and H. F. York, Phys. Rev. 77, 213 (1950).

of a neutral meson which decays in a period of less than $2\times10^{-13}$ sec. Finally, the recent work at Berkeley on the absorption of slow $\pi^-$-mesons by hydrogen[1], which we have considered in an earlier section, has shown that the mass of the neutral meson is $261 \pm 4 m_e$. The value obtained by the Bristol group is in reasonable agreement with this figure.

From a theoretical viewpoint the experimental demonstration of the existence of a neutral meson of short lifetime is very satisfactory. It has been known for some years that the strength of the force acting between a proton and a neutron is about the same as that existing between a proton and a proton, or a neutron and a neutron. Whilst the first case may be accounted for by the exchange of a charged meson, viz.:

$$P \longleftrightarrow N + \pi^+,$$
$$N \longleftrightarrow P + \pi^-,$$

the latter cases can best be explained by the existence of a neutral meson, viz.:

$$P \longleftrightarrow P + \pi^0,$$
$$N \longleftrightarrow N + \pi^0.$$

Thus, as in the case of Yukawa's particle, the existence of a neutral meson was postulated long before it was found in nature. It has not been possible, as yet, to compare the predicted and actual properties of this meson.

### (8) *The existence of other types of mesons*

During the past few years evidence has been obtained for the existence of mesons of mass different to that of the $\pi$-,$\pi$-$^0$ and $\mu$-mesons. Such particles occur infrequently and the evidence for their existence has normally consisted of isolated photographs obtained in cloud chambers or in photographic emulsions. These photographs often appear to represent entirely different types of particle; we shall therefore confine our attention to the reasonably good evidence for the existence of charged mesons of mass about 1,000 $m_e$ and for the existence of neutral mesons with mass greater than 700 $m_e$.

We will first consider the evidence for heavy charged mesons. In 1949 the Bristol group[2] published a photograph, obtained in a photographic emulsion exposed at the Jungfraujoch, which apparently showed a meson decaying at rest, into three charged particles. The photograph is reproduced in figure 11. It was established that the particle $K$ had a mass of the order of 1,000 $m_e$. One of the decay products was apparently a $\pi^-$-meson, since it produced a small nuclear disintegration. In this photograph whilst track a was of sufficient length to permit its identification as either a $\pi$- or $\mu$-meson. An important feature or the event was the observed coplanarity of the supposed decay products of the particle $K$. This strongly suggested that the three charged particles were the sole products of the disintegration; the directions of motion and the momenta of the particles supports this conclusion.

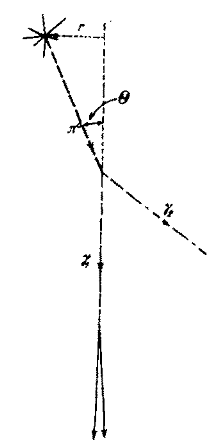


Fig. 10.—A schematic representation of the decay of a neutral meson to two $\gamma$-rays, one of which subsequently produces an electron pair.

Four similar photographs have recently been obtained in photographic plates exposed at the Jungfraujoch[1].

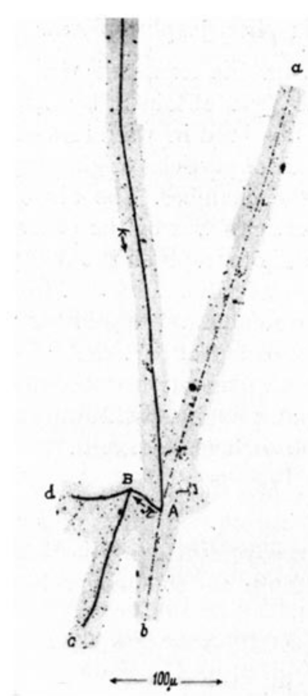


Fig. 11.—A photograph of the $\tau$-meson observed by the Bristol group.

"The evidence is now strong that all three decay particles are $\pi$-mesons. Particles which decay in this

[1] W. K. H. Panofsky, L. Aamodt, and H. F. York, Phys. Rev. *78*, 825 (1950).—W. K. H. Panofsky, L. Aamodt, and J. Hadley, ib. *81*, 565 (1951).

[2] Miss R. H. Brown, U. Camerini, P. H. Fowler, H. Muirhead, C. F. Powell, and D. M. Ritson, Nature *163*, 82 (1949).

[1] J. B. Harding, Phil. Mag. *41*, 405 (1950).—P. E. Hodgson, ib. *42*, in press (1951).—P. H. Fowler, M. G. K. Menon, C. F. Powell, and O. Rochat, ib. *42*, in press (1951).

manner are called $\tau$-mesons, and their mass has been estimated to be $966 \pm 8\, m_e$[1]. Heavy charged mesons which decay to only one charged particle have recently been observed by O'CHALLAIGH[2]."

Because of its low frequency of occurrence, no serious attempt to determine the lifetime of this particle has been made. A lower limit may be set by the time taken by the particle to traverse the emulsion before coming to rest. In this way the Bristol group obtained a value of about $10^{-11}$ sec.

Evidence for the existence of a heavy charged meson behaving somewhat differently to that described above was first put forward by ROCHESTER and BUTLER[3] in 1947. In a cloud chamber photograph, taken at sea level, they observed the track of a penetrating particle which apparently suffered a considerable deflection in the gas of the chamber. They interpreted this as the decay of a heavy meson, with a mass greater than $980\, m_e$, to a lighter meson and some neutral entity. ANDERSON and his collaborators[4], working at mountain altitudes in the United States, have recently observed four similar events, whilst ARMENTEROS *et al.*[5] have operated a large cloud chamber at the top of the Pic-du-Midi in France and have observed seven such events. It has been tentatively proposed by ANDERSON and BLACKETT that these particles should be called $V$-particles, to distinguish them from the heavy mesons observed in photographic plates.

The evidence for the existence of a heavy neutral meson was also first obtained by ROCHESTER and BUTLER[5]. They observed in a sea level cloud chamber photograph, a pair of particles originating from a point in the gas of the chamber. The angle between the tracks of the particles was of the order of 67°. They interpreted this photograph as the decay of a neutral particle to two charged particles, and from momentum considerations were able to put a lower limit of $700\, m_e$ on the mass of the neutral particle. ANDERSON, in the experiment we have mentioned above, has recently observed 30 similar events, while ARMENTEROS *et al.* have obtained 36 such photographs.

"Recent work has shown that these events correspond to the decay of two types of neutral particle. They are collectively termed $V^0$-particles and appear to decay according to the following schemes:

$$V_1^0 \rightarrow \pi^+ + \pi^-$$

and

$$V_2^0 \rightarrow p \ + \pi^-.$$

The mass of the particle in the first decay process has been estimated to be $\sim 1{,}000\, m_e$, and in the second, $\sim 2250\, m_e$.

In 12 of the cases reported by ANDERSON *et al.* the calculated line of motion of the supposed neutral meson, may be produced back very close to the point of origin of a penetrating shower in lead blocks placed above the chamber. The rate of occurence of these neutral particles was estimated to be 3% of that of the charged shower particles. In favourable cases it was found possible to determine the distance travelled by the neutral particle between its points of origin and decay; in this way its mean lifetime was estimated to be $3 \pm 2 \times 10^{-10}$ sec.

Thus it now seems to be well established that heavy mesons, both charged and uncharged, exist in nature, but that they are rare compared with the $\pi$-, $\pi^0$-, and $\mu$-mesons. It will probably be many years before their properties are known in detail, and the role that they play in the nucleus is understood.

### (9) *Meson processes in the cosmic radiation*

Since much of the fundamental work concerning mesons has been performed with those ocurring in the cosmic radiation, it has seemed to us appropriate to include in this review a brief description of the nature of the cosmic radiation, and of the role played in it by the various kinds of meson.

(*a*) *The primary radiation.*—Experiments by HULSIZER and ROSSI[1] and BRADT and PETERS[2], have shown that the primary cosmic radiation consists of protons and the nuclei of heavier atoms. At the top of the atmosphere protons comprise 80% of the number of incident primary particles. The frequency of occurence of a nucleus carrying a charge greater than unity decreases rapidly with increasing nuclear charge. Nuclei heavier than that of iron are rarely observed. The origin of this primary radiation has not yet been established.

(*b*) *The production of mesons in the atmosphere.*—As the primary radiation traverses the atmosphere nuclear collisions are sometimes made and showers of mesons are produced[3]. An example of the production of a shower of $\pi$-mesons by a nucleus of charge $Z = 16 \pm 1$ is shown in figure 12. At the top of the atmosphere there are comparatively few air atoms per unit volume; at lower depths the atmopheric pressure increases and consequently the rate of production of meson showers increases. In these collisions the protons and heavier nuclei are removed from the primary flux which therefore decreases in intensity with increasing atmospheric pressure. Consequently it is found that a maximum exists in the curve of the production of mesons as a

[1] See footnote 1, page 333, right column.

[2] C. O'CEALLAIGH, Phil. Mag. *42*, in press (1951).

[3] G. D. ROCHESTER and C. C. BUTLER, Nature *160*, 885 (1947).

[4] A. J. SERIFF, R. B. LEIGHTON, C. HSIAO, E. W. COWAN, and C. D. ANDERSON, Phys. Rev. *78*, 290 (1950).

[5] R. ARMENTEROS, K. H. BARKER, C. C. BUTLER, A. CACHON, and A. H. CHAPMAN, Nature *167*, 501 (1950).

[1] R. HULSIZER and B. ROSSI, Phys. Rev. *73*, 1402 (1948).

[2] H. L. BRADT and B. PETERS, Phys. Rev. *74*, 1828 (1948); *77*, 54 (1950).

[3] A. D. DAINTON and D. W. KENT, Phil. Mag. *41*, 963 (1950).

function of atmospheric depth. This occurs in the atmospheric layer at roughly 22 km altitude.

(*c*) *The fate of the particles produced in the meson showers.*—The charged $\pi$- and neutral $\pi^0$-mesons produced in the penetrating showers rapidly decay to $\mu$-mesons and photons respectively. Owing to the relativistic contraction of the time scale, many of the $\mu$-mesons traverse most of the atmosphere before decaying to electrons and neutrinos; consequently $\mu$-mesons comprise the major part of the hard component at mountain altitudes and at sea level. As we have described above, these particles have an extremely weak interaction with nuclei and rarely lose energy by nuclear collisions. Fast $\mu$-mesons may therefore penetrate to great depths underground.

Fast neutrons and protons frequently accompany the charged and neutral mesons emitted in penetrating showers. These nucleons seldom pösses enough energy to create another shower, but many of them are sufficiently energetic to cause the disintegration of a nucleus when a collision is made. Such an event is the most common process observed in a nuclear emulsion which has been exposed to the cosmic radiation, and is known as a "star". Fast and slow $\pi$-mesons also cause "stars" but it is not yet known if a $\pi$-meson can create a shower of mesons.

(*d*) *The role of the mesons in the formation of the soft component.*—In the introduction we showed how the cosmic radiation may be described in terms of a hard component and a soft component. The latter consists almost entirely of electrons and photons. For many years its origin has been obscure since electrons from the decay of $\mu$-mesons, and knock-on electrons, could only account for approximately 25% of the total intensity of the soft component throughout the atmosphere[1]. It is now believed that the $\gamma$-rays from the decay of the neutral $\pi^0$-meson provide the source of the remainder of the soft component. A fast photon may be converted to an electron-positron pair if it passes close to the nucleus of an atom, whilst if a fast electron undergoes a deflection in the Coulomb field of a nucleus a photon is produced[2]. Thus the primary photons and electrons, produced in the decay of $\pi^0$- and $\mu$-mesons respectively, rapidly suffer a degradation in energy, and at the same time their number increases rapidly[3]. This process is intensified by nuclei of high atomic number, and is also dependent upon the density of the medium traversed. The effect is beautifully demonstrated in the two photographs reproduced in figures 8 and 9. The multiplication of the electrons and photons is known as the formation of a "cascade shower" or alternatively as a "soft shower". Whilst a cascade shower does not develop so rapidly in air as in heavy elements, large cascade showers are sometimes detected in the cosmic radiation.

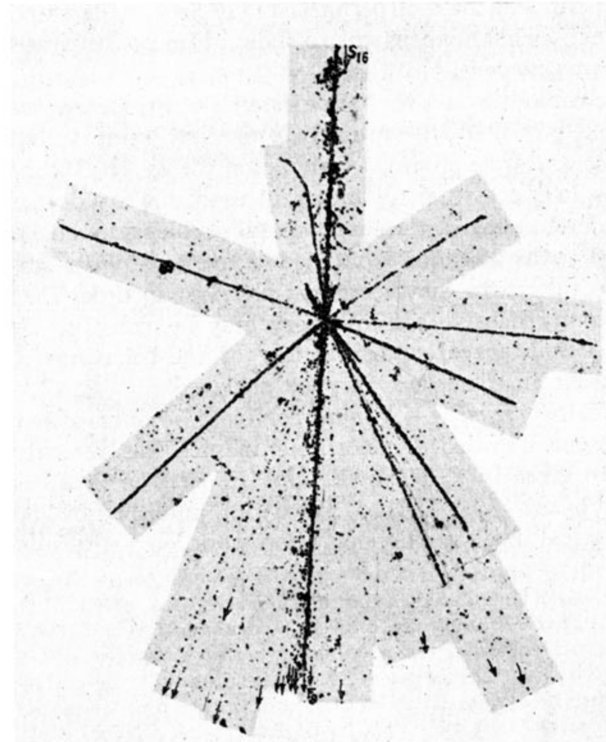


Fig. 12.—A photograph of the production of a penetrating shower by a nucleus of charge $Z = 16 \pm 1$. The incident nucleus was not completely disrupted but emerged with a charge of $Z = 9 \pm 1$.

(10) *Conclusions and outstanding problems*

It is only 15 years since Yukawa postulated the existence of the meson, but in this period a considerable amount of information has been acquired. Instead of the one meson predicted by Yukawa at least seven varieties ($\mu, \pi, \pi^0, \tau, V, V_1^0, V_2^0$) are now known to exist.

Much of the knowledge we have gained, however, concerns the nature of the isolated meson— its mass, lifetime, etc. Very little is known about the behaviour of the meson in nuclear processes— wheie nucleons are involved as well as mesons.

It is in these processes that the meson must studied in order to understand its role in a normal stable nucleus. Probably the most fruitful subjects for study are the interaction of fast and slow mesons with individual nucleons and with nuclei. Despite the wide variations in the energies of the particles found in the cosmic radiation, the intensity of the radiation is relatively weak, and it is in an experiment of this nature that the giant accelerators can make an important contribution through their ability to produce large numbers of mesons. The accelerators will also allow a detailed study to be made of the meson production process in the low energy region, whilst many more cosmic ray

[1] B. Rossi, Rev. Mod. Phys. *20*, 537 (1948).
[2] H. A. Bethe and W. Heitler, Proc. Roy. Soc. A. *146*, 83 (1934).
[3] H. J. Bhabba and W. Heitler, Proc. Roy. Soc. A. *159*, 432 (1937).—J. F. Carlson and J. R. Oppenheimer, Phys. Rev. 51, 220 (1937).

experiments must be performed in order to understand exactly what happens when a shower of mesons emerges from a nucleus.

Despite the fact that the existence of the meson was first predicted theoretically and that some initial successes were obtained with meson theory, the theory has, in effect, stagnated in recent years due to a deeper understanding of the fundamental problems involved. The paths of enquiry outlined above may give important aid to the theoretical physicist in order that a comprehensive meson theory may be constructed, and that a real understanding of the behaviour of mesons in a nucleus may be achieved.

*Further reading.*—A more complete account of our present knowledge concerning mesons has recently been given by C. F. Powell in "Reports on Progress in Physics" Vol. XIII, p. 350 (1950), published by the Physical Society, London. For work on artificially produced mesons reference should be made to the Berkeley report "Review of Work on Artificially Produced Mesons" by H. Bradner. U.C.R.L. 486.

*Zusammenfassung*

Die Übersicht gibt den Stand unserer Kenntnis der verschiedenen Mesonarten bis Ende des Jahres 1950 wieder. Die frühe Geschichte des Mesonproblems ist summarisch zusammengefaßt und die Entdeckung des $\pi$- und $\mu$-Mesons beschrieben worden. Die verschiedenen Methoden der Massenbestimmung dieser Teilchen sind kurz erwähnt, gefolgt von einer Beschreibung ihrer Eigenschaften und unserer gegenwärtigen Kenntnis von den Prozessen, die zur Entstehung der $\pi$-Mesonen führen. Die neueren Beobachtungen, die auf die Existenz von neutralen und schwereren als $\pi$-Mesonen deuten, sind diskutiert. Der Aufsatz schließt mit einem allgemeinen Überblick über die Mesonenerzeugungsprozesse in der Höhenstrahlung und über Probleme, deren Lösung noch aussteht.

# Brèves communications - Kurze Mitteilungen
# Brevi comunicazioni - Brief Reports



## Degradazione microbica della digitonina

Nel quadro degli studi che si stanno svolgendo nel nostro Istituto sull'attacco microbico degli steroli in genere[1], è parso interessante indagare il comportamento dei microrganismi nei riguardi delle saponine ed, in particolare, di quelle aventi nella molecola una genina a carattere sterolico.

Nel corso di queste ricerche è stata usata digitonina prodotta dalla casa Roche (P.F. 235°C, titolo emolitico 1:100.000 rispetto ai globuli rossi di montone al 5%).

Onde isolare i microrganismi capaci di attaccare questa sostanza ed avviare lo studio del meccanismo di tale attacco, si allestì una serie di culture di arricchimento, partendo da foglie in decomposizione di *Digitalis purpurea*. Queste vennero poste in un mezzo nutritivo costituito da una soluzione salina[2] con aggiunta, come unica fonte di C, di digitonina all'uno per mille e messe ad incubare a varie temperature (30°, 37°, 40°C). Già dopo 5 giorni dalla semina si poteva notare, soprattutto nelle culture a 37° e 40° e più tardi anche in quelle a 30°, la scomparsa della caratteristica schiuma del mezzo nutritivo e la formazione di un precipitato fioccoso di natura non microbica. Questi fenomeni non si osservarono mai in provette di controllo tenute alle stesse temperature. In questa nota preliminare sono raccolti i dati delle esperienze eseguite sulle culture tenute a 40°.

Allo scopo di selezionare la abbondante flora microbica presente nelle prime culture, vennero eseguiti 20 passaggi successivi, sempre nello stesso terreno nutritivo, a pochi giorni di distanza l'uno dall'altro. Dal ventesimo passaggio si isolarono i microrganismi ancora presenti in piastre di agar sali digitonina e agar brodo con aggiunta di digitonina. In tal modo vennero isolate 3 forme microbiche:

*Ceppo 1*, bastoncino sporigeno che, per le sue caratteristiche morfologiche e fisiologiche è probabilmente identificabile col *Bacillus macerans* Schardinger.

*Ceppo 2*, bastoncino non sporigeno in corso di identificazione.

*Ceppo 3*, cocco.

Dei tre ceppi isolati, messi a sviluppare nella solita soluzione salina con aggiunta di digitonina, solo il ceppo 1 cresce dando luogo alla formazione del solito precipitato fioccoso, ad un innalzamento della tensione superficiale ed ad un abbassamento del titolo emolitico del liquido culturale. Gli altri due ceppi non crescono che scarsamente e la digitonina, in loro presenza, non subisce alcuna trasformazione.

Onde stabilire se queste due ultime forme microbiche sopravvissute nelle culture di arricchimento anche dopo 20 passaggi successivi non esercitano alcuna influenza sull'attacco della sostanza esperimentata, vennero eseguite e confrontate culture con miscele dei 3 microbi e cioè: culture del solo ceppo 1, culture con il ceppo 1 e 2 ed altre con il ceppo 1 e 3. Confrontando i dati del potere emolitico dei 3 liquidi culturali, dopo 10, 30 e 60 giorni di incubazione, si è constatato che solo la miscela dei ceppi 1 e 2 già dopo 30 giorni dà una quasi totale scomparsa di emolisi nel liquido culturale, mentre, sia con il ceppo 1 che con la miscela 1 e 3, il valore emolitico determinato

[1] C. Arnaudi, Exper. *7*, 81 (1951).

[2] $KH_2PO_4$: 1 g; $NH_4NO_3$: 1 g; $MgSO_4 \cdot 7H_2O$: 1 g; $H_2O$ dist.: 1000 cm$^3$; pH 6,8–6,9.