MESONS

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§ 1. INTRODUCTION

The previous Reports in this series which bear on the subject of mesons were written by Heitler (1939) and Peierls (1940), and contained an account of the main features of our knowledge of these particles up to the end of 1939. Since that date, and especially in the past four years, there has been a rapid development of the subject; and to-day, although many points of detail remain to be elucidated, it seems reasonable to suppose that the most important facts—at least about the most common of the different types of mesons—have been established, and that the relationship of the particles to the cosmic radiation is well understood.

In giving an account of the discoveries of the last ten years I propose to begin with a brief historical survey of the main line of development, then to discuss in more detail the properties of the \( \pi \)- and \( \mu \)-mesons, together with the evidence for the existence of other types, and finally, to give an account of our present picture of the principal processes associated with the creation of mesons which take place as a result of the passage of cosmic radiation through the atmosphere.

A part of decisive importance in the extension of our knowledge of mesons has been played by the development of new technical resources: the method of recording the tracks of charged particles as a result of their passage through photographic emulsions. Apart from the well-known features of the method—its simplicity and flexibility, the 'integrating' property of the emulsion due to its continuous sensitivity, and the direct and detailed insight into nuclear processes which it allows—it has the advantage of providing a remarkably extended time-scale for the study of certain types of transient phenomena. In particular, particles of very short life-time, such as the \( \pi \)-mesons, which commonly decay 'in flight' when moving in the atmosphere, are arrested in a solid material in a time interval more than a thousand times shorter than when moving in a gas. It is thus possible to study the spontaneous decay of the particles when stopped in an emulsion, or their interaction with nuclei, and thus to observe phenomena which it has proved very difficult, or impossible, to record by other methods.

Because of the important rôle which it has played, an account of the results obtained with the new method necessarily forms an important part of the present report. It is an interesting feature of the historical development of the subject that the \( \pi \)-mesons were discovered very shortly after the development of those technical resources necessary for their observation.
§ 2. HISTORICAL SURVEY

2 (i). The 'Heavy Quanta' of Yukawa

The idea that there should exist in nature particles with a mass intermediate between that of the proton and that of the electron first appeared, in 1935, as a result of theoretical speculations by Yukawa (1935). It had been known for some years that the forces between the nucleons of a nucleus—the protons and the neutrons of which it is composed—cannot be electromagnetic in origin. The observed degree of stability of the nuclei can only be accounted for if it is assumed that special forces of a new type—the nuclear forces—come into play between the nucleons, forces which we do not meet in other fields.

Further, it had been shown, as a result of accurate determinations of the masses of the nuclei, that the energy which has to be supplied in order to remove a nucleon from a nucleus—the 'binding-energy' per nucleon—does not change widely in passing from the light to the heavy elements of the Periodic Table. It follows that the nuclear forces are of 'short range', that they vary with the distance between two nucleons more rapidly than in the case of forces governed by an inverse-square law.

Proceeding from these facts, and on the basis of a formal analogy described in detail in the previous Reports, Yukawa concluded that free 'quanta' should exist corresponding to the nuclear field analogous to the photons of the electromagnetic field, that they should have a finite rest-mass of about $150 \times m_e$, where $m_e$ is the mass of the electron, and that they should be unstable and decay with the emission of an electron, the life-time of the particles being about $10^{-7}$ sec. Just as the electromagnetic field of an electron can be regarded, in the quantum theory of radiation (see Flint 1939), as equivalent to the emission of photons, and the force between two electrons as due to a mutual emission and absorption of photons, so the forces of nuclear cohesion between nucleons was attributed by Yukawa to the 'virtual' exchange of charged quanta between the neutrons and protons in a nucleus.

The hypothetical 'heavy quanta' of the nuclear field were thus visualized as differing in important respects from photons. In the first place, the finite rest-mass of the particles was a necessary consequence of the short-range character of the nuclear forces. Secondly, since the continuous exchange of 'quanta' between the neutrons and protons in a nucleus was assumed to be accompanied by an exchange of charge, the neutrons becoming protons and vice versa, it was assumed that, at least in some cases, the 'quanta' carry a positive or negative electric charge. And thirdly, the assumption of the instability of the particles was introduced in order to account for the $\beta$-activity of radioactive substances, the process of nuclear decay being attributed to the spontaneous disintegration of the charged 'quanta' into electrons and neutrinos.

In addition to the charged quanta, it appeared necessary to postulate the existence of neutral particles of a similar type in order to account for the forces between like nucleons: between neutrons and neutrons, protons and protons (Fröhlich et al. 1938). These forces are known to be of the same order of magnitude as those between protons and neutrons; and, if they have a similar origin, the particles involved in the exchange must be electrically neutral. In what follows it will be convenient to refer to these hypothetical 'quanta', both charged and neutral, as Yukawa particles.
The actual emission of the particles from stable nuclei was not to be expected because such processes are energetically impossible, but in the nuclear collisions involving particles of great energy which occur in the cosmic radiation it was anticipated that such a limitation would not be present.

2 (ii). Discovery of the $\mu$-Mesons

What appeared to be a remarkable verification of the correctness of Yukawa's speculations was provided by observations of Anderson and Neddermeyer and of other workers, including Street and Stevenson, in experiments on the nature of particles in the cosmic radiation in the years 1936–8. This radiation can be divided, phenomenologically, into two components with different absorption coefficients in matter. The ‘soft’ component, which is rapidly absorbed in lead, is responsible for the well-known phenomena of the ‘cascade showers’ commonly studied with Wilson expansion-chambers and counters (Blackett and Occhialini 1933), and was known to be due to photons and electrons. Anderson (1937, 38) showed that among the particles of the ‘hard’ or penetrating component there were present particles of mass about 200 $m_e$, which were able, unlike the electrons, to penetrate many centimetres of lead without losing a large fraction of their energy by the well-known process of ‘bremsstrahlung’. These particular particles are now commonly referred to as $\mu$-mesons (Lattes et al. 1947b), and the latest measurements of their mass give the value of $(215 \pm 5)m_e$.

The view that the $\mu$-mesons were to be identified with the particles of Yukawa was strengthened by observations which suggested that they are unstable and that they decay with a life-time of about $1.5 \times 10^{-6}$ sec., a value only about ten times greater than that anticipated by Yukawa. Further, it was found possible to modify some of the original features of the theory, and thus to account for the magnetic moments of the proton and the neutron and for certain features of the states of energy of the light nuclei, notably the ground and first excited states of the deuteron.

These remarkable successes encouraged the hope that the fundamental features of Yukawa's views were substantially correct, that the $\mu$-mesons were to be identified with the Yukawa particles, and that it would be possible to elaborate the theory to provide a firm basis for the description of the main features of the atomic nuclei and of nuclear collision processes. These hopes were reflected in the previous Reports, but already certain serious theoretical difficulties were beginning to emerge.

2 (iii). The Fate of the $\mu$-Mesons

The original estimates of the life-time of the $\mu$-mesons were based on the observation that the reduction in the intensity of a stream of these particles in the atmosphere depends not only on the mass (gm/cm$^2$) of material traversed, but on the length of the path in which the matter is distributed. The penetration of a given mass of air produces a greater diminution of intensity the lower the density. This effect could only be interpreted by assuming that the removal of mesons by interaction with atoms is accompanied by a spontaneous decay of the particles, the latter process becoming increasingly probable the greater the time of flight (see Follett et al. 1936, Auger et al. 1937).

Decisive support for the view that the $\mu$-mesons do indeed suffer spontaneous decay with the emission of a charged particle of small rest-mass, tentatively
assumed to be an electron, was provided by experiments of Williams and Roberts (1940). These workers obtained two photographs, by means of a Wilson chamber operated in a magnetic field, of penetrating particles which, after passing through a lead plate, reached the end of their range in the gas of the chamber. From the end of the resultant track a fast particle originated which had a specific ionization near the minimum value for a particle with the elementary electronic charge, and of which the momentum, as determined by the observed curvature of the trajectory in the magnetic field, was equal to \( 70 \pm 35 \text{ MeV/c} \).

The observed specific ionization of the decay particle showed that it was ejected with a velocity closely approaching that of light, \( c \). It therefore followed that its kinetic energy \( E \) was approximately equal to \( pc \), where \( p \) is the momentum of the particle, and that the energy of the particle was of the order of 50 MeV. This result suggested that in the spontaneous decay of the \( \mu \)-meson the momentum of the emitted charged particle is balanced by that of a single neutral particle of small rest-mass, a neutrino; for in such a case the total energy corresponding to the disappearance of the rest-mass of the parent meson, \( \sim 100 \text{ MeV} \), will be shared equally between the two products into which it decays, and the energy of emission of the electron will be unique and equal to approximately 50 MeV. We shall see in a later paragraph that this conclusion was incorrect.

A more direct and precise determination of the life-time of the \( \mu \)-mesons was carried out by Rasetti (1941), and later, with greater accuracy, by Rossi and Nereson (1942) and Chaminade et al. (1944), by the method of 'delayed coincidences'. In principle, the method consisted in detecting, by suitable arrays of counters, the instants of arrival of \( \mu \)-mesons of the cosmic radiation (Figure 1). The apparatus selects those particles which, having penetrated a thick layer of lead, are brought to rest in a second block of material; and the time interval is measured between the instant of arrest of a \( \mu \)-meson and the subsequent discharge of another set of counters by the action of the charged particle which is emitted in the process of decay. The distribution in the observed values of the time delay was found to be similar to that expected from the exponential law of decay characteristic of radioactive substances. The mean life-time of the particles, according to the latest determinations by this method, is \( 2.15 \times 10^{-6} \text{ sec} \).

Hitherto, the results of most of the new experiments had given support for Yukawa's speculations. It was, however, difficult to understand why experiments with Wilson chambers indicated that \( \mu \)-mesons interact very rarely with nuclei in passing through matter. Further difficulties began to appear when observations to distinguish the properties of positive and negative \( \mu \)-mesons were undertaken.

It had been suggested by Tomonaga and Araki (1940) that when a positive \( \mu \)-meson is brought to rest in a material we must assume that it will be prevented from approaching a nucleus as a result of the Coulomb repulsion between like charges, and will remain free until the instant of its decay. On the other hand, the electrostatic forces will tend to make the negative particles approach nuclei. It was anticipated that if the spin of the particles is equal to that of an electron, they will fall to states of lower energy round the nucleus, the transitions being accompanied by the emission of radiation or of Auger electrons. As a result of the much greater mass of the particles as compared with that of the electron, they will, in their state of lowest energy, be two hundred times nearer to the nucleus than an electron in its ‘k-orbit’; and when in this
state they will spend an appreciable fraction of their time in the nucleus itself. In accordance with these anticipations, both Rasetti and Rossi found that only about half the mesons arrested in their apparatus gave evidence of decay.

In order to confirm the view that the $\mu^-$-particles do indeed interact with nuclei when arrested in solid substances before they have had time to decay, experiments were therefore undertaken by Conversi, Pancini and Piccioni (1947). Delayed coincidence experiments were made with positive and negative $\mu$-particles, the two types being separated from one another by magnetic deflection before being allowed to enter the recording apparatus. When the particles were brought to rest in iron, it was found, in accordance with anticipation, that the positive mesons decayed with a life-time equal to that found for the undifferentiated particles, whilst the negative particles disappeared without giving rise to a decay electron.

The above result was at variance with observations by Auger, Maze and Chaminade (1941) which indicated that nearly all the negative mesons arrested in aluminium suffer decay. Although this result was subsequently found to be incorrect (Rossi and Nereson 1942), the experiments described above were extended to the case in which the $\mu$-particles were arrested in a block of material of low atomic number, and for this purpose graphite was chosen. The remarkable result was obtained that in carbon at least a large proportion of the $\mu^-$-particles decay with the emission of an electron.

The time occupied by a meson after being reduced to a velocity in the 'thermal' region in falling to the state of lowest energy round a nucleus has been subject

![Figure 1. A characteristic modern design of apparatus for the determination of the life-time of $+ve$ or $-ve$ $\mu$-mesons. The two halves of the block of iron are magnetized so that in each case the magnetic intensity is normal to the plane of the paper; but in one half the intensity is directed outwards from the paper, and in the other half into it. This arrangement serves to concentrate particles of one sign. Those particles are selected which discharge a counter in $C_A$, $C_B$ and $C_C$, and which do not discharge counters $A$. Such particles have been arrested in the absorber and the time interval is measured between their instant of arrival and the subsequent discharge of a counter of the set $D$. The distribution in the values of this time interval gives a measure of the half-value period of the particles—see, for example, Figures 17 and 20. By reversing the magnetic fields, particles of opposite sign can be collected. (After Rossi.)
to some discussion and will, it appears, depend on the nature of the material in which it is moving; but it was generally considered to be less than about $10^{-12}$ sec. (Fermi et al. 1947). It was therefore anticipated that such a particle, when brought to rest in solid materials, would approach a nucleus in a time short compared with its life-time. If, further, the $\mu$-mesons are to be identified as the 'heavy quanta' of the nuclear field, such a particle should interact with the nucleus, and the probability of its suffering spontaneous decay should be very small. There was no firm basis for estimating the consequences of this nuclear interaction; whether the disappearance of the particle and the resultant liberation of the energy corresponding to its rest-mass would lead to the emission of $\gamma$-radiation, to the disintegration of the nucleus, or to other processes, remained uncertain.

In view of these considerations, the experiments of Conversi et al. were of decisive importance, for they appeared irreconcilable with the view that the $\mu$-mesons are to be identified with the Yukawa particles. They indicated that in the process of interaction with carbon, a $\mu^-$-particle can reside in its $k$-orbit for a period of the order of $2 \times 10^{-6}$ sec. without interacting with the nucleus. The conclusion was drawn that the strength of the interaction between $\mu$-particles and nucleons is less, by many orders of magnitude, than that to be expected if the $\mu$-mesons are identified with the heavy quanta of the nuclear field. Some attempts (Fröhlich 1947) were made to explain the difficulty by assuming that the time occupied by the particle in being brought to rest, and in falling to its state of lowest energy, is much greater than the first estimates had suggested; but whilst some doubt was thrown upon the precise values of this interval, it was made clear that it must be shorter, by some order of magnitude, than the life-times of the particles. A fundamental difficulty therefore remained to be resolved.

Even before the very serious nature of these difficulties had been widely understood, Sakata and Inoue (1946) had suggested that the cosmic-ray evidence appeared to indicate the existence of mesons of two types; and Möller (1941, 1946), on the basis of very general theoretical considerations, had been led to postulate, tentatively, the existence of several kinds of particles of intermediate mass with genetical relationships between them. A little later, Marshak and Bethe (1947), as a result of the contradiction between the large cross-section for the creation of mesons in nucleon-nucleon collisions, and the subsequent very weak interaction of the penetrating particles with nuclei, suggested that the primary products of the nuclear interactions taking place in the atmosphere are heavy mesons, and that these particles decay spontaneously, with a life-time of the order of $10^{-8}$ sec., to form the mesons commonly observed among the particles of the penetrating component.

2 (iv). Discovery of the $\pi$-Mesons

It was at this stage in the development of the subject that results were obtained in investigations of the cosmic radiation by means of the more sensitive photographic plates—the 'Nuclear Research' emulsions produced by Ilford Ltd. It was shown by Perkins (1947) and by Occhialini and Powell (1947) that if such plates are exposed at mountain altitudes, the tracks of charged mesons brought to rest in the emulsion can be detected. The masses of the particles were estimated by 'grain-counts' and by studying the deviations in the trajectories
Mesons

due to multiple Coulomb scattering, and were shown to be of the order of 200–300 \( m_e \). It therefore appeared to be certain that some at least of these particles were identical with the \( \mu \)-mesons of the penetrating component of the cosmic radiation.

The new plates, whilst greatly superior to the 'half-tone' emulsions which they displaced, were not sufficiently sensitive to record the tracks of electrons moving at relativistic velocities, and it was therefore impossible to observe any fast decay particles emitted by the mesons at the end of their range. On the other hand, it was found that about 10% of the mesons, when stopped in the emulsion, led to a nuclear disintegration with the emission of slow protons, \( \alpha \)-particles etc. (see Plates II and III). At the time that this observation was made, it was assumed that this process corresponded to the capture of a \( \mu^- \)-particle by a silver or bromine nucleus in the emulsion: that it was of the same type as that which, in heavier elements, leads to the disappearance of negative \( \mu \)-mesons before they have had time to decay with the emission of an electron. It was shown later, however, that the mesons which produce nuclear disintegrations are not \( \mu \)-particles.

Shortly after the observation of the nuclear disintegrations produced by charged mesons, it was discovered in Bristol (Lattes \textit{et al.} 1947a) that about 10% of the mesons, when brought to rest, lead to the emission of a second meson. Further, it was established that the range of the secondary particle is always constant within narrow limits. It was therefore reasonable to assume that it is always ejected with constant velocity, the departures of the individual values of the range from the mean being due to 'straggling'. This strongly suggested that the process corresponds to the spontaneous decay of the parent particle: that two types of mesons exist of different mass, the kinetic energy of the secondary mesons being provided by the disappearance of part of the rest-mass of the heavier, primary mesons. This was subsequently shown to be the case, and it was proved that the secondary mesons are identical with the \( \mu \)-mesons of the penetrating component of the cosmic radiation. The heavier primary particles were therefore referred to as \( \pi \)-mesons, and their spontaneous transformation, by analogy with the \( \beta \)-decay, was named the \( \mu \)-decay.

In addition to the isolated tracks of mesons, plates exposed to cosmic radiation were also found to record nuclear disintegrations from which mesons of low kinetic energy were emitted. A large proportion of these 'ejected' mesons, at the end of their range, produce nuclear disintegrations. It was therefore suggested that they are the negative counterparts of the \( \pi \)-mesons, the latter being positively charged and thus unable to interact with nuclei when reduced to low velocities. It was suggested further that the positive and negative \( \pi \)-particles are the primary products of nuclear interactions of great energy occurring in the atmosphere; that being short-lived, however, they decay 'in flight' and thus produce the positive and negative \( \mu \)-mesons of the penetrating component of the cosmic radiation (Lattes \textit{et al.} 1947b). Further experiments have shown that this view of the origin of the particles, and of their relationship to the cosmic radiation—closely similar to that put forward at the same time by Marshak and Bethe on the basis of other evidence—is substantially correct.

In the three years which have followed the discovery of the \( \mu \)-meson, great progress has been made in the detailed study of the properties of the particles:
this development forms the subject of the second section of the report. The observations have been facilitated by the discovery, in Berkeley (Gardner and Lattes 1948), of the artificial generation of the $\pi$-particles in the bombardment of matter by fast $\alpha$-particles and protons, and the possibility of making experiments in controlled conditions in the laboratory.

Recent evidence appears to confirm earlier reports from a number of laboratories of the existence of particles of mass about 1,000 $m$, which it is convenient to refer to as $\pi$-mesons. The question of the existence of these particles may be of decisive importance for the development of a satisfactory theory of the mesons and of the nuclear forces, and today the elucidation of their nature and properties is one of the central problems of nuclear physics.

2 (v). Nomenclature

Following the first observations of the tracks of mesons in photographic emulsions, and because of the difficulty of determining the mass and the sign of the charge of the particles, they were classified, phenomenologically, according to the secondary processes observed at the end of their range in the emulsion. A $\pi$-meson was defined as one which, when at rest, emits a second meson, $\mu$, with a range of about 600 microns. Later experiments have now confirmed the original view (Lattes et al. 1947 b) that these particles are positively charged, and they will be referred to as $\pi^+$ and $\mu^+$-particles, respectively.

Secondly, those mesons which produced an observable nuclear disintegration when stopped in the emulsion were referred to as $\sigma$-mesons. It is now known that they are exclusively, or almost exclusively, $\pi^-$-particles which are captured by nuclei. The resulting nuclear disintegrations which produce tracks of charged particles radiating from a centre are commonly referred to as 'stars'. The individual tracks making up a 'star' are sometimes called the 'prongs'.

Most of the mesons produced no secondary particles which could be observed in the most sensitive emulsions available in the early experiments, and were classed as $\rho$-mesons. It is now known that in 'electron-sensitive' emulsions (Berriman 1948)—which record the tracks of particles with the elementary electronic charge even when they are moving at relativistic velocities—about 65% of the $\rho$-mesons give evidence of decay with the emission of a fast electron. This fraction of the $\rho$-mesons is due mainly to $\mu^-$-particles formed by the decay of $\pi^-$-particles outside the emulsion, and to $\mu^+$-particles—formed by the decay in flight of $\pi^-$-particles—which have been captured by the light elements in the gelatine of the emulsion, carbon, oxygen and nitrogen. In addition, however, a small proportion of these $\rho$-mesons may be due to $\pi^+$-particles which have undergone direct $\beta$-decay.

Of the 35% of the $\rho$-mesons without associated electron tracks, the majority are due to $\mu^-$-particles which have been captured by the silver and bromine atoms of the emulsion. The particles interact with these nuclei before they have had time to decay, but no charged particles giving visible tracks are produced in the resulting transmutations. In addition, a small fraction of the $\rho$-mesons is due to $\pi^-$-particles which have been captured by nuclei without leading to the production of a recognizable disintegration. Such events will occur if neutral particles alone are emitted in the nuclear transmutation resulting from the capture of the meson, as is the case, for example, when the $\pi^-$-particle interacts with hydrogen.
In describing the properties of the different types of particles, the terms \( \pi^+ \) and \( \pi^- \) particles or mesons, \( \mu^+ \) and \( \mu^- \) -particles or mesons will be employed whenever possible, \( \rho \) -mesons or \( \sigma \) -mesons being referred to only when the precise nature of the particles under discussion is ambiguous.

Reference has already been made to the distinction between the 'hard' and 'soft' components of the cosmic radiation, and to the fact that the experiments of Blackett and Occhialini with the counter-controlled Wilson chamber showed that many particles of the 'soft' component often arrive together in the form of the well-known 'cascade showers', which are produced by the multiplication of an original energetic electron or \( \gamma \)-ray. On the other hand, the experiments of Wataghin, Jánossy and others have shown that the penetrating particles of the 'hard' component, most of which we now know to be \( \mu \) -mesons, can be produced in groups—the so-called 'penetrating showers'. It will be important, in certain sections of this report, to remember the distinction between the 'showers' of the two types.

§ 3. MASS AND MODE OF DECAY OF THE \( \pi \) -MESONS

3 (i). The Decay of \( \pi^+ \) -Particles

When a positive \( \pi \) -meson is arrested in a solid material it decays spontaneously with the emission of a meson of smaller mass, a \( \mu^+ \) -particle, see Plate I. The distribution in range of 90 \( \mu^- \) -particles formed by the decay of \( \pi^+ \) -particles stopped in Ilford C2 photographic emulsions is shown in Figure 2, the mean value being 612 microns. As mentioned above, the observed distribution is consistent with the assumption that the velocity of ejection of the \( \mu \) -meson is constant within narrow limits. It follows that during the emission of the \( \mu \) -meson the momentum balance is provided by the ejection of a single neutral particle. The question of the nature of this particle immediately arises: whether it is a photon, a neutrino, or a neutral particle of considerable rest-mass, i.e. a 'neutretto'.

The observed value of the mean range of the \( \mu \) -mesons in the emulsion allows the momentum and energy of the particle to be determined if its mass is known. When a charged particle passes through matter, it loses energy as a result of interactions of various types with atoms lying near its line of motion: (a) by bremsstrahlung, the creation of photons in inelastic collisions with electrons;
(b) by inelastic collisions with nuclei in which the latter are excited or disintegrated; (c) by ionization loss, due to elastic collisions with electrons; and (d) by the production of pairs of electrons in the field of nuclei. With particles of relatively low velocity, the loss of energy by ionization is the dominant process and the others may be neglected.

The rate of loss of energy by ionization per unit length of the trajectory depends on the charge of the particle, $Ze$, and its velocity, $v$, but is independent of the mass. For particles with the elementary electronic charge we can therefore write

$$\frac{dE}{dR} = f(v). \quad \ldots \ldots (1)$$

It follows that the ranges $R_{M,v}$ and $R_{m,v}$ of two particles, each of velocity $v$, but of masses $M$ and $m$ respectively, are proportional to their masses, viz.

$$\frac{R_{M,v}}{R_{m,v}} = \frac{M}{m}. \quad \ldots \ldots (2)$$

Suppose that the relation between the mean range of protons for different values of the initial energy has been determined. As is made manifest by the well-known Bragg curve for $\alpha$-particles, the specific ionization of a particle increases rapidly as its velocity decreases, and the relation between the range and energy is therefore not linear.

It has been found that for protons, the relationship can be expressed with a high degree of accuracy by the equation

$$E = kR^n, \quad \ldots \ldots (3)$$
\( k \) and \( n \) being constants which must be determined for the particular type of emulsion employed (see Figure 3). From equation (2) it follows that for a particle with a mass \( M \) times that of the proton the relation between range and energy can be written

\[
E = kM^{1-n} R^n.
\]  

The range-energy relation for particles of any assumed mass can therefore be derived from the corresponding curve for protons, and the energy and momentum of the \( \mu \)-meson can be determined for any assumed value of its mass, \( m_\mu \).

Taking \( m_\pi \) as \( 215m_e \), where \( m_e \) is the mass of the electron, it is found that the energy of ejection of the \( \mu \)-meson is 4.2 MeV.

Let \( m_\pi \), be the mass of a \( \pi \)-particle, \( E_\pi \), \( p_\pi \), the kinetic energy and momentum of the \( \mu \)-meson formed by its decay, and \( E_\nu \), \( p_\nu \), \( m_\nu \) the corresponding quantities for the neutral particle providing the momentum balance. It then follows from the principles of the conservation of mass-energy and momentum that

\[
m_\pi c^2 = m_\mu c^2 + m_\nu c^2 + E_\pi + E_\nu,
\]

\[
p_\mu = p_\nu.
\]

For any assumed value of \( m_\pi \), \( p_\pi \) and hence \( E_\pi \) can be determined; and thence, from equation (5), \( m_\pi \). In this way it can be shown that if \( m_\pi = 0 \), \( m_\mu \), \( m_\nu = 1.32 \). The ratio of the masses of the two types of mesons would be equal to this value if the neutral particles were photons or neutrinos. On the other hand, if the mass of the neutral particle were equal to 200 \( m_e \), the value of \( m_\pi / m_\mu \) would be 2.1. Valuable information about the neutral particle can thus be obtained from accurate determinations of the masses of the \( \pi \)- and \( \mu \)-mesons.

3 (ii). Mass of the \( \pi \)-Particles

In approaching the problem of determining the mass of the \( \pi \)- and \( \mu \)-particles, the difficulty is met that a single observed quantity, such as the curvature of the trajectory of a particle in a magnetic field of known intensity, depends upon both \( E/M \), the ratio of the charge to the mass, and the velocity of the particle, \( v \). As in the classical experiments on the electron, it is therefore necessary to make two observations which allow \( E/M \) and \( v \) to be determined separately. The value of \( E/M \) defines the mass \( M \) if the charge on the particle is assumed to be equal to that of the electron—an assumption which appears to be almost certainly correct, and for which the evidence is summarized in § 4 (i). For the determination of \( E/M \) and \( v \), a variety of methods have been employed, the most important of which may be divided into five classes.

Method (A). Residual Range and Grain-Density

The first method employed in the determination of the mass of the \( \pi \)-meson (Lattes et al. 1948) was based on the observation of (a) the grain-density in the tracks of individual particles in a photographic emulsion, and (b) the residual range of the same particles. The grain-density in a track, the number of developed grains per unit length, is proportional to the rate of loss of energy of the particle producing it. This quantity, in turn, depends only on the velocity and charge of the particle. For particles with the electronic charge the observed grain-density therefore gives a measure of the velocity in a certain range of values.

The simplest mode of application of the method is to observe the grain-density in a restricted region of the track, and thus to measure the average velocity in this
part of the trajectory, and to combine this result with the residual range. Thus equation (4) can be rewritten, for particles moving with non-relativistic velocities,

\[ E = \kappa M^{1-n} R^b = C M v^2, \quad \ldots \ldots (7) \]

from which it follows that

\[ M = k_i R v^{-2.6}, \quad \ldots \ldots (8) \]

The determination of the required relation between the velocity and the grain-density can be made by measurements on the tracks of long-range protons. The velocity of such a particle, for any given value of the residual range, is known from the range–energy equation—see equation (3). The grain-density in a restricted region of the trajectory can therefore be determined, together with the corresponding value of the velocity. Although measurements by this method have recently been made, its application was prevented, in the early experiments, by the limited ranges of the particles available for measurement. Any determination of the grain-density made by observations on a length of a track sufficiently restricted to ensure that the velocity was approximately constant was subject to large statistical errors as a result of the relatively small number of grains counted. To avoid these errors it was necessary to count the total number of grains in the complete track, and to modify the analysis to take account of the changing velocity of the particle along the trajectory.

We have seen that the loss of energy per unit length of path depends only on the velocity of a particle with the electronic charge:

\[ \frac{dE}{dR} = f(v). \]

Further, the number of grains per unit length, \( dN/dR \), depends only on the rate of loss of energy, and we can therefore write \( dN/dR = \phi(v) \). Consider two particles of mass \( M, m \), and charge \( e \), moving in an emulsion with velocity \( v \). The grain-density in the two tracks will then be equal. For a given change in velocity, however, the heavier particles traverse a distance \( M/m \) times that of the lighter particles, and this result is independent of the particular values of the velocity. It follows that the total numbers of grains in the tracks of the two particles, \( N, n \), respectively, are in the ratio of their masses:

\[ N/n = M/m. \]

Since, however, the initial velocities of the two particles were the same, \( R/R' = M/m \), and we can write:

\[ N/n = M/m = R/R' = \mathcal{M}. \]

Suppose for particles of known mass \( m \), the relation between \( n \) and \( r \) has been determined:

\[ n = f(r). \]

It follows that, for particles of mass \( M, N = \mathcal{M} F(R, R') \), i.e. the relation between the total number of grains in the track of a particle of any mass and the range can be computed. Alternatively, the observed relation between \( N \) and \( R \) defines the mass of the particle.

In applying this method, it is usual to plot \( \log N \) against \( \log R \) for the two types of particles of which the masses are to be compared. In such a diagram, points on a line inclined at 45° to either axis correspond to particles of constant velocity. Thus the range \( r \) of a proton can be written \( r = \phi(v) \). It follows that \( R/\mathcal{M} = \phi(v) \);

\[ \text{but } N = \mathcal{M} F(R, \mathcal{M}), \text{ so that } N/\mathcal{M} = \psi(v) \text{ and } R/N = \xi(v), \]

where \( \phi(v), \psi(v) \) and \( \xi(v) \) are all related functions. For a 45° line in the \((\log N, \log R)\) diagram

\[ \xi(v) = R/N = \text{constant}. \]

The intercept of any such line with the two curves representing the results of measurements on the two types of particles gives a measure of the ratio of their masses; if the values of the range for the two intercepts are \( R \) and \( r \), then

\[ \mathcal{M} = M/m = R/r \] (see Figure 4).
In the early work employing this method (Lattes et al. 1948) it was necessary to confine the observations to the tracks of \( \pi^- \) and \( \mu^- \)-particles of the same event. The two related tracks of such a pair were certainly produced contemporaneously, but their relationship in time to other particles producing tracks in the emulsion, such as isolated protons, was unknown, and the effects of fading of the latent image could not therefore be estimated. In experiments on cosmic radiation at mountain altitudes, exposures of several weeks are commonly employed. As a result of fading of the latent image there was, with the types of emulsion in use at the time, a considerable difference in the grain-density of particles with the same specific ionization, according to whether the particles were recorded early or late in the exposure. The observations on the two tracks from the \( \pi^- \) and \( \mu^- \)-mesons of the same pair made it possible to deduce the ratio of their masses, \( m_\pi/m_\mu \); but the absolute values of the mass could not be determined by a comparison with the tracks of protons. A further difficulty was that in the relatively thin emulsions available at the time, very few long tracks, which give the most favourable conditions of measurement, were found. The value obtained for \( m_\pi/m_\mu \) is now known to be much too high.

Recent experiments by the method have been undertaken in the more favourable experimental conditions provided by employing new emulsions of greater thickness, and by making short exposures. A typical result obtained by Bowker in experiments on artificially generated \( \pi^- \)-mesons is shown in Figure 4(a). Figure 4(b) shows an alternative treatment of observations on \( \pi^- \) and \( \mu^- \)-mesons of the cosmic radiation by Brown and Fowler. The conditions provided by the former experiments are particularly favourable, for the duration of the exposure.
and any fading of the latent image are negligible. The results, included in Table 1, are in good agreement with those obtained in other experiments, and prove that when applied in favourable conditions the method is capable of giving reliable results in the hands of experienced observers.

3 (iii). Method B. Scattering and Residual Range

When a charged particle passes through a material medium, it is subject to frequent small deviations in its direction of motion as a result of Coulomb scattering. The problem was first analysed by E. J. Williams (1939). It has recently become of great importance because of its bearing on the determination of the energy of particles by the photographic method. Essentially, the observation of the average angular deviation per unit length of the trajectory, \( \bar{z} \), gives a measure of the quantity \( p\beta \) for the particle, where \( p \) is its momentum and \( \beta = c/v \), the ratio of the velocity of the particle \( v \) to the velocity of light \( c \).

Table 1. Determinations of the Masses of \( \pi^- \) and \( \mu^- \)-Particles

<table>
<thead>
<tr>
<th>Authors</th>
<th>Date</th>
<th>Method</th>
<th>Types of particles</th>
<th>( m_\pi )</th>
<th>( m_\mu )</th>
<th>( m_\pi/m_\mu )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lattes et al.</td>
<td>(1948)</td>
<td>(A) P.P.</td>
<td>( \pi^+ ), ( \mu^+ )</td>
<td>272±12</td>
<td>202±8</td>
<td>1±65±0.15</td>
</tr>
<tr>
<td>Goldschmidt et al.</td>
<td>(1948)</td>
<td>(B) P.P.</td>
<td>( \pi^+ ), ( \pi^- ), ( \mu^+ ), ( \mu^- )</td>
<td>290±20</td>
<td>290±20</td>
<td></td>
</tr>
<tr>
<td>Lattimore</td>
<td>(1948)</td>
<td>(B) P.P.</td>
<td>( \pi^- )</td>
<td>270±23</td>
<td>220±26</td>
<td></td>
</tr>
<tr>
<td>Brown et al.</td>
<td>(1950)</td>
<td>(A) P.P.</td>
<td>( \pi^+ ), ( \pi^- )</td>
<td>281±7</td>
<td>217±4</td>
<td></td>
</tr>
<tr>
<td>F. Barbour</td>
<td>(1949)</td>
<td>(C) P.P.</td>
<td>( \pi^+ ), ( \pi^- )</td>
<td>283±7</td>
<td>217±4</td>
<td></td>
</tr>
<tr>
<td>Camerini et al.</td>
<td>(1950)</td>
<td>(D) P.P.</td>
<td>( \pi^+ ), ( \pi^- )</td>
<td>270±23</td>
<td>220±26</td>
<td></td>
</tr>
<tr>
<td>Fretter, Retallack and Brode</td>
<td>(1949)</td>
<td>(C) W.C.</td>
<td>( \mu^+ ), ( \mu^- )</td>
<td>313±16</td>
<td>215±2</td>
<td>1±32±0.01</td>
</tr>
<tr>
<td>Gardner et al.</td>
<td>(1949)</td>
<td>(C) P.P.</td>
<td>( \pi^- )</td>
<td>264±24</td>
<td>202</td>
<td></td>
</tr>
<tr>
<td>Bowker</td>
<td>(1950)</td>
<td>(A) P.P.</td>
<td>( \pi^- )</td>
<td>280±15</td>
<td>202</td>
<td></td>
</tr>
<tr>
<td>Van Rossum</td>
<td>(1930)</td>
<td>(A) P.P.</td>
<td>( \pi^- )</td>
<td>305</td>
<td>202</td>
<td></td>
</tr>
<tr>
<td>Barkas et al.</td>
<td>(1950)</td>
<td>(A) P.P.</td>
<td>( \pi^- ), ( \mu^- )</td>
<td>280±6</td>
<td>202</td>
<td></td>
</tr>
<tr>
<td>Barkas et al.</td>
<td>(1950)</td>
<td>(C) P.P.</td>
<td>( \pi^- )</td>
<td>278±8</td>
<td>212±6</td>
<td></td>
</tr>
<tr>
<td>Bishop et al.</td>
<td>(1950)</td>
<td>(E) P.P.</td>
<td>( \pi^- )</td>
<td>276±6</td>
<td>212±6</td>
<td></td>
</tr>
</tbody>
</table>

W.C.; P.P., indicates experiments with Wilson Chambers and Photographic Plates, respectively.

The simplest mode of application of the method would be to determine \( \bar{z} \), and hence \( p\beta \), by observations on a restricted length of the initial part of the trajectory of a particle which subsequently reached the end of its range in the emulsion. The range–energy relation expressed by equation (4) can be employed to deduce relations between range and velocity, and hence between range and \( p\beta \) for particles of any assumed mass; the mass of the particle can then be deduced from the observations.

It has recently been possible to employ this method in the case of \( \pi^- \)-mesons of relatively high energy which, by chance, reach the end of their range in the emulsion (Camerini et al., unpublished). In the early experiments, however, as with Method A, the tracks available for measurement were commonly of short range, less than 1 mm. It was therefore necessary to measure the scattering over the entire length of the track and to make allowance for the variation in the
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velocity of the particle. In this way Goldschmidt-Clermont, King, Muirhead
and Ritson (1948) obtained values for the mass of the π- and µ-mesons which appear
to be in good accord with those of later and more accurate experiments (see
Table 1).

Although the method is less accurate than some others, it provides an important
technical resource which has sometimes been of great value in conditions in which
more refined methods cannot be brought to bear, see for example, Brown et al.
(1949 a).

3 (iv). Method C. Momentum and Residual Range

(a) Experiments of Barkas et al.

The most accurate methods developed hitherto for the determination of the
mass of mesons have depended on the determination of the momentum of
individual particles by magnetic deflection experiments, and their residual range

![Diagram of apparatus for determining the mass of π+-particles generated artificially in the 384 in. synchro-cyclotron at Berkeley.](image)

Figure 5 (a). Apparatus for determining the mass of π+-particles generated artificially in
the 384 in. synchro-cyclotron at Berkeley. The apparatus is placed within the vacuum
tank of the cyclotron and the energetic protons or α-particles bombard the ‘ribbon’ target
and produce π+- and π--particles which are emitted in all directions. The channel in the
metal screens prevents particles from reaching the plates unless they have been emitted
from the target in directions making angles less than about 14° with the line of motion of
the bombarding particles. By employing a thin target the uncertainty in the point of origin
of a particle and the radius of curvature of its trajectory in the magnetic field is reduced.

Figure 5 (b). Determination of the mass of π--particles.

in a given medium. For particles of charge e, moving in a photographic
emulsion, we may modify equation (3) and write:

\[ E = k_e m^{1-n} R^n, \]

where \( m \) is the mass of the particles. Further, if \( \rho \) is the radius of curvature
of a particle in a magnetic field of intensity \( H \), we may write

\[ E = e^2 (H\rho)^2 / 2m, \]

the quantities being measured in appropriate systems of units. It follows that

\[ m = \left\{ \frac{e^2 (H\rho)^2}{2k_e R^n} \right\}^{1/(2-n)}, \]

(9)

This method has been employed by Barkas et al. (1950) for the determination
of the mass of the π-particles generated artificially in the Berkeley synchro-
cyclotron using the method illustrated in Figure 5 (a) and (b). The bombardment
of the matter of the target by fast protons or α-particles leads to the creation of
π+- and π--mesons which are emitted in all directions. Only particles which
are emitted from the thin ribbon target in directions making angles less than 14° with the line of motion of the bombarding particles are allowed to reach the recording photographic plates. The point of entry, and the direction of the initial part of the track of a given particle in the emulsion, allows its trajectory to be computed, and thence the corresponding value of \( H_\rho \). This observation and the observed range of the particle, when inserted in equation (9), allows the mass to be calculated. It is necessary to make corrections to allow for inhomogeneities in the magnetic field of the synchrotron. A histogram showing the results obtained by Barkas \textit{et al.} is shown in Figure 6 (a). The mean value thus obtained, after suitable corrections, is \( m_\pi^- = 280.5 \pm 6 m_e \).

A similar determination for the positive \( \pi^- \)-mesons, has been made by Barkas with the apparatus shown in Figure 5 (b), and the result thus obtained was \( 278 \pm 8 m_e \). In this case observations were also possible on \( \mu^- \)-particles formed by the decay of \( \pi^- \)-particles arrested in the target. The value thus obtained was \( 212 \pm 6 m_e \) (see Figure 6 (b)).

![Histograms showing the distribution of the values of the mass of (a) \( \pi^- \) and (b) \( \pi^+ \) and \( \mu^- \)-particles, determined by Barkas \textit{et al.}, using method C.](image)

(b) \textit{Experiments of Franzinetti, of Barbour, and of Goldschmidt-Clermont.}

Experiments similar in principle to those described above, to determine the mass of \( \pi^- \)-mesons produced by cosmic radiation, have been carried out by Franzinetti (1949), by Barbour (1949), and by Goldschmidt-Clermont (1950). The apparatus employed by Franzinetti is shown in Figure 7. The method depends upon observing the tracks of individual particles in the emulsions of two plates, placed parallel to each other and face to face, in a field of 30,000 gauss provided by an electromagnet. The two emulsions are 3 mm. apart, and attention is confined to those particles which pass across the gap at a small glancing angle to the surfaces of the emulsions, and which reach the end of their range in one of them. The tracks produced by a single particle in the two emulsions can be recognized, and the change in the direction of motion due to the magnetic field—and hence the corresponding value of \( H_\rho \)—can thus be determined. The distribution in the values of the masses of the \( \pi^- \) and \( \mu^- \)-mesons obtained by Franzinetti is shown in Figure 8, and the mean values in Table 1.
Figure 7. Apparatus employed by Franzinetti for determining the mass of particles produced by cosmic radiation in magnetic deflection experiments—Method C.

Figure 8. Distribution in the values of the mass of (a) +ve and (b) −ve particles produced at an altitude of 11,000 ft. by cosmic radiation. The results indicate that any particles of mass \( \sim 1,000 m_e \) are present in numbers less than 5% of the \( \pi^- \) and \( \mu^- \)-mesons. The black squares represent \( \pi^+ \) and \( \pi^- \) particles definitely identified by secondary effects observed at the end of their range. \textit{(After Franzinetti.)}
(c) Experiments with Wilson chambers.

The experiments with photographic plates are similar in principle to observations carried out over many years with Wilson chambers operated in magnetic fields. In such experiments, the curvature of a track is directly measured from the photograph, and the range of the particle deduced from the number of lead plates which it is subsequently observed to traverse. Modern forms of such an apparatus employed by Brode, and by Fretter, to which reference is made in § 8 in connection with the problem of the existence of other types of mesons more massive than the \( \pi \)-particles, are shown in Figure 9. The method has the disadvantage that the accuracy with which the range of the particles can be determined is limited by the finite thickness of the lead plates in which they are arrested, and by the fact that any secondary effects occurring at the end of the range of a particle are commonly unobserved. It has, however, been employed with success to determine the mass of the \( \mu \)-particles and, in particular, has provided the only accurate information hitherto available on the mass of \( \mu^- \)-mesons.

3 (v). Method D. Grain-Density and Scattering

It has been known for many years that in the case of charged particles moving with velocity less than 0.8\( c \), the simultaneous observation of the specific ionization and the momentum of the particle allows its mass to be determined. Experiments based on this principle have been made with Wilson chambers.
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The specific ionization, which gives a measure of the velocity of the particles if the charge is known, has been determined by drop-counts and the momentum from the observed curvature of the trajectories of the particles due to the magnetic field.

The precision of these observations has been limited by the inaccuracy of the method of 'drop-counting'. Especially in experiments with 'counter-controlled' Wilson chambers, it has proved to be difficult to establish precisely the same degree of super-saturation in each expansion, and the drop-counts for particles of the same specific ionization are subject to uncontrolled fluctuations. In spite of these difficulties, the method has been of great importance. It allowed the μ-mesons of the penetrating component of the cosmic rays to be distinguished from electrons and protons; and it has been employed by Rochester and Butler, and by Anderson and his colleagues, in their experiments on τ-mesons described in §9.

A method very similar in principle to the above has been employed recently by Camerini et al. (1949), and by Fowler (1950), using photographic plates. The theory of the method has been studied independently by Goldschmidt-Clermont (1950). The velocity of the particle is determined by grain-counts, and the quantity $p\beta$ by observations on the scattering. Apart from difficulties due to fading of the latent image, which appear to be unimportant when using modern 'electron-sensitive' emulsions and short exposures, the determination of the grain-density in a track depends only on the number of grains counted and on variations in the uniformity of development and the sensitivity of the emulsion. It is therefore superior to drop-counts obtained with counter-controlled Wilson chambers. Secondly, the measurement of the quantity $p\beta$ by observations on the scattering can be made with a precision not inferior to that commonly achieved in the determination of the momentum by observations on the curvature of the tracks in Wilson chambers operated in magnetic fields.

A characteristic result obtained by this method is shown in Figure 10 in which the corresponding values, for individual tracks, of the quantities $\bar{z}$, the average angular deviation of the trajectory per unit length, and $g$, the number of grains per unit length, have been plotted. The results all refer to particles of great range, and the variation of $\bar{z}$ and $g$ over the measured length of the track can be neglected. The lines marked $\pi$, P, D, T etc. represent the calculated distributions for $\pi$-particles, protons, deuterons and tritons, and the grouping of the experimental points round the calculated curves for $\pi$-particles and protons is particularly well marked. The distance from the line P of any observed point in such a diagram, measured parallel to the axis of the scattering parameter $\bar{z}$, is proportional to the ratio of the mass of the corresponding particle to that of the proton. A characteristic mass spectrum deduced by this method—for the particles emitted in the disintegrations produced by protons and $\alpha$-particles of great energy present in the cosmic radiation—is shown in Figure 11. The results prove that fast $\pi$-particles are commonly created in such disintegrations, and they allow the mass of the particles to be determined. The results are included in Table 1.

An important feature of this particular method of determining the mass of charged particles is that it can be applied to the tracks of particles of great range which escape from the recording medium. It is thus applicable in conditions in which the other four methods cannot be employed.
Figure 10. Distribution in the values of $\vec{\alpha}$ (the scattering parameter) and $g$ (grain-density) for particles emitted from stars (Fowler 1950)—Method D.

Figure 11. Distribution in the values of the mass of particles emitted from stars as determined by Method D. (Camerini et al. 1950.)
3 (vi). *Method E. Ratio of the Ranges and of the Momenta of Protons and \(\pi\)-Particles*

One of the most important sources of error in the experiments of Barkas et al., described under Method C—experiments which have given the most accurate values for the mass of the \(\pi\)-particles obtained hitherto—is that associated with an uncertainty in the precise form of the range–energy relationship for protons. In order to overcome this difficulty, Bishop, Bradner and Smith (1949) have employed a method which is independent of the absolute magnitude of the magnetic field and of a precise knowledge of the range–energy relationship.

We have seen that for particles of the same velocity, and of masses \(M\) and \(m\) respectively, we may write

\[
\frac{M}{m} = \frac{R}{r} = \frac{(H_p)_M}{(H_p)_m},
\]

a result which is independent of the form of the range–energy relation. The method therefore consists in determining that value of the ratio of \(H_p\) for protons and \(\pi\)-particles for which the ranges of the particles stand in the same ratio. It is carried out by means of the apparatus shown schematically in Figure 12.

![Figure 12. Apparatus of Bishop et al. (1949) for the determination of the mass of \(\pi^+\)-particles by Method E.](image)

The two ribbon targets \(T_p\) and \(T_\pi\) serve as sources of protons and \(\pi\)-mesons respectively. The two radii, \(\rho_p\) and \(\rho_\pi\), are approximately in the ratio of the masses: 

\[
\rho_p : \rho_\pi = m_p : m_\pi.
\]

The apparatus placed in the vacuum tank of the synchro-cyclotron is provided with two ribbon targets \(T_p\) and \(T_\pi\) (Figure 12) designed to act as sources of protons and \(\pi\)-mesons respectively, and so located with respect to the photographic plate that the ratio of the energies of the two types of particles recorded is approximately equal to the ratio of the masses. In passing across the plate, there is a rapid variation in the velocity of the \(\pi\)-mesons and therefore in their range, and a much smaller variation in the corresponding values for protons. The observations consist in determining, for a succession of narrow elements of length along the plate, the ratios \(R_p / R_\pi\) and \((H_p)_p / (H_p)_\pi\). A characteristic set of observations thus obtained is shown in Figure 13. The interception of the best straight line through the experimental points with the line \(R_p / R_\pi = (H_p)_p / (H_p)_\pi\) gives the ratio of the mass \(m_p / m_\pi\). The value given by this method is \(m_\pi = 276 \pm 6 m_\pi\), and the authors state that it will be possible to obtain a more precise result by further attention to detail.
The values shown in Table 1 indicate that any difference between the masses of the $\pi$-mesons of the cosmic radiation and of those produced artificially is less than the errors of measurement. They therefore give strong support for the view that the two types of particles are identical. Further, any difference in mass between the $\pi^+$- and $\pi^-$-particles is small.

3 (vii). The Nature of the Neutral Particle emitted during $\mu$-decay

Since an application of the conservation laws leads to the conclusion that the neutral particle providing the momentum and energy balance during the decay of a $\pi$-meson is of small or zero rest-mass, it may be assumed to be either a $\gamma$-ray or a neutrino. Recent observations by O'Ceallaigh (1950) provide strong evidence that the first of these possibilities can be excluded, and it is reasonable to regard the neutral particle as a 'neutrino'; i.e. some form of neutral radiation of small or zero rest-mass.

Suppose the process of decay to be accompanied by the emission of a photon which recoils in the opposite direction to the $\mu$-meson. The line of motion of the photon, and its energy $\sim 30$ Mev., is defined. If, therefore, a search is made of 'electron-sensitive' photographic plates in which the decay of $\pi$-mesons is recorded, it should be possible to observe pairs of electrons created by any photons recoiling from the $\mu$-mesons. Photons of energy 30 Mev. produce pairs in photographic emulsions with a divergence of about $3^\circ$ (King 1950), and the bisector of the line of motion of the two electrons defines that of the parent photon within narrow limits. Further, in favourable cases, the Coulomb scattering of the electrons enables their energies to be determined, and thence the quantum energy of the photon. Because of these features it is possible to establish whether or not an observed pair has characteristics consistent with its having arisen during the decay of a neighbouring $\pi$-meson arrested in the emulsion, or whether it is due to a $\gamma$-ray not associated with the decay.

O'Ceallaigh has scrutinized the emulsion in the neighbourhood of $\pi$-mesons stopped in plates exposed to cosmic radiation and has found no pairs in a total length of path of the recoiling neutral particles of 38 cm. The 'conversion length' of $\gamma$-radiation in the emulsion, for photons of energy equal to 30 Mev., is 6.5 cm. If the process of decay leads to the ejection of a photon, six pairs of electrons

![Figure 13. Observations of $R_p/R_\pi$ for the tracks of individual $\pi$-mesons against $p_p/p_\pi$. The intercept of the $45^\circ$ line with the best line through the experimental points gives a measure of $m_p/m_\pi$ which is independent of a knowledge of the range-energy relationship—Method E.](image-url)
should have been observed in the conditions of the experiments, and the probability of observing none is <0.005. It may therefore be concluded that the momentum balance is provided by a neutral radiation of a different type, by some form of neutrino.

It is well known that during the $\beta$-decay of radioactive nuclei there is a disappearance of energy which has been attributed by Fermi and by Pauli to the emission of a neutral particle of low rest-mass—a 'neutrino'. Further, experiments on the masses and the $\beta$-decay of certain of the light nuclei prove that if such particles exist their rest-mass must be less than 0.1 $m_e$. For some years it has been recognized that important evidence for the existence of the neutrino would be provided if it could be proved that the conservation of momentum, as well as that of mass-energy, required the assumption of the emission of such a neutral particle. A number of experimenters have therefore measured the recoil of the nucleus during $\beta$-decay, and have concluded that the results demonstrate the existence of a neutrino.

In the case of the decay of the $\pi$-mesons, the secondary charged particle, the $\mu$-meson, is of small rest-mass compared with the atomic nuclei, and the energy of the recoiling neutral particle is large. The momentum and energy of the $\mu$-meson can therefore be determined with precision. Since the possibility can now be excluded that the neutral particle providing the momentum balance is a photon, the observed values of the masses of the $\pi$- and $\mu$-mesons and the characteristics of the $\mu$-decay provide important additional evidence for some other form of neutral radiation—for the existence of some form of neutrino.

§ 4. PROPERTIES OF THE $\pi$-MESONS

4 (i). Charge of the $\pi$-Particles

Photomicrographs of examples of the successive decay of $\pi$-particles according to the scheme $\pi \rightarrow \mu \rightarrow e$ are shown in Plate I. If charge is to be conserved in these transmutations—and if no particles with a charge much smaller than that of the electron are emitted which escape observation—the charge on the three types of particles must be equal. If the final particle formed in the process of decay is indeed an electron, a view for which the evidence is summarized in § 5 (iii), the charge on the $\pi$- and $\mu$-particles must be equal to the elementary electronic charge.

It has been pointed out by Bradner that the consistency between the values of the mass deduced by different methods provides a powerful demonstration that the charge on the $\pi$-mesons is very close to the electronic charge. In particular, he has shown that the observed degree of consistency of the measurements by methods A and B, shown in Table 1, indicates that the charge in the $\pi$-particles is equal to that of the electron to within 3% (Bradner 1949).

4 (ii). Life-time of the $\pi$-Particles

The most accurate determinations of the life-time of the $\pi$-mesons have been made at Berkeley by the method represented schematically in Figure 14. Under the impact of fast $\alpha$-particles, positive and negative $\pi$-mesons are created. Those of the negative $\pi$-mesons which emerge from the target in a suitable direction and with momenta in a narrow range of values spiral in the magnetic field in the channel cut in a solid block of metal and are recorded by one or other of two
photographic plates (Figure 14). Because of the well-known ‘focusing effects’ associated with the spiral trajectories of particles in a magnetic field—and in the absence of any spontaneous decay of the particles—the relative numbers recorded in these two plates, per unit area, will be inversely proportional to the lengths of path in the magnetic field, i.e. as 3 to 1 for the particular experimental arrangement shown in Figure 14. If, however, the particles suffer decay in flight, the number reaching the plates will be reduced and the effect will be more marked the greater the length of path. There will therefore be departures from the simple ratio to be observed in the case of stable particles (Richardson 1948).

The method outlined above is practicable only if the life-time is of the same order of magnitude as the period of the motion, $T$, of the particles in the magnetic field. For particles of mass $275\,m_e$ moving at right angles to a field of 15,000 gauss, $T \sim 10^{-8}$ sec., a value known to be close to that of the $\pi$-particles. The latest measurements by this method show that the life-time, $\tau_\pi$, lies between the values $1.4$ and $0.9 \times 10^{-8}$ sec. (see, however, Martinelli and Panofsky 1950).

Figure 14. Apparatus of Richardson (1949) for the determination of the lifetime of the $\pi^-$-particles generated artificially in the synchro-cyclotron. In the absence of decay, the numbers of particles per unit area of either photographic plate should be inversely as the length of path to the corresponding plate, owing to the effects of semi-circular focusing in one plane. The trajectory of the $\alpha$-particle beam bombarding the target is not shown.

A determination of the life-time of the $\pi$-mesons of the cosmic radiation has also been made by Camerini et al. (1948), using a method based on the following considerations: at mountain altitudes (c. 11,000 ft.) the bombardment of matter by fast nucleons of the cosmic radiation stream leads to the creation of $\pi$-mesons of great energy. Some of these particles are emitted in the upward direction so that, in addition to the prominent downward flux of $\mu$-mesons constituting the penetrating component, there is a weak upward-moving stream of mesons arising from the surface of the earth. At their point of creation in the surface layers of the earth the mesons are made up, at least predominantly, of $\pi$-particles. As their time of flight increases, the initial stream of $\pi$-particles transforms spontaneously into a stream of $\mu$-particles. Photographic plates were therefore exposed at 2 metres above the surface of the earth. Particles of the upward moving stream which stop in the emulsion are identified by the directions of the trajectories at their points of entry into the emulsion in which they are brought to rest. Further, mesons of different types can be distinguished by the secondary processes produced at the end of their range. A study could thus be made of the rate of transformation of the $\pi$-particles into $\mu$-particles by determining the proportion of the two types at different heights above the ground. The value thus obtained for the life-time $\tau_\pi$ is $0.6 \times 10^{-8}$ sec., a result consistent with that given by the more accurate methods available with artificially produced particles.
The short life-time of the $\pi$-particles allows us to account for the failure to observe them in experiments with expansion chambers and counters. It will be shown in a later paragraph that most of the $\pi$-mesons of the cosmic radiation are emitted during nuclear explosions with a kinetic energy greater than 100 MeV. When moving in the atmosphere, the rate of loss of energy due to ionization is so slow that only a minute fraction of the particles are brought to rest before decaying into $\mu$-mesons. It follows that there is only a very small chance of observing the spontaneous decay of a $\pi^+$-meson in the gas of a Wilson chamber.

4 (iii). Disintegrations produced by $\pi^-$-Particles

The original observations of nuclear disintegrations produced by mesons arrested in photographic plates were interpreted as due to $\mu^-$-particles captured by silver or bromine nuclei. It is now established that at least most of them, and possibly all, are in fact due to $\pi^-$-particles. The evidence rests on the following observations:

The mesons observed in photographic plates exposed at high altitudes are composed of $\pi^-$ and $\mu^-$-particles in proportions which depend upon the amount of matter in the immediate vicinity of the emulsions. This is due to the fact, discussed in more detail in a later paragraph, that the great majority of the mesons in the atmosphere are $\mu^-$-particles produced by the decay of $\pi$-particles. Most of the $\pi$-particles, the primary products of nuclear explosions, are created with a kinetic energy less than $10^9$ ev.; and because of their short life-time, they commonly travel distances of less than 50 metres before decaying 'in flight'. In exposures at a height of approximately 10,000 ft., the downward stream of $\mu^+$- and $\mu^-$-particles thus formed, most of which are moving in directions inclined at less than $40^\circ$ to the vertical, can be distinguished by the inclination of the tracks at the points of entry into that emulsion in which the particles are brought to rest. On the other hand, the majority of the $\pi$-particles are locally generated. Their directions of motion depend on the location of the neighbouring matter, and are commonly distributed nearly isotropically. Further, in plates exposed in isolation from neighbouring matter, the $\pi$-particles are found to be present in numbers less than 10% of the $\mu$-mesons, but their numbers can be increased by concentrating lead blocks round the plates during the exposure.

In a series of exposures made at a wide range of altitudes, and with varying amounts of local matter of high atomic number, it has been found that the number of $\pi^-$-particles recorded, per cm$^3$ of emulsion, is nearly equal to that of the mesons which produce nuclear disintegrations, $\sigma$-mesons, and that there is no significant variation in the proportion of the two types in a wide range of experimental conditions. This observation can be easily explained if the $\pi^+$- and $\pi^-$-particles are created in approximately equal numbers in the bombardment of matter of high atomic number by cosmic radiation, and if the $\pi^-$-particles alone produce nuclear disintegrations with the emission of protons and other charged particles when captured by the nuclei present in the emulsion.

On the other hand, if an appreciable proportion of the $\mu^-$-particles also produced disintegrations, the number of $\sigma$-mesons would be correspondingly increased, and the ratio $N_\sigma/N_\pi$ would vary with the experimental conditions and, in particular, with the amount of local matter round the plates. The absence of such an effect gives strong support for the view that very few or none of the $\mu^-$-particles produce disintegrations with the emission of protons or $\pi^+$-particles.
The experiments at Berkeley on negative $\pi$-particles produced artificially give very strong support for this view. Although $\mu$-particles are sometimes recorded in these experiments, their points of origin are usually unknown, for it is probable that $\pi$-particles alone are produced directly in nucleon–nucleon collisions, and that $\mu$-particles arise only by the decay of the heavier particles. The identification of the $\mu$-particles is therefore difficult. On the other hand, the $\pi$-particles can be identified with certainty. It is thus possible to determine the relative frequency with which $\pi$-particles, when brought to rest in the emulsion, produce disintegrations with the emission of different numbers of protons, $\alpha$-particles, etc. The distribution thus obtained (Adelman et al. 1949) is shown in Figure 15(b). The corresponding distribution for the cosmic-ray mesons is given in Figure 15(a).

![Figure 15](image)

Figure 15. 'Prong distributions' for the disintegrations produced by $\pi$-particles in photograph c emulsions: (a) for cosmic-ray particles; (b) for artificial particles; (c) and (d) show similar results, attributed to heavy and light elements in the emulsion respectively.

The two distributions shown in Figure 8 are indistinguishable within the limits corresponding to statistical fluctuations. This result can be interpreted either as indicating that the $\pi$-particles alone produce disintegrations, or that the disintegrations produced by $\mu$-particles are similar in type to those produced by $\pi$-particles. Support for the former assumption was provided by experiments on determinations of the mass of the $\sigma$-mesons by Goldschmidt-Clermont et al. (1948) and by Lattimore (1948), using the scattering method. The mean values obtained, $m_\pi = 272 \pm 12$ and $m_\sigma = 290 \pm 80 m_\pi$, were in accord with the assumption that the $\sigma$-mesons are $\pi$-particles.

Recent experiments by Franzinetti, in which the masses of cosmic-ray mesons have been determined by magnetic deflection experiments, show that less than 5% of the $\mu$-particles stopped in the emulsion produce nuclear disintegrations in which heavy charged particles with a range greater than 5 $\mu$ are emitted.
Whilst this body of evidence is not conclusive, it shows that at most only a small proportion of the $\mu^-$-particles produce observable disintegrations in photographic emulsions, and it is consistent with the view that none of them do so. At least the great majority of the $\sigma$-mesons are therefore to be identified as $\pi^-$-particles. The Berkeley experiments also prove that about 27% of the $\pi^-$-particles fail to produce recognizable disintegrations. In these particular cases it may be assumed that nuclear capture followed by disintegration does occur, but that fast neutrons are liberated which escape observation and that, if they are accompanied by charged particles, the latter are of very short range. Further, the recent experiments by Panofsky et al. (1950) shows that in the interaction of a $\pi^-$-particle with hydrogen, the most common element in the emulsion, no visible star is produced (see, however, § 8 (vi)).

Experiments with artificially produced $\pi^-$-particles (Bradner 1950) show that when stopped in photographic emulsion they never, or only very rarely, decay with the emission of $\mu^-$-particles, the process by which the majority of the $\mu^-$-mesons are created in the atmosphere. We must therefore conclude that, unlike the $\mu^-$-particles, the $\pi^-$-particles commonly interact with nuclei and produce disintegrations before they have had time to decay; and this is in spite of the fact that the life-time of the $\pi^-$-particles is only about one two-hundredth part of that of the $\mu^-$-particles.

It is reasonable to assume that the process of atomic capture of a $\pi^-$-particle is similar to that of a $\mu^-$-particle. The above result therefore indicates that a $\pi^-$-particle has a much stronger interaction with nucleons than a $\mu^-$-particle, that, having reached its state of lowest energy, the $\pi^-$-particle interacts with the nucleus of a light element such as carbon in a time short compared with $10^{-8}$ sec.

4 (iv). Capture of $\pi^-$-Particles by Particular Elements

The process of nuclear capture of $\pi^-$-particles has been studied by Heidmann and Leprince-Ringuet (1948) and by Perkins (1949), who have suggested that the first interaction takes place between a $\pi^-$-particle and a pair of nucleons. By studying the fate of artificially produced $\pi^-$-particles brought to rest in a 'sandwich' made up of successive layers of pure gelatine and normal photographic emulsion, Menon et al. (1950) have shown that it is possible to distinguish some of the characteristics of the disintegrations of light elements on the one hand—carbon, nitrogen or oxygen—and of silver or bromine on the other. Characteristic nuclear disintegrations of the light and heavy nuclei distinguished by these methods are shown in Plates II and III.

In studying the disintegration of light nuclei by $\pi^-$-particles it is usually difficult to distinguish the particular element involved. The disintegration is commonly accompanied by the emission of neutrons of which the energy and directions of motion cannot be determined. In certain rare instances, however, in which a single neutron is emitted in addition to the charged particles, it appears to be possible to determine the momentum of the uncharged particle by an application of the principle of the conservation of momentum, and thus to examine the total energy distributed among the emitted nucleons. A particular example of this type is the reaction $^6_0$C + $\pi^- \rightarrow ^4_2$He + $^4_0$He + $^3_1$H + $^0_1$n (Menon et al. 1950). Such a study would appear to be of great importance for the extension of our knowledge of the process of nuclear capture by $\pi^-$-particles. It is the
opinion of some authors that in the initial process of capture of \( \pi^- \)-particles the energy liberated by the disappearance of the rest-mass is commonly shared amongst a considerable number of nucleons; amongst an \( \alpha \)-particle group for example. This may lead to the emission of one or more fast nucleons and the formation of an excited nucleus which subsequently ‘evaporates’. For a detailed discussion of these questions see Menon et al. (1950), Tamor (1950), Adelman and Jones (1949), and Cheston and Goldfarb (1950).

4(v). Spin of the \( \pi^- \)-Particles

It has been suggested by Wentzel (1949) that the \( \pi^- \)-mesons created in the interaction with matter of a directed beam of fast nucleons might be ‘polarized’: that there might be some degree of orientation of an axis of spin of the particles, with respect to the line of motion of the ‘primary’ nucleons which produced them. Further, it is possible that if the particles are arrested in solid materials, the Coulomb forces brought into play in the atomic encounters which cause the particles to lose kinetic energy would not completely destroy the initial polarization. Such a polarization, if it exists, might be made manifest by privileged directions of emission of the \( \mu^+ \)-particles, created in the spontaneous decay of \( \pi^+ \)-particles when at rest, with respect to the line of motion of the ‘primary’ nucleons.

![Figure 16. Distribution—relative to the vertical—of the directions of emission of \( \mu^+ \)-particles produced by the decay of \( \pi^- \)-particles of the cosmic radiation arrested in photographic emulsions.](image)

At mountain altitudes (11,000 ft.) the cosmic-ray stream contains a large proportion of protons and neutrons, most of which move downwards in directions inclined at less than 40° to the vertical. In traversing photographic plates these particles produce nuclear explosions some of which are accompanied by the emission of \( \pi^- \)-mesons, and some of these particles stop in the emulsion. An examination of the directions of motion of the \( \mu^+ \)-particles emitted in the decay of \( \pi^+ \)-particles can thus be made, and a typical result is shown in Figure 16. It will be seen that the particles are emitted at all directions to the vertical and any departures from an isotropic distribution are small.

In the above experiment we are observing the decay of \( \pi^- \)-mesons which are emitted from nuclear explosions with a wide range of values of the kinetic energy. Further, in many cases the particles may have been produced as one of a number
of mesons created in a single nuclear event—as one of a penetrating shower—see §7 (ii). In these circumstances the absence of an observed anisotropy is indecisive and no conclusions regarding the nature of the spin of the \( \pi \)-particles can be drawn from the experiments.

Similar conclusions have been drawn from preliminary experiments made with artificially produced \( \pi^+ \)-particles by Richman et al (1950).

Decisive evidence in support of the view commonly held that the \( \pi^- \)-mesons have spin zero or unity is provided by the experimental evidence of Panofsky et al. (1950) on the capture of \( \pi^- \)-particles by protons and of the mode of disintegration of the resulting neutral mesons (see §8 (ii)).

4 (vi). \( \beta \)-Decay of the \( \pi \)-Particles

The properties of the \( \pi \)-particles set out in the preceding sections are closely similar to those attributed to Yukawa particles, except that the former commonly suffer \( \mu \)-decay instead \( \beta \)-decay. Observations have been made at Berkeley to determine whether the spontaneous transformation of a \( \pi \)-meson invariably leads to the emission of a \( \mu \)-meson, or whether it sometimes undergoes \( \beta \)-decay. The proportion of the \( \pi^+ \)-particles, identified by their mass, which stop in the emulsion and emit a \( \mu \)-meson has been determined by means of an apparatus of the type shown in Figure 5 (b).

The experimental results indicate that at least 95\% of the \( \pi^+ \)-particles undergo \( \mu \)-decay, and not more than 5\% direct \( \beta \)-decay. If therefore we assume that the \( \pi^- \)-meson can decay in either of two modes, we can set an upper limit to the decay constant for the process, which leads to the emission of an electron, and an equivalent upper limit to the effective life-time. The result thus obtained is as follows:

\[
\tau_{\pi}(\beta) > 20 \times 10^{-8} = 2 \times 10^{-7} \text{sec.}
\]

This value is very close to that postulated by Yukawa for the life-time, against \( \beta \)-decay, of his heavy quanta.

§ 5. PROPERTIES OF THE \( \mu \)-MESONS

5 (i). Mass of the \( \mu \)-Particles

The most accurate determinations of the mass of the \( \mu \)-mesons have been made by measurements on the curvature of the trajectory of the particles in Wilson chambers operated in magnetic fields, together with the corresponding values of the residual range in lead plates—method C (Fretter 1946, Retallack and Brode 1949, Brode 1949). The essential features of the methods are illustrated in Figure 9 and the results summarized in Table 1.

The mass of the particles has also been determined by observations on the tracks in photographic plates by grain-counting and by the scattering method (Goldschmidt-Clermont et al. 1948), but the results are not so reliable as those obtained in the best experiments with the Wilson chamber. Recently, determinations have also been made by magnetic deflection experiments, detecting the particles with photographic plates, see method C, §3 (iv). The observations, by this method, on the \( \mu^- \)-particles produced by the decay of artificially generated \( \pi^- \)-particles appear very promising—see Table 1 and Figure 6.
Reference has already been made to the original observation by Williams and Roberts (1940) which demonstrated that the $\mu$-meson sometimes decays with the emission of a charged particle of energy $\sim 50$ MeV. and low rest-mass, and to the support which was thus given for the view that the particle transforms into an electron together with a neutral particle also of low or zero rest-mass—a neutrino or a photon. The evidence that the emitted charged particle is an electron, summarized in a later paragraph, is now very strong. Although its nature remains to be finally established, it will be convenient in what follows to refer to it as an electron.

No further successful observations with Wilson chambers of the decay of mesons were made for a number of years. In 1947, however, Anderson obtained two examples in both of which the energy of the electron appeared to be of the order of 25 MeV. Later, other observers, employing a variety of methods, obtained indications that the energy of the electron is not unique (Thompson 1948, Fowler et al. 1948, Zar et al. 1948 and Steinberger 1948, 1949). Steinberger deduced the energy distribution of the electrons by observations on the ranges of the particles in solid materials. Leighton, Anderson and Seriff (1949) on the other hand determined their momenta from the curvature in the tracks in a Wilson chamber operated in a magnetic field at sea level. Finally, with the development of the electron-sensitive emulsions, it also became possible to record the tracks of the decay particles and, in favourable cases, to determine their energies by the scattering method. In this way it was shown by Brown et al. (1949 a) that the values of the energy of ten of the particles were distributed in the interval from 10 to 50 MeV.

It is now certain that the energy of the electron emitted during the decay of the $\mu$-meson is not constant but may have any value distributed in a range up to a maximum of about 55 MeV. In the decay of a meson into an electron and some form of neutral radiation, a simple application of the principles of the conservation of energy and momentum enables the maximum permissible value for the energy to be calculated. The value quoted above, 55 MeV., corresponds to the maximum energy of the electron when the rest-mass of the meson is $215 m_e$, the neutral particle, or particles, providing the momentum balance being of zero rest-mass. The best determination of the form of the energy 'spectrum' is that of Leighton et al. (1949), which is reproduced in Figure 17(a). The results indicate that there is a maximum in the distribution at about 35–40 MeV., and a finite probability of the decay particle being ejected with the maximum possible energy. These results are consistent with those of Steinberger.

A second determination of the energy spectrum has been made by Davies et al. (1949), applying the scattering method to a study of the tracks of the decay particles in photographic emulsions. The result obtained is shown in Figure 17(b). It is a feature of this method that a homogeneous group of particles appears as an asymmetrical peak in the energy distribution, with a 'tail' extending to higher energies. The presence of a small proportion of particles with an apparent energy greater than that theoretically possible, shown in Figure 17(b), is therefore not unexpected. The authors show that the mean mass of the mesons which were the parents of these particular tracks is $204 \pm 19 m_e$. Most of them must therefore be attributed to $\mu$-mesons, and not to the presence of a small proportion of heavier
particles with a similar mode of decay. It has been pointed out by O'Ceallaigh, however, that some of them may be due to the direct $\beta$-decay of $\pi^+$-particles.

In four cases the authors have been able to determine the energy of the electrons arising from $\mu$-mesons which were themselves produced in the emulsion by the decay of $\pi$-particles. The values thus obtained fall in the range of energies from 10 to 50 Mev. and give additional support for the view that the $\mu$-mesons are identical with the mesons of the penetrating component of the cosmic radiation. Examples of the successive decay $\pi^-\mu^-\nu$ are shown in Plate I.

It has been remarked by Rossi (1949) that, in order to study the decay products of free $\mu$-mesons, attention should be confined to the positive particles, for the negative particles are believed to fall into Bohr orbits round atomic nuclei when arrested in solid materials. Strong evidence for the existence of the atomic

![Figure 17(a)](image)

**Figure 17 (a).** Distribution in energy of the electrons produced by decay of $\mu$-particles. Observations of Leighton et al. (1949).

![Figure 17(b)](image)

**Figure 17 (b).** Distribution in energy of the electrons produced by the decay of $\mu$-particles. Observations of Davies et al. (1950); the dotted curve corresponds to the distribution to be expected for a homogeneous group of electrons of energy 40 MeV.

capture of mesons has been provided by experiments of Cosyns et al. (1949). These authors have studied the distribution in energy of slow electrons, in the interval from 10 to 50 kev., which originate at the end of the range of about 10% of the $\mu$-mesons arrested in photographic plates exposed to cosmic rays. The authors show that the distribution in energy of these electrons can be accounted for in terms of Auger transitions accompanying the atomic capture of $\mu$-particles by silver and bromine. These transitions result in the ejection of atomic electrons as the mesons fall to states of low energy round the nucleus (see also Chang 1949). The $\mu^-$-particles only decay, however, when captured by light elements. While the process of atomic capture must occur in these elements also, the loss of energy of the decay electron in escaping against the Coulomb attraction of the nucleus will be small—not more than approximately 1,000 ev. It is therefore reasonable to suppose that the effect on the form of the energy distribution of the decay electrons is small, and that the results by the photographic method, some of which correspond to the decay of $\mu^-$-particles, are not seriously in error from this cause.

Since the energy of the electron is not unique, it must be assumed that at least two neutral particles are emitted during its transmutation. Both the distributions shown in Figure 17 indicate that there is a maximum at about 40 Mev.,
and that the mean energy of the electron is about 35 mev. This value is about one-third the total energy liberated by the disappearance of the rest-mass of the \( \mu \)-meson. This result suggests that two neutral particles of small rest-mass are created, the average energy of each of the three particles being one-third of the available energy.

The form of the energy spectrum of the charged and uncharged decay particles is of great importance for determining the nature of the forces between them. The expected distributions for various types of forces have been calculated by Tiomno, Wheeler and Rau (1949). Some of them, notably the vector and pseudo-scalar varieties, appear to be in satisfactory agreement with the observed distributions. It is important to increase the accuracy and statistical weight of the observations in order that a more precise comparison between theory and experiment may be possible (see also Michele 1950).

5 (iii). Nature of the Decay Particles

It has been commonly assumed that the charged particle formed by the decay of a \( \mu \)-meson is an electron. In support of this view Hincko and Pontecorvo (1949) have studied the passage of the particles through matter and the rate of loss of energy through bremsstrahlung. This process is less probable the greater the rest-mass of the particle, and observations of the rate of loss of energy of the particles when compared with that of an electron with an energy within the same range of values allows conclusions to be drawn about the ratio of the rest-masses. The experiments show that the decay particle must have a rest-mass less than \( 2m_e \), where \( m_e \) is the mass of the electron.

Support for this view has recently been obtained by Camerini and Fowler (unpublished), who have observed the collision of a decay particle with an electron in a photographic plate. The energies of the initial particle and of the two components producing the forked track resulting from the collision can be determined by the scattering method. The analysis of the event indicates that mass of the decay particles is \((3 \pm 2)m_e\) or \((1.2 \pm 0.5)m_e\), according to which arm of the fork is assumed to be that of the recoiling electron.

This evidence therefore proves that if the decay particle is of a type of which the existence is already established, it is an electron, and that, in any case, its rest-mass is less than \( 2m_e \).

We have seen that the distribution in energy of the charged particles liberated by the decay of the \( \mu \)-meson indicates that at least two neutral particles are also created. There is very strong evidence that this neutral radiation is not made up of photons. Thus Hincks and Pontecorvo (1948) have searched for coincidences due to the decay electron from a \( \mu \)-meson on the one hand, and a discharge in other counters resulting from the materialization of any accompanying \( \gamma \)-radiation on the other. They have found that any such quanta, if they occur at all, appear much less frequently than the charged decay particles, and similar results have been obtained by Sard et al (1948).

In view of these results, and of the fact that the experimental evidence suggests that the maximum energy of the decay particles is of the order of 55 mev., it is generally assumed that the neutral radiation must consist of particles of small or zero rest-mass, of some form of ‘neutrino’. The decay of the \( \mu \)-meson is therefore commonly represented by the equation

\[
\mu \rightarrow e + \nu + \nu,
\]
Mesons

where $\nu$ represents a neutrino. This decay scheme, and that for the $\pi$-mesons represented by the equation $\pi \rightarrow \mu + \nu$, are consistent with the assumption that the $\mu$-meson is of spin $\frac{1}{2}$ and the $\pi$-meson of spin 0 or 1 (Marshak 1949, Serber 1949). It remains to be established, however, whether the three neutral particles represented in the above equations are of the same type, and whether or not they are identical with the neutrino of the nuclear $\beta$-decay.

5(iv). Life-time of the $\mu$-Particles

A modern form of apparatus to determine the life-time of $\mu$-mesons of the cosmic radiation, due to Valley and Rossi (1949), is illustrated in Figure 18. 'Delayed coincidence' counters, similar in their mode of operation to those illustrated in Figure 1, are employed in conjunction with an expansion chamber operated in a magnetic field. The sign of the charge of a meson arrested in the final absorber is deduced from the sense of its deflection in the magnetic field.

Preliminary reports have recently appeared (Alvarez 1950) of a determination of the life-time of $\mu^+$-particles produced artificially. When energetic protons or $\gamma$-rays fall on matter, $\pi^+$- and $\pi^-$-mesons are created (see §6(iv)) which can be arrested in neighbouring absorbers. The $\pi^+$-particles then decay to give $\mu^+$-particles which in turn produce decay electrons. The total time between the instant of formation of a $\pi^+$-particle and the arrest of the resulting $\mu^+$-particle is of the order of $10^{-8}$ second, a period short compared with the life-time of the $\mu$-particles. Advantage can therefore be taken of the characteristics of the synchrocyclotron of producing short pulses of protons, detecting the decay electrons with scintillation counters. A pulse leads to the sudden creation of a large number of $\pi^+$-particles, and the distribution in the times of delay in the emission of the decay electrons arising from the $\mu$-mesons is determined. It is thus possible to make observations of great statistical weight, and it appears probable that the method will yield very accurate values for the life-time of the $\mu$-mesons. A characteristic example of the observed distribution of the delay times obtained by this method is shown in Figure 19; see also Steinberger et al. (1950).
The important bearing which the study of the behaviour of $\mu^-$-particles, when stopped in materials of different atomic number, has had on the historical development of our knowledge of mesons has already been stressed in an earlier paragraph. In materials of low atomic number the process of spontaneous decay predominates, and the delayed coincidence experiments indicate that the life-time of the particles is $2.15 \times 10^{-6}$ sec., whereas in heavy elements no delayed coincidences are observed. These effects were attributed to nuclear capture, and there is now decisive evidence that this explanation is correct. No decay electrons are observed, for example, from $\mu^-$-particles stopped in silver bromide. At the time of the first observations, however, an alternative possibility was not excluded: that the absence of delayed coincidences was to be attributed to an acceleration of the rate of decay of the meson in the strong field of the nucleus (Valley 1945). In this case the $\mu$-particles would emit electrons, but with delay times less than those characteristic of a mean life of the order of 2 $\mu$sec. With the resolving time of the counters then available, such electrons would appear in coincidence with the meson, i.e. without detectable delays. In these circumstances the assumption of an accelerated decay was eliminated by ingenious experiments of Ticho and Schein (1948) and Valley and Rossi (1948) on the behaviour of $\mu^-$-particles arrested in

![Figure 19. Observations on the delay in the instants of decay of artificially produced $\mu^-$-particles (Alvarez et al. (1950)).](image-url)
Four examples of the successive decay \( \pi \rightarrow \mu \rightarrow e \). The photo-micrographs display the increase in the grain-density of the tracks of the \( \mu \)-mesons as the particles approach the end of their range. The sparseness of the grains in the tracks of the electrons may be clearly seen.

**Plate I.**
Mosaics of photo-micrographs of the disintegrations of the nuclei of the light elements in the emulsion, carbon, oxygen or nitrogen, following the capture of a $\pi^-$-particle; see Menon et al. (1950).

Plate II.
Disintegrations of heavy elements by the capture of \( \pi^- \)-particles.

Plate III.
Disintegration produced, at the point A, by a particle, track p, moving at relativistic velocities. Five fast 'shower' particles and a negative π-meson are ejected; the latter, of short range, comes to rest at the point B and produces a second disintegration. In addition, a single heavily ionizing particle is emitted of which the nature cannot be established. It was probable a proton.

Plate IV.
Mosaic of photo-micrographs of a nuclear explosion accompanied by the ejection of a \( \pi^+ \)-particle. The track of the \( \pi^+ \)-particle is given in two parts which should join at the point 'a'. The \( \pi^+ \)-particle shows the transmutation \( \pi \rightarrow \mu \rightarrow e \).

Plate V.
Characteristic 'double-star'. One of the 'shower' particles emerging from a nuclear explosion produces a second disintegration.

Plate VI.
A fast particle, track p, makes a nuclear collision at the point A, as a result of which seven 'shower' particles are produced. No. 3 of the shower particles produces a second 'shower' at the point B. The event at point A may be due to a proton–proton collision.

Plate VII.
An α-particle of great energy, of which the track enters the field-of-view, top left, interacts with a nucleus and produces thirty-five shower particles, most of which are in the main 'jet'.

Plate VIII.
A nucleus of aluminium \((Z = 13 \pm 1)\), makes a nuclear collision from which a jet of six \(\alpha\)-particles emerges with nearly equal velocities. They must be attributed to the disintegration of the original nucleus.

Plate IX.
Plates X and XI. Successive overlapping sections in the track of an iron nucleus \((Z = 26 \ldots 2)\) which between sections seven and eight is due to the particle crossing an air-gap between two and other features associated with the capture
enters the emulsion, top left, and reaches the end of its range, bottom right. The break in the track of electrons by the nucleus, a well displayed.

The decrease in the range of the $\delta$-rays as the velocity of the particle is reduced,
A sulphur nucleus \((Z=16 \pm 1)\) collides with one of silver or bromide in the emulsion. As a result of the encounter a fluorine nucleus and twenty-five 'shower' particles—protons and \(\pi\)-mesons—emerge.

**Plate XII.**
materials of intermediate atomic number. The experiments depended on the following considerations:—

If the disappearance of \( \mu^- \)-particles in materials of high atomic number is due to nuclear capture, there must be a rapid variation of the speed of the process with the value of \( Z \), for while it is dominant for iron \((Z = 26)\), for carbon it is negligible in comparison with spontaneous decay. It was therefore anticipated that for materials with some intermediate value of the atomic number, the two competing processes would be of approximately equal importance. This would have the result that, first, the average life-time of the particles should be reduced in comparison with that observed in light elements; and second, that the proportion of mesons producing electrons would be reduced as the result of the removal of some of the particles by nuclear capture. On the other hand, if

the effects were due to an acceleration of the decay, whilst the effect on the life-time would be indistinguishable from that expected on the alternative hypotheses, the proportion of mesons observed to produce decay electrons should be the same as that observed in light elements.

A typical result showing the variation of the number of electrons as a function of the time of delay for mesons stopped in \((a)\) sodium fluoride and \((b)\) aluminium is shown in Figure 20. It will be seen that the life-time in the heavy material is approximately half that of the positive particles, and that the number of electrons emitted per unit time, for zero time of delay, is also reduced.

Values of the life-time of \( \mu^- \)-particles stopped in various materials of different atomic number are summarized in Table 2. In addition to the values of the life-time \( \tau^- \), the Table gives the ratio, \( \tau^-/\tau^+ \), of this quantity to that for the positive
particles, and the fraction $f$ of the negative mesons which decay with the emission of an electron. $1 - f$ therefore represents that fraction of the negative $\mu$-mesons which interact with nuclei.

These results establish the fact that the $\mu^-$-particles stopped in solid materials are in general removed by two competing processes, and the number of particles removed from an original sample in time $\delta t$ can be written

$$\delta N = -(k_0 + k_0)N\delta t,$$

$N$ being the number of surviving particles, and $k_0$ and $k_0$ 'decay constants' corresponding to nuclear absorption and spontaneous decay, respectively. It follows that

$$f = \frac{k_0}{k_0 + k_0} = \frac{\tau_0}{\tau_f},$$

where $\tau_0$ is the apparent life-time due to both competing processes and $\tau_f$ is the life-time of the free particles. It has been shown by Wheeler (1947, 1949) that theoretical considerations indicate that $k_0$ should vary as $Z^4$, where $Z$ is the atomic number of the absorbing material. Although the experimental results are in reasonable agreement with this prediction, the statistical weight of the observations is not sufficiently great to provide a detailed verification of the relationship.

Table 2. Mean Life-time (in micro-seconds) of $\mu^-$-Particles arrested in Solid Materials of different Atomic Numbers (after Rossi)

<table>
<thead>
<tr>
<th>Substance</th>
<th>$Z$</th>
<th>Life-time ($\tau^-$)</th>
<th>$\tau^+ / \tau^-$</th>
<th>$f$</th>
<th>Author</th>
</tr>
</thead>
<tbody>
<tr>
<td>O</td>
<td>8</td>
<td>$1.89 \pm 0.15$</td>
<td>$0.87 \pm 0.08$</td>
<td>$0.83 \pm 0.08$</td>
<td>Ticho</td>
</tr>
<tr>
<td>NaF</td>
<td>9, 11</td>
<td>$1.23 \pm 0.12$</td>
<td>$0.57 \pm 0.06$</td>
<td>$0.60 \pm 0.065$</td>
<td>Ticho and Schein</td>
</tr>
<tr>
<td>Mg</td>
<td>12</td>
<td>$0.96 \pm 0.06$</td>
<td>$0.45 \pm 0.04$</td>
<td>$0.52 \pm 0.04$</td>
<td>Ticho</td>
</tr>
<tr>
<td>Mg</td>
<td>12</td>
<td>$1.1 \pm 0.2$</td>
<td></td>
<td></td>
<td>Valley</td>
</tr>
<tr>
<td>Al</td>
<td>13</td>
<td>$0.75 \pm 0.07$</td>
<td>$0.35 \pm 0.04$</td>
<td>$0.40 \pm 0.04$</td>
<td>Ticho</td>
</tr>
<tr>
<td>Al</td>
<td>13</td>
<td>$0.70 \pm 0.06$</td>
<td>$0.35 \pm 0.035$</td>
<td>$0.47 \pm 0.05$</td>
<td>Valley</td>
</tr>
<tr>
<td>S</td>
<td>16</td>
<td>$0.54 \pm 0.12$</td>
<td>$0.25 \pm 0.03$</td>
<td>$0.27 \pm 0.03$</td>
<td>Ticho</td>
</tr>
</tbody>
</table>

It remains to consider the nature of the transmutations produced by the capture of $\mu^-$-mesons by the heavier nuclei. The evidence is now very strong that the process of capture is never, or very rarely, accompanied by the emission of charged particles. Several observers have recorded the tracks of $\mu$-particles which are brought to rest in thin plates of heavy metals within Wilson chambers (Wang and Jones 1948, Chang 1949). In no case has a charged particle which could be identified unambiguously as a proton been observed. Further, the evidence obtained in experiments with photographic plates indicates that none, or very few, of the $\mu^-$-particles arrested in silver bromide produce stars (Camerini et al. 1948, Franzinetti 1950). It is therefore concluded that the disappearance of the rest-mass of the $\mu$-meson results in the emission of neutral radiations.

Counter experiments by Piccioni (1948) provide convincing evidence that the nuclear absorption of the $\mu^-$-particle does not lead to the emission of photons. On
the other hand, it has been shown by Sard et al. (1948, 1949) that the process does lead to the production of neutrons. These authors find about one neutron for the nuclear absorption of every \( \mu^- \)-meson. The simplest explanation of these results is that in the process of nuclear capture the meson interacts with one of the protons to produce a neutron and a neutrino in accordance with the equation

\[
P + \mu^- \rightarrow N + \nu.
\]

General theoretical considerations suggest that in such a process most of the energy will be carried off by the lighter of the two particles, so that the energy of recoil of the neutron will be small. It follows that even in those cases in which the neutron collides with other nucleons, the excitation energy of the nucleus is commonly insufficient to lead to the ‘evaporation’ of charged nucleons and the production of a detectable nuclear explosion (see Tiomno et al. 1949 and Chang 1949).

For a more detailed discussion of these considerations see Rossi (1948).

§6. ARTIFICIAL PRODUCTION OF MESONS

The first observations of the artificial production of mesons were made early in 1948 by Gardner and Lattes by means of the beam of fast \( \alpha \)-particles generated by the 384 in. synchro-cyclotron at Berkeley, California. In the past two years, important progress in the detailed study of the properties of the particles has been made, a study which has recently been extended to include the generation of the \( \pi^- \)-mesons by fast protons and energetic \( \gamma \)-rays. In addition to providing the favourable conditions for the determination of the mass and life-time of the \( \pi^- \)-particles by the methods already discussed, these experiments give detailed information about the production of mesons by particles of relatively low energies, near the ‘threshold’ for \( \pi^- \)-meson production, where only a small fraction of the nuclear disintegrations are accompanied by the emission of mesons. It will therefore be convenient to consider the results obtained in these experiments before those derived from a study of the cosmic radiation.

6(i). Excitation Curve for the Production of Mesons

The apparatus of the type shown schematically in Figure 5(a) has been employed by Jones and White (1948) to determine the excitation-curve and the distribution in energy of the \( \pi^- \)-particles produced by fast \( \alpha \)-particles. The relative probability of producing \( \pi^- \)-particles, as a function of the energy of the primary \( \alpha \)-particles, was determined by making exposures with the apparatus placed at different distances from the centre of the vacuum chamber of the cyclotron. In standard conditions of operation, the energy of the particles generated by the machine varies approximately as the square of the radius of the orbit, and by a suitable location of the target, particles of any desired energy can be chosen for experiment.

For each value of the \( \alpha \)-particle energy, the number of mesons with kinetic energy in the interval from 2 to 10 MeV., emitted from the target in a direction within 45° of that of the primary particles, was determined by observations on the number of tracks per unit area of the plates recorded in an exposure of standard duration. The results are shown in Figure 21, curve (b). Results of similar
Figure 21. The variation in the yield of $\pi^-$-mesons as a function of the energy of the generating particles: Curve (a) protons, curve (b) $\alpha$-particles.

Figure 22. Distribution in energy of the mesons produced artificially by fast protons.

Figure 23. Apparatus of Richman and Wilcox for studying the generation of mesons by a beam of 345 MeV. protons emerging from the vacuum tank of the synchro-cyclotron.
experiments on the generation of mesons by fast protons, obtained by the same authors are shown in curve (a).

The cross section, per carbon nucleus, for the production of mesons of energy from 2 to 5 MeV by 390-MeV \( \pi^- \)-particles has been measured by V. Peterson who has obtained an approximate value of \( 3.0 \times 10^{-32} \) cm\(^2\) per unit solid angle per MeV.

6 (ii). Energy Spectrum of the Mesons

The distribution in energy of the \( \pi^- \)-particles generated by 390-MeV \( \pi^- \)-particles has also been determined by Jones and White by means of apparatus similar in principle to that illustrated in Figure 5 (a), but in which the mesons in an extended range of values of \( H_\rho \) can be simultaneously recorded. The 'energy spectrum' of the mesons ejected in directions inclined at less than 30° to that of the \( \pi^- \)-particle beam can thus be determined.

Preliminary results have recently been obtained by Richman and Wilcox (1949) for the energy spectrum of the mesons produced by 345-MeV protons. The apparatus employed is shown schematically in Figure 23. In these experiments the energy of the mesons has been deduced from the thickness of the absorber which they must have traversed in order to reach the particular photographic emulsion in which they were arrested. The observations shown in Figure 22 display a distribution in energy similar in form to that observed for the \( \pi^- \)-particles created by protons of great energy in the cosmic radiation: see §7 (iii). The results have not been corrected to take account of the nuclear collisions of the \( \pi^- \)-particles in the absorbing material: see §7 (v).

Cartwright et al. (1950) have recently described experiments on the positive and negative \( \pi^- \)-mesons emitted in the direction of the incident radiation as a result of the incidence of high-energy protons on targets of graphite and of a suitable hydrocarbon. By employing targets containing the same numbers of carbon atoms, the effects due to hydrogen nuclei alone can be determined. It has thus been found that the distribution in energy of \( \pi^- \)-mesons—resulting from the interaction of 345-MeV protons with protons, and emitted in the forward direction—shows a pronounced maximum at an energy of about 70 MeV. This value is near the maximum possible for the \( \pi^- \)-mesons as determined by the conservation laws. The authors direct attention to the possibility of extending their observations to include a detailed study of the distribution in energy of the \( \pi^- \)-particles in any direction from a target bombarded by protons or \( \pi^- \)-particles of known energy.

Reference has been made in §5 (iv) to the measurement of the lifetime of \( \mu^- \)-particles, arising from artificially produced \( \pi^+ \)-particles, in which advantage is taken of the short 'pulses' of protons which are delivered by the synchro-cyclotron. In the case of the \( \gamma \)-radiation generated by an electron synchrotron, the duration of the pulse cannot be made sufficiently short to allow a similar technique to be employed. In this case, however, it has been possible to employ crystal counters to detect the successive instants of occurrence of (a) the arrest of a \( \pi^+ \)-particle, (b) the emission of the \( \mu^+ \)-particle, if this is delayed by more than \( 3 \times 10^{-8} \) sec., and (c) the emission of the decay electron. Preliminary measurements by this powerful method by Kraushaar et al. (1950) give the value for the mean lifetime of the \( \pi^+ \)-particles \( \tau_{\pi^+} = 1.65 \pm 0.33 \times 10^{-8} \) sec.; and by Steinberger and Bishop (1950) for the decay of the \( \mu^- \)-mesons, \( \tau_{\mu^-} = 2.16 \times 10^{-8} \) sec.
6(iii). Ratio of the Numbers of $\pi^+$- and $\pi^-$-Particles

The direct observations of the production of $\pi$-mesons in photographic plates exposed to cosmic radiation, see §7(i), have shown that in the case of emitted particles of low energy, there is a large excess of negative over positive particles. This effect may be readily explained in terms of the Coulomb field of the parent nucleus in which the particles are created. If the energy spectra for the two types at their points of creation are similar, then, especially for particles of low energy, the nuclear charge will exert an important influence on the distributions actually observed, the positive particles being accelerated and the negative retarded by the Coulomb forces. Such effects should depend on the nuclear charge, and they have been studied by Barkas who has bombarded targets of elements of different atomic number by $\alpha$-particles of energy 390 Mev. The relative numbers of positive and negative particles, $\pi^-$ and $\pi^+$, produced by the bombardment of the different elements are shown in Figure 24.

For mesons of greater energy, $E>50$ Mev., the effects of the Coulomb field will be small. In the case of the bombardment of matter by protons, there should, however, be a disparity in the numbers of positive and negative $\pi$-particles created. Thus, suppose a nucleus to be composed of $N$ neutrons and $Z$ protons. An incident proton can react with a nuclear proton, either particle transforming to a neutron and leading to the creation of a positive meson: $P + P \rightarrow P + N + \pi^+$. On the other hand, if the primary proton interacts with a neutron, there are two possibilities for the production of charged mesons represented by the equations

$$P + N \rightarrow N + N + \pi^+,$$
$$P + N \rightarrow P + P + \pi^-.$$

If these two reactions are equally probable, the numbers of positive and negative mesons produced should be in the ratio $(2P + N)/N$. If the nuclei are of atomic weight $A$, charge $Z$, we may therefore write

$$\mathcal{N}(\pi^+)/\mathcal{N}(\pi^-) = (A + Z)/(A - Z). \quad \ldots \ldots \quad (10)$$
Experiments by Bradner and Jones (1950) indicate that the ratio of the numbers of positive to negative mesons of energy between 50 and 70 MeV, produced by the impact of 345-MeV protons in carbon, is approximately equal to five, instead of three as indicated by the formula (23).

6(iv). **Experiments with \( \gamma \)-Radiation**

Similar experiments to those with protons, but employing \( \gamma \)-radiation produced by the impact on matter of the electrons produced by a 335-MeV electron synchrotron, have been made by White, McMillan and Peterson (1950). The results obtained with the apparatus shown diagrammatically in Figure 25 indicate that the directions of emission of the \( \pi \)-particles are distributed isotropically. The. distribution in energy of the mesons created in carbon appears to be similar to that produced by fast protons, for it extends up to 150 MeV, and has a maximum at 35 MeV. The cross section for the creation of a meson is found to be \( 5 \times 10^{-28} \text{ cm}^2 \) per steradian per carbon nucleus. In the case of production of mesons by photons, the negative particles are more numerous than the positive:

\[
\frac{\mathcal{N}(\pi^-)}{\mathcal{N}(\pi^+)} = 1.7 \pm 0.2.
\]

The above results appear to have an important bearing on the theory of the meson, for it has been shown by Brueckner (1949) that the experimental curves for the distribution in angle and energy of the emitted mesons can be best accounted for in terms of a pseudo-scalar theory. In contrast with the observations, scalar theory predicts a strong anisotropy in the angular distribution. Further, a comparison of the theoretical predictions with the observations appears to exclude the possibility that the mesons have spin 1.

6(v). **Production of Mesons by Energetic Neutrons**

Beams of neutrons of high energy are produced when fast protons are incident on matter, as a result of charge exchange with the nucleons of the struck nuclei. Neutrons of energy approximately 270 MeV. are thus created by the 340-MeV. proton beam from the synchro-cyclotron, and they may be allowed to emerge from the concrete shielding round the machine through suitable channels. By allowing the neutrons to pass through photographic plates, disintegrations can be recorded. About one in ten thousand of the resultant 'stars' shows the creation of mesons of short range, a phenomenon frequently observed in plates exposed to the cosmic radiation—see Smith et al. (1950).
§ 7. CREATION OF $\pi$-MESONS BY COSMIC RADIATION

7 (i). Ejection of $\pi$-Particles of Relatively Low Energy during Nuclear Explosions

Shortly after the discovery of the $\pi$-mesons, nuclear explosions were observed in photographic plates which were accompanied by the emission of $\sigma$-mesons, particles which we have seen can now be identified as $\pi^-$-particles (Lattes et al. 1947 b). A photomicrograph of an event of this type, of which many hundreds of examples have now been observed, is shown in Plate IV.

The analogous process in which a $\pi^+$-particle is emitted which comes to rest in the emulsion is much rarer, and only few examples have been reported (Leprince-Ringuet 1949, Powell 1949). In the example, of which photomicrographs are shown in Plate V, a $\pi^+$-particle is emitted during the explosive disintegration of a nucleus. It reaches the end of its range and emits a $\mu$-meson which is also stopped in the emulsion, and which decays in turn to produce an electron.

The inequality between the observed numbers of 'ejected' $\pi^+$- and $\pi^-$-particles of low velocity can be explained as a consequence of the Coulomb field of the nucleus in which the particle is created. In the early experiments, an ejected meson could only be identified if it reached the end of its range in the emulsion, so that any secondary effects which it produced could be distinguished. The probability that a particle will be brought to rest in the emulsion decreases rapidly with its velocity of emission. Further, any positive particle will be repelled from the parent nucleus as a result of the Coulomb forces, and will therefore necessarily have an energy of at least a few MeV. On the other hand, negative particles must escape against an attractive force and may therefore emerge with low velocity. Effects of this type are accentuated by the rapid increase in the range of a particle with increase in its initial velocity, and as a result the probability of observing an event of this type shown in Plate V is very small.

No observations have been reported which indicate that slow $\mu$-particles can be created in nuclear interactions, and recent experiments by Piccioni (1950) and Fowler (1950), which are described in a later paragraph, make it almost certain that at least the majority of the mesons which are created in the form of 'showers' of fast penetrating particles are made up of $\pi$-particles. Both the mode of production of the $\pi$-mesons, and the features of the nuclear capture of the particles already discussed, are consistent with the view that they have a strong interaction with nucleons. In this respect, therefore, they are much more closely analogous to the Yukawa particles than the $\mu$-mesons which, we have seen, have a very weak interaction with nucleons.

Although the $\pi$-particles appear to emerge from nuclei as the primary products of the interactions between nucleons, it can be objected that there is no evidence from the cosmic-ray experiments that they do not arise as the products of decay of a very short-lived 'primary' particle of even greater mass—that the observed chain of processes $\pi$-$\mu$-$e$ represents only the last stages of a longer succession of spontaneous transmutations. It is difficult to exclude this possibility in all cases because, if the life-time of such a postulated particle were less than $10^{-14}$ sec., the distance it would travel before decaying would be less than a few microns. Even with the photographic method—which, for this particular purpose, has a more extended time scale than any other—the recognition of the independent existence of the parent particle would, in such circumstances, appear to be impossible. Although a final opinion is not yet possible, the observations of the artificial
production of $\pi$-particles at Berkeley make it almost certain that $\pi$-mesons can be created directly and singly in nuclear collisions. The evidence is based on the following considerations:

The original observation of the artificial generation of $\pi$-mesons was made with a beam of $\alpha$-particles of energy approximately 360 MeV. At a first glance it might be assumed that these particles would be essentially equivalent to four nucleons, each with an energy of about 90 MeV. In the collision of such a nucleon with a neutron or a proton, the principles of the conservation of momentum and mass-energy require that an energy of not more than 45 MeV shall disappear as a result of the creation of particles of finite rest-mass. It might therefore be anticipated that it would be impossible for the 360 MeV $\alpha$-particles to create new particles with a rest-mass greater than about 90$m_e$. Experiments showed, however, that $\pi$-particles were created by the bombardment of matter by $\alpha$-particles of even lower energy, the 'threshold' for the process occurring at about 300 MeV. (see Figure 21).

This apparent contradiction arises because no account is taken in such speculations of the internal motions of the nucleons composing the $\alpha$-particle and the nucleus with which it collides. If reasonable estimates of the magnitude of these internal velocities are made—and if it is assumed that meson production occurs in those most favourable cases in which the relative velocity of the interacting nucleons has the greatest possible value—it is found that the observed energy 'threshold' is in satisfactory agreement with that expected for the creation of a particle of mass $300m_e$ (McMillan and Teller 1947). It would, however, be difficult to explain the creation of particles of appreciably greater mass, particles which could be regarded as the parents of the $\pi$-particles. The results therefore strongly suggest that the $\pi$-particles can be created directly in nuclear interactions.

7(ii). Production of 'Showers' of Penetrating Particles

For many years, following the pioneer work of Wataghin et al. (1940), Jánossy (1941) and other workers, it has been known that 'showers' of penetrating particles are sometimes created in the atmosphere by cosmic radiation. Characteristic apparatus for detecting events of this type is shown in Figure 26. It detects the simultaneous discharge of a number of independent Geiger counters, so arranged in massive lead blocks that the phenomenon cannot be due to cascade 'showers' of electrons and photons.

Observations with the expansion chamber, made by Fretter and others, appear to provide evidence of the mode of origin of these penetrating showers. Charged particles are observed which are able to penetrate several centimetres of lead. These particles sometimes interact with nuclei in one of the lead blocks, and from it groups of particles emerge which, since they are able to penetrate lead plates without producing cascade showers, cannot be electrons. It has commonly been assumed that these events correspond to the interaction of fast nucleons with nuclei, leading to the production of many mesons. The observed processes are reminiscent of those visualized by Heisenberg, Heitler and Jánossy, Oppenheimer and others in their theories of meson production.

Until recently, three important features of the phenomena have remained obscure. First, the nature of the shower particles has not been established, although it has been suggested that they are composed of a mixture of protons and mesons, the protons being projected with great energy in collisions with the primary particle
and the mesons being generated in nucleon–nucleon collisions during the penetration of the nucleus by the incident particle. Secondly, many mesons are often created in a nuclear interaction, and it has not been clear whether all, or many of them, commonly arise as a result of a single nucleon–nucleon collision, or, alternatively, whether they are usually produced singly in a succession of collisions of the primary particle with the nucleons lying near its line of motion in the traversal of a nucleus.

The first of these alternative theories of the origin of the 'showers' of penetrating particles is referred to as 'multiple production', and has been advocated by Heisenberg (1949) and Lewis et al. (1948). It is visualized that in a close collision between two nucleons a large fraction of the total energy available in the encounter may be emitted in the form of radiation as heavy 'quanta'—the limit to their number being imposed only by the requirements of the conservation laws of mass-energy and of momentum. On the other hand, Heitler and Jánossy (1949)—while not regarding the possibility as excluded that multiple production can sometimes occur—consider that the dominant process is that of 'plural' production—the creation, that is, of mesons singly in a succession of encounters of the primary nucleon in passing through the nucleus.

A third feature observed in connection with the penetrating showers is that they are frequently observed to be accompanied by soft radiation—by electrons and photons which 'multiply' in traversing the lead plates of the apparatus and produce characteristic showers of 'soft' radiation. Until recently it has not been clear whether this soft radiation is also created in the nuclear encounter, together with the penetrating particles, or whether it is of secondary origin.

The weight of the attack on these problems has recently been greatly increased by the observation of phenomena of the same type in 'electron-sensitive' photographic emulsions (Brown et al. 1949). Characteristic photo-micrographs of events of this type are reproduced in Plates VI, VII and VIII. It is an important

![Figure 26. Apparatus of (a) Wataghin and (b) Jánossy for the observation of showers of penetrating particles.](image)
feature of the new observations that the 'shower' particles are observed at their points of creation, and that secondary processes associated with their production, such as the subsequent 'evaporation' of the nucleus, the ejection of protons and $\alpha$-particles of relatively low energy, can also be observed.

7 (iii). Nature of the Shower Particles

The first definite evidence on the nature of the shower particles was obtained in experiments of great ingenuity carried out by Piccioni (1950) using apparatus shown diagrammatically in Figure 27. There are three trays of counters separated by lead blocks, A, B and C, and the third tray can be surrounded by additional blocks, D and E, which can be either of carbon or of sulphur. The method takes advantage of the difference in the behaviour of $\mu^-$ and $\pi^-$-particles arrested in light and heavy elements. Thus while $\pi^-$-particles interact with nuclei when stopped in either carbon or sulphur, the $\mu^-$-particles are absorbed by nuclei only in the heavier element; in carbon they decay with the emission of an electron ($\S$ 5 (v)).

Piccioni showed that when single penetrating particles traverse the apparatus and are stopped in D or E, delayed coincidences due to the discharge of a counter in tray (3) can be observed. The ratio of the number of such events observed per unit time in the case of the sulphur and carbon absorbers, $N_C/N_S 1.8$. This result is in good accord with that to be expected for $\mu$-particles; the electrons are produced by the arrest of both positive and negative particles in the case of carbon, and of positive particles only in the case of sulphur. The result is a little different from 2 because of a well-known excess of positive particles among the $\mu$-mesons of the penetrating component.

In contrast with the effects due to isolated penetrating particles, nuclear explosions occurring in the lead block A which are accompanied by the emission of shower particles can result in the discharge of two or more of the counters in tray A. It was found further that coincidences of two such counters with one or

Figure 27. Apparatus of Piccioni for the identification of 'shower' particles.
more in B are almost all due to such locally produced showers. In the case of
these events, the delayed coincidences in the absorber C were found to occur with
almost equal frequency whether D and E were of graphite or of sulphur. This is
consistent with the assumption that the locally produced mesons are all \( \pi \)-particles,
for in this case, both in light and heavy elements, only the positive particles will
transform to give \( \mu \)-particles and then decay electrons; and the results are inconsis-
tent with the assumption that more than a small fraction of the locally produced
mesons are \( \mu \)-particles.

Whilst Piccioni's experiment provided very strong evidence for the production
of \( \pi \)-mesons in nuclear explosions, it gave no indication of their frequency of
occurrence among the shower particles, or of their distribution in energy. Most
of the particles of the 'penetrating showers' are ejected with velocities in the
relativistic region, and it is well known that this renders difficult the determination
of their rest-mass. Certain conclusions can, however, be drawn from the
simultaneous observation of the curvature of the trajectory of a particle in a Wilson
chamber operated in a magnetic field—which gives a measure of its momentum—and
of its specific ionization as determined by 'drop-counts'. Such experiments
are difficult to make with precision—see §3 (v)—and they have recently been
supplemented by experiments with photographic plates, determining the momentum
of the particles by observations on the deviations in the tracks due to multiple
Coulomb scattering (Camerini et al. 1949, Occhialini 1949, Goldschmidt-Clermont
1950). The scope of the method has been greatly extended by the development
of a very simple and rapid method of measuring the scattering (Fowler 1950).

A typical result obtained by Fowler is shown in Figure 10, in which the grain-
density for each track is plotted against the scattering parameter, \( z \), the average
deviation per unit length. The tracks on which measurements were made were
chosen only because their lengths were greater than 3 mm., and irrespective of
their relation to the 'stars' with which they were associated. Some of the tracks
were therefore due to primary particles which produced nuclear explosions, but
these occur rarely compared with those of secondary particles.

The results shown in Figure 10 show that a large proportion of the particles
which produce tracks with a grain-density near the minimum value are less massive
than the proton. Further, the average value of the mass of those of the mesons
with a specific ionization greater than the minimum value—as deduced from the
displacement of the points from the corresponding curve due to protons—is
283 \( \pm 7 \) \( m_e \) (see Figure 11). They may therefore be identified as \( \pi \)-particles. The
observations prove that if any \( \mu \)-mesons or electrons are emitted from the nuclear
explosions with an energy less than 150 MeV., they are fewer than 2% of the
\( \pi \)-mesons with energies in the same range; and the observations strongly suggest
that, apart from ejected nucleons, \( \pi \)-particles form the great majority of the charged
particles directly produced in nuclear reactions.

It has been known for many years (Blackett and Wilson 1938) that most of the
electrons of the soft component at sea level have energies less than 200 MeV. The
results of the new experiments therefore suggest that most of the electrons do not
arise as a direct result of nuclear interactions, but are of secondary origin. From
these experiments alone the possibility is not excluded that \( \gamma \)-radiation is created
in the nuclear interactions, and this could also lead to the production of cascade
showers. We shall see in a later paragraph, however, that the soft radiation
accompanying the penetrating showers can be accounted for in other ways—by assuming that it arises from \( \gamma \)-radiation formed by the decay of neutral mesons which are created together with the showers of charged \( \pi \)-mesons in nuclear interactions.

7 (iv). Distribution in Energy of the Mesons of the Penetrating Showers

The methods described in the preceding paragraph can be employed to determine the distribution in energy of the mesons created in the disintegrations produced by cosmic-ray particles of great energy. Results thus obtained by Camerini et al. are shown in Figure 28. These results may be compared with the distribution in energy of the mesons of the penetrating component of the cosmic radiation. From observations of the intensity of slow \( \mu \)-mesons at different depths in the atmosphere, and the energy distribution of the particles at sea level, Sands (1950) has computed the distribution in energy of the particles at their points of production. If it is assumed that the \( \mu \)-mesons arise by the decay in flight of \( \pi \)-mesons, Sands' results can be transformed to correspond to the energy distribution of the parent \( \pi \)-particles at their points of creation, the corresponding curve is found to be in good agreement with the distribution shown in Figure 28. This result gives strong support for the view that the \( \mu \)-mesons of the penetrating component arise by the decay in flight of the \( \pi \)-mesons forming in nuclear explosions occurring in the atmosphere.

In favourable cases the energy of the primary particles producing nuclear explosions in photographic emulsions can also be measured. By a statistical study of a large number of events it is then possible to determine the average energy of the primary particles which produce disintegrations in which different numbers \( n_s \) of fast 'shower' particles are created. Further, a comparison can be made between the average energy \( \bar{E}_p \) of the primary particles producing showers of a given multiplicity \( n_s \), the total energy represented by the emitted mesons, \( n_s \bar{E}_m \), and that of the ejected nucleons and \( \alpha \)-particles forming the 'star'.

Figure 28. Distribution in energy of the mesons among the shower particles observed at an altitude of 70,000 ft.
The results of a preliminary study of this type by Camerini et al. are represented in Figure 29. The results indicate (a) that the average energy of the mesons changes very little with the multiplicity \( n_s \), the greater the energy of the 'primary' particle, the greater the number of mesons of approximately the same kinetic energy that are produced, and (b) that a fraction of the energy of the primary particles is unaccounted for. It is believed that this missing energy contributes to the creation of neutral mesons which commonly escape observation (see § 8).

![Figure 29. Energy balance in stars of different multiplicity: \( \bar{E}_p \) is the mean energy of the primary protons, \( n_s \bar{E}_s \), the average value of the total energy (\( mc^2 \)) of the shower particles and \( \bar{E}(N_h) \) the mean energy represented by the star. It will be seen that some energy is missing, and it is suggested that this may be due to the creation of neutral mesons.](image)

7 (v). **Nuclear Interactions of the Shower Particles**

A problem which has had an important bearing on the nature of the shower particles is the frequency with which they make nuclear collisions in passing through matter. The \( \mu \)-mesons are able to penetrate to great depths underground because they interact with nuclei very rarely. If, therefore, the argument runs, many of the particles emitted in 'showers' are \( \mu \)-mesons, the average length of path before making a nuclear collision should be much greater than the value calculated on the assumption that the particles interact with every nucleus through which they pass, the cross section for collision then being given, approximately, by the geometrical values: \( \sigma = A^{2/3} \times 6.8 \times 10^{-26} \text{cm}^2 \). On the other hand, if the shower particles, near their points of production, are \( \pi \)-particles, the average path-length for nuclear collision should not be widely different from the value deduced from a 'geometrical' cross section.

About 80% of the shower particles are now known to be \( \pi \)-mesons. The significance of the observations of the average path length has therefore changed, and it now bears on the important question of the strength of the interaction of \( \pi \)-mesons with nucleons. Examples of the secondary nuclear interactions of 'shower' particles, as observed in photographic emulsions, are shown in the photomicrographs reproduced in Plates VI and VII.

Determinations of the average path length of the shower particles have been made in a number of experiments with widely differing results. The method most commonly adopted has been to observe the creation of the shower particles
as a result of nuclear explosions occurring in lead plates within Wilson chambers. The shower particles subsequently traverse other lead plates within the chamber, and estimates are made of the fraction of the particles which fail to emerge from these subsequent absorbers as a result of nuclear interactions. The results obtained by a number of experimenters with this method are included in Table 3. In order to be able to compare the results of different experiments employing different absorbers, the Table includes the ratio of the observed 'mean free path' to the value calculated on the assumption that the nuclei of the absorber present a cross section for interaction equal to the geometrical value.

Table 3

<table>
<thead>
<tr>
<th>Authors</th>
<th>Method</th>
<th>Result</th>
<th>Observed M.F.P. Geom. value</th>
<th>Energy range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Piccioni (1950)</td>
<td>Counters at mountain altitudes</td>
<td>1200 gm.cm⁻² Fe</td>
<td>14-0</td>
<td>&gt;400 MeV.</td>
</tr>
<tr>
<td>Fretter (1949)</td>
<td>Cloud chamber with Pb plates</td>
<td>750 gm.cm⁻² Pb</td>
<td>4-7</td>
<td>&gt;150 MeV.</td>
</tr>
<tr>
<td></td>
<td>Uncorrected</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lovati, Mura, Salvini and Tagliaferri (1949)</td>
<td>Cloud chamber with Pb plates</td>
<td>300±100 gm.cm⁻² Pb</td>
<td>1-9</td>
<td>&gt;150 MeV.</td>
</tr>
<tr>
<td></td>
<td>at mountain altitudes</td>
<td>Corrected</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brown and McKay (1950)</td>
<td>Cloud chamber with Pb plates</td>
<td>316±70 gm.cm⁻² Pb</td>
<td>2-0</td>
<td>&gt;150 MeV.</td>
</tr>
<tr>
<td></td>
<td>at mountain altitudes</td>
<td>Corrected</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Butler, Rosser and Barker (1950)</td>
<td>Cloud chamber with Pb plates</td>
<td>400 gm.cm⁻² Pb</td>
<td>2-5</td>
<td>Average</td>
</tr>
<tr>
<td></td>
<td>at sea level</td>
<td>Uncorrected</td>
<td>2-5</td>
<td>energy of shower</td>
</tr>
<tr>
<td></td>
<td></td>
<td>200 gm.cm⁻² Pb</td>
<td>1-4</td>
<td>~7000 MeV.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Corrected</td>
<td></td>
<td>&gt;100 MeV.</td>
</tr>
<tr>
<td>Harding and Perkins (1949)</td>
<td>Photographic plates exposed under ice</td>
<td>120 gm.cm⁻² Ice</td>
<td>2-0</td>
<td>&gt;150 MeV.</td>
</tr>
<tr>
<td>Camerini, Fowler, Lock and Muirhead (1950)</td>
<td>Electron-sensitive plates exposed at high altitudes</td>
<td>100 gm.cm⁻² emulsion</td>
<td>1-1</td>
<td></td>
</tr>
</tbody>
</table>

Observations with photographic plates which have led to values for the mean free path substantially smaller than that obtained with Wilson chambers have been described recently by Camerini et al. (1950). These experiments indicate that the average path length, both for fast protons and for π-mesons, is close to the 'geometrical' value. These authors show that the π-mesons commonly produce small 'stars', and they suggest that the experiments with Wilson chambers are complicated by the fact that the particles emitted as a result of the secondary interactions occurring within the lead plates will often not emerge from the lead. In such cases the secondary interactions will escape observation, so that an over-estimate of the average path-length between collisions will result.
Whilst final values for the cross section for the collision of \( \pi \)-mesons with nuclei are not yet available, the evidence suggests that they have a high probability of interacting with every nucleus which they penetrate. This question is of great importance for a detailed study of the processes leading to the production of the 'showers'. Especially in heavy nuclei, secondary interactions within the parent nucleus of mesons produced in nucleon–nucleon collisions may play an important role.

7 (vi). Multiplicity of Production of Mesons

Reference has already been made to the problem of the multiplicity of production of mesons in nucleon–nucleon collisions. The question is of decisive importance, and in the discussions on the subject which took place at the International Conference at Como in September 1949 it was generally agreed that a decisive experiment would consist in observing the generation of many mesons in the interaction of a proton or neutron of great energy with a hydrogen nucleus.

Suppose a fast proton interacts with second proton at rest. In the absence of the production of charged mesons, the collision will lead to the projection of the struck proton, so that the collision will give rise to a forked track. If, alternatively, production of charged mesons occurs, the particle must be produced in pairs in order to provide for the conservation of charge, so that the number of secondary particles will be two, four, six, etc. This conclusion is not altered if charge exchange occurs so that one or both of the original protons involved in the collision emerge as neutrons. The total charge carried by the particles involved in the collision, including that of the original fast particle, must therefore be odd. The same result is obtained if a fast neutron is assumed to collide with a proton, for in this case the total number of secondary particles is odd and the primary particle produces no track.

Events of the type discussed in the previous paragraph if they occur in photographic emulsions could be expected to produce 'stars' in which all, or nearly all the tracks have a grain-density equal to the minimum value for fast particles of charge \( |e| \). They would therefore commonly escape observation except in the examination of the plates under high magnification. Following the Como discussions, several observers directed their attention to making such a search, and already a number of examples have been found which appear to correspond to the expected process.

In a private communication, Professor Heisenberg informs me that he and his colleagues have found an event in which a fast particle produces a star from which the tracks of six particles diverge. Five of these tracks are of minimum grain-density, and the sixth is that of a slow \( \pi^- \)-particle. These features are consistent with the assumption that the event corresponds to a proton–proton collision in which four \( \pi \)-mesons are created. A similar event is shown in Plate IV, in which, in addition to the \( \pi \)-particle which produces a disintegration, five fast particles and a single heavily ionizing particle are produced. In another event observed in Bristol, the star is made up of a total of eight tracks, one primary and seven secondary all of which are of minimum ionization. In this case, the event cannot be finally identified because the total number of tracks is even, but it is reasonable to assume that a ninth track is associated with the star which cannot be distinguished because of an unfavourable direction of motion of the particle. It is known that steeply dipping tracks are sometimes difficult to detect.
Further observations, which appear to be very difficult to explain in terms of pure plural production, have been made on the interaction with nuclei of $\alpha$-particles of great energy. Thus Bradt, Kaplan and Peters (1950) have observed such a collision in photographic plates exposed at altitudes of the order of 90,000 feet by means of free balloons. The $\alpha$-particle produces a nuclear explosion which is accompanied by the creation of a narrow 'jet' of about 23 fast particles most of which we may assume to be $\pi$-mesons. A similar event in which an $\alpha$-particle produces 35 fast particles is shown in Plate VIII. It will be seen that in this case only three heavily ionizing particles are emitted. The evidence given in a later section strongly suggests that the charged mesons produced in these events are accompanied by neutral mesons in considerable numbers. It appears to be very improbable that a process of pure plural production could lead to the production of about 40 mesons in a nuclear collision, and that only three protons should emerge from the encounter. Further, it seems probable, to judge from the preliminary evidence which has been accumulated up to the present, that the $\alpha$-particles of great energy have an appreciable probability of producing effects of the type shown in Plate VIII, and that the ejection of only a relatively few charged nucleons is not usual. It appears therefore that the event is not exceptionally rare and that it does not display unusual features.

The evidence at present at our disposal appears to indicate that multiple production of $\pi$-mesons in individual nucleon–nucleon collision does occur; but the relative importance of single and multiple production in the creation of shower particles and the detailed understanding of the process occurring within the nucleus remain to be elucidated. For this purpose the determination of the mean path length of $\pi$-particles between nuclear collisions is insufficient. It allows only an upper limit to be given for the range of the forces between a $\alpha$-particle and a single nucleon, and it is the magnitude of this quantity which is decisive.

7(vii). Production of 'Showers' at great Depths Underground

Recent experiments by George have shown that nuclear explosions accompanied by the emission of 'showers' of particles moving at relativistic velocities occur at considerable depths underground. The 'electron-sensitive' emulsions were prepared 30 m underground, exposed for some time at the same depth, and processed. In this way the possibility that the phenomena are due to pre-exposures at sea level is completely excluded.

The plates prepared in this way record about $10^{-2}$ nuclear disintegrations per cm$^2$ per diem, and of these about one-fifth are accompanied by the emission of showers. In about a quarter of the events the track of a fast particle of charge $e$ which produced the disintegration can be distinguished. The nature of the shower particles remains to be established, but the events appear to be closely similar to those observed at high altitudes, and it is reasonable to suppose, tentatively, that the shower particles are $\pi$-mesons.

It is very difficult to account for those disintegrations in terms of their production by energetic protons or $\pi$-particles which have penetrated underground without being absorbed as a result of nuclear interactions. On the other hand, at these depths, there is a flux of $\mu$-mesons of considerable intensity. Further, recent experiments at Berkeley have shown that electromagnetic radiation can interact with nuclei to produce mesons. It is therefore reasonable to suggest that the
'showers' are due to the electromagnetic interaction of fast $\mu$-mesons with nuclei. From the known flux of these particles and the rate of production of showers, the cross section for the process is found to be of the order of $10^{-29}$ cm$^2$. Many of the stars observed at the same depth, but unaccompanied by 'showers', may be attributed to $\pi$-mesons and fast nucleons arising as secondary particles from the 'showers' (George and Evans 1950).

§ 8. NEUTRAL MESONS

8 (i). Transmutation of Neutral Particles into Quanta

In the first section of the present report it was pointed out that if the basic features of Yukawa's theory are correct, the approximate equality of the forces between like and unlike nucleons appears to require the assumption of the existence of neutral as well as of charged mesons. Recent observations by Bjorkland et al. (1950) strongly suggest that such neutral particles, of rest-mass approximately $300m_0$, are created in energetic nuclear collisions, that they are of short lifetime, less than $10^{-11}$ sec., and transform into two $\gamma$-rays. Before considering the details of the experimental results, it will be convenient to establish the principal characteristics of the radiation to be expected from such a mode of decay of a material particle.

If a neutral meson, moving with a given velocity, suffers decay into two photons, the energy of the quanta will depend on their directions of emission relative to the line of motion of the parent particle. The problem is precisely analogous to the emission of radiation by a moving source; the wavelengths and intensity distributions are governed by the well-known Doppler principles. Let $m_0$ be the rest-mass of the particle, and $\beta c$ its velocity; its momentum is then $m\beta c$, where $m = m_0\sqrt{1 - \beta^2}$. Further, suppose that $h\nu_1$ and $h\nu_2$ are the energies of the two quanta, and that they are emitted in directions making angles $\theta$ and $\phi$ with respect to the line of motion of the neutral meson. The vector sum of the momenta of the two quanta, $h\nu_1/c$ and $h\nu_2/c$ (see Figure 30), must equal the momentum of the parent particle $m\beta c$; $AB + BC = AC$. By the conservation of energy, however, $h\nu_1 + h\nu_2 = m_0c^2/\sqrt{1 - \beta^2} = Bm_0c^2 = \text{constant}$. It follows
Mesons

that $AB + BC$ is a constant, and the locus of $B$ is an ellipse. It is easily shown that the energy of the quantum emitted at an angle $\theta$ is given by the relation

$$h\nu = \frac{m_0c^2}{2B(1 - \beta \cos \theta)}.$$  

Curves showing the calculated distributions of the photon energy for different directions of emission, and for different values of the total energy of the neutral mesons, $Bm_0c^2$, are shown in Figure 31 (b), the rest-energy of the meson, $m_0c^2$, being taken as 140 MeV.

![Energy distribution of photons from a monokinetic beam of neutral mesons.](image)

**Figure 31.**

Energy distribution of photons from a monokinetic beam of neutral mesons.

Characteristics of the radiation produced by the decay of neutral mesons into photons, (a) Spectral distribution of the radiation; (b) quantum energy as a function of the angle of emission. Curves for different values of $B$, where $Bm_0c^2$ is the total energy of a particle of rest-mass $m_0$.

The maximum and minimum values of the energy of the $\gamma$-rays corresponding to emission in the forward and backward directions with respect to the line of motion of the parent meson are given by the relations

$$h\nu (\text{max}) = B \frac{m_0c^2}{2} \left( \frac{1 + \beta}{1 - \beta} \right); \quad h\nu (\text{min}) = B \frac{m_0c^2}{2} \left( \frac{1 - \beta}{1 + \beta} \right).$$

Even for small values of the kinetic energy there is a considerable width in the spectral distribution of the emitted radiation. The calculated form of the spectrum, for different values of $B$, is shown in Figure 31 (a), each curve...
representing the results for a homogeneous group of neutral mesons of given kinetic energy.

Finally, it can be shown that the intensity of the radiation emitted at an angle \( \theta \), and measured in terms of the number of quanta per solid unit angle, is given by the relation

\[
I(\theta) = k/B^2(1 - \beta \cos \theta)^2,
\]
where \( k \) is a constant.

The curves showing the distribution of intensity become strongly asymmetric for values of \( B \) greater than 2, with a marked tendency for the radiation to be emitted in directions inclined at only a small angle to that of the parent particle.

8 (ii). Experimental Evidence for the Existence of Neutral Mesons

In the experiments of Bjorkland et al. fast protons produced by the synchrocyclotron were allowed to impinge on matter. When the generator is in operation, there is an intense background of radiation due to a variety of nuclear processes,

![Figure 32. Disposition of apparatus for observations on the \( \gamma \)-radiation produced by the impact of 340 MeV. protons in matter.](image)

and it is therefore surrounded by thick walls of absorbing materials. These are perforated with suitable channels so arranged that any radiation originating in the immediate vicinity of the target can escape to the outside (Figure 32). The emerging \( \gamma \)-rays were allowed to fall on the apparatus, shown in Figure 33, which consists of four sets of counters connected to record coincidences, and operated in a magnetic field.

![Figure 33. Apparatus for the determination of the intensity and quantum energy of \( \gamma \)-radiation. (After Bjorkland et al. 1950.)](image)
If a photon of high energy falls on the thin lead radiator (see Figure 33) it has an appreciable probability of producing a pair of positive and negative electrons. These are deflected in opposite directions by the magnetic field, and may then pass through each of the two pairs of counters. A pair of electrons of opposite sign, and with energies in a certain range of values, can therefore lead to the simultaneous discharge of the four counters—can lead, that is, to a ‘quadruple coincidence’. These coincidences give a measure of the intensity of the high energy $\gamma$-radiation emerging through the channel.

Estimates of the energy of the pairs of electrons can also be obtained by interposing metal sheets of suitable stopping-power between the counters of each pair. The greater the energy of the electrons, the greater the thickness of the absorbing sheets required to produce a given diminution in the rate of occurrence of the coincidences. Observations of the reduction in intensity produced by different absorbers therefore give a measure of the quantum energy of the $\gamma$-radiation.

![Figure 34. Characteristics of the radiation produced by the bombardment of carbon by protons of energy 340 MeV. The spectral distribution is shown for two directions of emission with respect to the line of motion of the generating particles.](image)

Provision was made to observe the $\gamma$-radiation, arising as a result of the bombardment of the target by protons of great energy, in either of two directions. In one case the direction of emission of the radiation was nearly parallel to that of the primary protons, and, in the other, the radiation emerging nearly backwards was examined.

The most striking of the results obtained may be summarized as follows: (a) If the intensity of the $\gamma$-radiation emitted in a given direction is studied as a function of the energy of the protons bombarding the target, it is found that the production of radiation begins rather suddenly at a certain ‘threshold’ energy, and this ‘threshold’ occurs at nearly the same value as that for the production of charged $\pi$-mesons. The intensity of the emitted radiation increases rapidly with the increase of the proton energy above the ‘threshold’. (b) The energy of the $\gamma$-radiation observed in a given direction has a certain ‘spectral distribution’, with a well-marked maximum (Figure 34). The average quantum energy is
considerably greater for the photons emitted forward in the direction of the proton beam than for those emitted backward. Further, the intensity of the radiation is greater in the forward direction.

These and other secondary features of the observations can be very simply explained if the γ-radiation is assumed to arise as a result of the creation of neutral mesons, together with charged mesons, in energetic nucleon–nucleon collisions. The neutral meson is assumed to be very unstable, with a life-time less than $10^{-11}$ sec., before decaying into two γ-rays. The assumption of a short life-time is necessary because it can be shown that the observed γ-radiation originates from points within 3 mm. of the 'target', and it follows that any parent neutral meson has a large probability of suffering spontaneous decay in traversing this distance.

The observed quantum energies and intensities observed in the experiments are in good accord with the view that the neutral mesons are emitted isotropically in the centre-of-mass system of pairs of colliding nucleons, one of which is provided by the incident particle and one by a nucleon in a target nucleus.

The tentative conclusions drawn by the authors from these experiments appear to have received decisive support from two recent results obtained at Berkeley. It has been shown by Steinberger et al. (1950) that the high energy photons from a target bombarded by energetic protons are produced in pairs. The quantum energies of these photons vary with the direction of emission with respect to the beam of primary particles in a manner consistent with their suggested mode of origin by the decay of neutral mesons.

Secondly, experiments on the capture of π⁻-mesons in high pressure hydrogen have been made by Panofsky et al. (1950). It has been found that the process of capture commonly leads to the production of a neutron and a neutral meson, the latter particle being detected by the observation of the pairs of γ-rays into which it decays. More rarely the meson produces a neutron and a single γ-ray. The two reactions can therefore be written

\[
\begin{align*}
(a) \quad \pi^- + H^1 &\rightarrow n^0 + \pi^0; \quad \pi^0 \rightarrow 2h\nu (h\nu \sim 70 \text{ MeV.}) \\
(b) \quad \pi^- + H^1 &\rightarrow n^0 + h\nu; \quad (h\nu \sim 140 \text{ MeV.}),
\end{align*}
\]

where $\pi^0$ represents a neutral meson.

It is clear from the known masses of three of the particles in equation \((a)\) that the mass of the $\pi^0$-particle is less than that of the charged meson. Further, the experiments allow an estimate to be made of the inhomogeneity in energy of the γ-rays from reaction \((a)\). We have seen that the extent of such an inhomogeneity will be very sensitive to the kinetic energy of the recoil of the neutral meson, and the observations show that the velocity of recoil is small. It follows that the mass of the $\pi^0$-particle is only a little less than that of the charged meson, and the preliminary results indicate that $m_{\pi^0} - m_{\pi^+} \approx 4m_e$, where $m_e$ is the mass of the electron. It follows that $m_{\pi^0} \approx 270m_e$.

8 (iii) Evidence for the Production of Neutral Mesons by Cosmic Radiation

Reference has been made in §7 (vi) to the observation by Bradt, Kaplan and Peters (1950) of a highly collimated 'jet' of shower particles produced in the collision of an α-particle of great energy with a nucleus. This event occurred in the emulsion of one of an assembly of many plates, and the 'jet' could be followed in its passage through a succession of emulsions.
Bradt et al. found that at a distance of a few centimetres from the nuclear explosions pairs of electrons were created among the charged particles of the shower. The electrons were of great energy and moved in directions inclined at only small angles to the ‘axis’ of the shower. We have referred to the pairs of particles as electrons. Although their nature remains to be established, it is reasonable to assume that they are indeed pairs of electrons created by \( \gamma \)-radiation. The authors observed nine such pairs within a distance equal to about a radiation-length from the nuclear explosion, and they concluded that the \( 56 \) shower particles must have been accompanied by about \( 35 \) energetic \( \gamma \)-rays.

We have seen that the recent experiments of Fowler (1950) prove that at least \( 80\% \) of the charged particles in the penetrating showers are \( \pi \)-mesons, and that very few, and possibly none, are electrons. Further, serious theoretical difficulties are met if it is assumed that large numbers of \( \gamma \)-rays are produced directly in energetic nuclear collisions. On the other hand, the observations of Bradt et al. are readily explained if the \( \gamma \)-radiation which creates the pairs of electrons observed in their experiments is attributed to the spontaneous decay of neutral mesons produced in numbers comparable with that of the charged \( \pi \)-particles. A detailed analysis of the characteristics of the event has led to the conclusion that the mean life-time of the particles is less than \( 3 \times 10^{-13} \) sec.

8(iv). *Mass and Energy of Neutral Mesons in Penetrating Showers*

Additional evidence bearing on the mode of origin of the \( \gamma \)-radiation present in the cosmic radiation, and a method which, in principle, makes it possible to determine the life-time of neutral mesons and to establish the independent existence of the particles, has been described recently by Carlson, Hooper and King (1950). These authors have determined the spectral distribution of the \( \gamma \)-radiation in the atmosphere at 70,000 ft. by measuring the energy of the individual pairs of electrons created by its passage through the emulsion. Assuming that this radiation also arises by the decay of neutral mesons created in nuclear interactions, and that the ‘spectrum’ has not been seriously modified by the presence of photons produced by ‘bremsstrahlung’, it is possible to deduce (a) the mass of the postulated neutral mesons, and (b) the energy ‘spectrum’ of these particles at their points of creation.

The method is based on the following considerations. Figure 31(a) shows the calculated distributions in energy of the photons produced by the decay of homogeneous groups of neutral mesons for different values of the total energy \( Bm_0c^2 \). For an inhomogeneous beam, in which the neutral mesons are distributed in an energy spectrum, there is a maximum in the distribution at an energy \( \frac{1}{2}m_0c^2 \). Further, suppose that the two values of the energy for which the intensity of the radiation is equal to any arbitrarily chosen value are \( E_1 \) and \( E_2 \). It can then be shown that \( (E_1E_2)^{1/2} = m_0c^2/2 \), whatever the chosen value of the intensity.

The above result shows that if the \( \gamma \)-radiation is produced by the decay of neutral mesons, the form of the ‘spectrum’ of the photons must display features consistent with the relation established above. The observed energy distribution at 70,000 ft., as determined by Carlson et al., is shown in Figure 35. Five pairs of values of the energy intercepts, for different values of the intensity, have been determined, and the corresponding values of the quantity \( (E_1E_2)^{1/2} \) are shown by circles in the figure. The degree of consistency of the values is remarkable, and the mean corresponds to a mass of \( 295 \pm 20 m_0 \) for the neutral meson.
Figure 35. Spectrum of the $\gamma$-radiation in the atmosphere at an altitude of 70,000 ft. (Carlson, Hooper and King 1950).

Figure 36. Energy distribution of the charged ($\bigcirc$) and neutral ($\times$) $\pi$-mesons in the atmosphere at 70,000 ft. The intensity scales are arbitrary (Carlson et al. 1950).
Using the value for the mass of the neutral meson thus determined, the observed \( \gamma \)-ray spectrum can be employed to deduce the distribution in energy of the neutral mesons at their points of creation. The result thus obtained is shown in Figure 36. Included in the same figure is the corresponding curve for the charged mesons observed to be created in 'showers' occurring in the same plates. It will be seen that there is no significant difference between the forms of the two distributions, an indication that the neutral and charged mesons are created in similar types of processes.

These observations provide convincing evidence that in the explosive disintegrations produced by protons and \( \alpha \)-particles of great energy, the charged \( \pi \)-particles of 'showers' are accompanied by neutral mesons of the same type as those observed to be produced artificially. For the successful application of the method of Carlson, Hooper and King it appears to be essential to make observations at high altitudes where the \( \gamma \)-radiation has not been modified appreciably by the development of cascade showers.

8 (v). *Life-time and Frequency of Production of Neutral Mesons*

The evidence for the existence of neutral mesons presented in the previous paragraphs, whilst very strong, is circumstantial. It is therefore a matter of importance to obtain, if possible, decisive evidence of the independent existence of the particles. For this purpose, and in order to measure the life-time of the particles, Carlson *et al.* have made observations on the pairs of electrons which are sometimes created, close to a 'star' in the emulsion, by \( \gamma \)-rays resulting from the nuclear explosion.

Suppose that a homogeneous beam of neutral mesons, each of rest-mass \( m_0 \), is moving with such a velocity that the total energy per particle is \( Bm_0c^2 \). We have seen that for values of \( B > 2 \) there is a pronounced tendency for the emitted \( \gamma \)-radiation to preserve the direction of motion of the parent particle. As a consequence of these features of the postulated mode of decay of the neutral mesons it follows that the line of motion of the photons will, in general, be inclined to that of the parent particle. Further, in the case of photons in the range of energies with which we are concerned, the two electrons into which each eventually converts will form a very narrow 'pair' with a divergence of the order of \( 0.1^\circ \). They will thus give an indication of the line of motion of the \( \gamma \)-ray which is subject to errors of the same order of magnitude, viz. \( 0.1^\circ \). It follows that the backward projection of the mean line of the pair will not, in general, pass through the centre of the parent disintegration, but at a distance \( r \) from it (Figure 37).

A simple analysis allows the expected distribution in the values of \( r \) for any assumed values of the energy of the neutral mesons, and of their mean life-time, to be calculated. It is a satisfactory feature of the method that for \( B > 2 \) the distributions are almost independent of the values of \( B \). It follows that the calculated distributions, for the case in which the kinetic energy of the neutral mesons is no longer assumed to be constant, are insensitive to the assumed energy spectrum of the neutral particles, provided most of them have an energy greater than 100 mev. This is due to the fact that although the emitted \( \gamma \)-radiation tends to be more closely collimated about the line of motion of the parent mesons as \( B \) increases—a factor which, if acting alone, would tend to reduce the values
of \( r \)—the effect is compensated by the relativistic extension of the time scale of the moving particles with increase in the value of \( B \).

The actual values of \( r \) observed are shown in Figure 38 and prove that if the \( \gamma \)-radiation is attributed to the decay of neutral mesons the life-time of the parent particles must be less than \( 5 \times 10^{-14} \) sec. The results suggest that the observed distributions are due to a life-time of about \( 2.5 \times 10^{-14} \) sec., and are not seriously affected by errors in measurement. If further results confirm that the

spread in the values of \( r \) are indeed due to a finite life-time of this order of magnitude, the experiments may be taken to establish the independent existence of the neutral mesons. From the frequency of occurrence of pairs of electrons in the neighbourhood of stars, Carlson et al. have shown that the ratio of the number of neutral to charged mesons emitted in nuclear explosions is

\[
\mathcal{N}(\pi^0)/\mathcal{N}(\pi^\pm) = 0.45 \pm 0.1,
\]

a result in good agreement with theoretical anticipations.
8 (vi). Spin and Parity of the \( \pi^0 \)-Particles

A brief reference has been made above, §8 (ii), to the experiments of Panofsky \textit{et al.} (1950) on the capture of \( \pi^- \)-particles in hydrogen gas, which lead to the emission of \( \gamma \)-radiation. The mode of decay into two photons of the neutral meson which is the immediate result of the process of capture is inconsistent with the view that the \( \pi^0 \)-particles are of spin 1. It is therefore reasonable to suppose that, like the charged particles, they are of spin 0. Further, the characteristics of the process of capture, in which the resulting neutron and \( \pi^0 \)-particle are emitted with small kinetic energy, appear to indicate that the parities of the negative and neutral \( \pi \)-mesons are equal.

It is an interesting and peculiar feature of the results of these workers that no photons have been observed in similar experiments in which the hydrogen gas was replaced by hydrogen compounds. When \( \pi^- \)-particles are arrested in such compounds—in lithium hydride for example—it is to be expected that many of them will be captured by lithium, and thence will eventually react with the nuclei and produce nuclear explosions. Some, however, should be captured by hydrogen, and these would be expected, at first sight, to lead to the emission of \( \gamma \)-radiation. The authors suggest that the absence of this radiation is due to a migration, from its original point in the crystal lattice, of the neutral complex formed by a proton and a \( \pi^- \)-particle: a migration which takes place before the \( \pi^- \)-particle has fallen to the state of lowest energy round the proton. As a result of this diffusion, the complex collides with neighbouring heavy atoms. In such collisions there is a large probability of the \( \pi^- \)-particle being captured from the proton by one of the heavy atoms and then by its nucleus. The assumption of the existence of such a neutral complex between a proton and a negative meson was made by Frank (1947) in an attempt to find an alternative explanation of the \( \pi^-\mu \) events other than that of a spontaneous decay of the \( \pi^- \)-particle.

§9. Evidence for the Existence of Mesons of Other Types

During the past five years, physicists in a number of different laboratories have presented evidence which has been interpreted in terms of the existence of particles intermediate in mass between \( \pi \)-mesons and protons. Although we may be dealing with several different types, it will be convenient to refer to these particles as \( \tau \)-mesons. In several instances the evidence has been based on a few isolated events observed in Wilson chambers or photographic plates; and, until recently, it has been an unsatisfactory feature of the observations that no two of them appeared to correspond to the same type of process. Opinion on the question of the existence of \( \tau \)-mesons has therefore vacillated. In several instances, however, recent observations have confirmed the earlier work and strong evidence for the existence of particles of mass of the order of 1,000 \( m_e \) is now available.

9 (i). Evidence for the Existence of \( \tau \)-Mesons

\( a \) The first observations were those of Leprince-Ringuet and Lheritier (1944) who observed the collision of a fast cosmic-ray particle with an electron in a Wilson chamber operated in a magnetic field. From an analysis of the event they were led to suggest that the mass of the incident particle, which carried a positive charge, was about 1,000 \( m_e \).
(b) Rochester and Butler (1947) observed two events in a Wilson chamber, in the first of which two particles appeared to originate in the gas of the chamber, the directions of motion being inclined at about 65°. The two particles, if they were moving away from the apparent point of origin, were of opposite sign. From the curvature of the tracks in the magnetic field, and the specific ionization of the particles as deduced from the density of droplets along the trajectory, it was concluded that the two secondary particles were of mass approximately 300 $m_e$, and it was suggested that they originated by the spontaneous decay ‘in flight’ of a neutral particles of mass not less than about 800 $m_e$.

In the second of the events a sudden deviation in the direction of motion of a particle in the gas of the chamber was observed. It was very difficult to account for this deviation in terms of nuclear scattering, and Rochester and Butler showed that the observed characteristics were consistent with the assumption that the event represented the decay in flight of a charged particle, of mass about 1,000 $m_e$, with the emission of a charged secondary particle and one or more neutral particles.

(c) Bradt and Peters, from a study of the grain-density in the tracks of a large number of particles in photographic plates exposed at great altitudes, suggested tentatively, at the Bristol Conference in 1948, that particles of mass approximately 700 $m_e$ are sometimes ejected with small kinetic energy from nuclear explosions. At the time the results were given with great reserve because of the possibility of pre-exposure of the plates and fading of the latent image. Further, it was an unsatisfactory feature of the observations that the particles showed no evidence for spontaneous decay or interaction with nuclei at the end of their range. The authors subsequently withdrew their suggestion as a result of further experiments, attributing their observations to a pre-exposure of the plates and fading of the latent image.

Other experimenters have made similar observations with varying results. Von Friesen and his colleagues (private communication) in Lund find no evidence for particles of mass in the interval from 500--1,500 $m_e$ in photographic plates exposed at high altitudes by means of free balloons. Brown and Fowler obtained a similar result in an examination of plates exposed at an altitude of 11,000 ft. on the Jungfraujoch. On the other hand, Alichanian, Alichanow and their colleagues, using the same method, claim to have obtained results which support their conclusions regarding the existence of ‘varitrons’.

(d) Leprince-Ringuet and his colleagues (1948) have observed an event in a photographic plate with the following features: A particle produces a track with characteristics which suggest that its mass is less than that of a proton. At the end of its range it appears to lead to a disintegration from which a $\pi^-$-particle emerges, and which produces a second disintegration. From the total release of energy in the first disintegration, and assuming that the initial track is indeed that of the parent particle which produced the event, it follows that the rest-mass of this particle is approximately 700 $m_e$.

(e) Brown et al. (1949 a) have observed an event in an ‘electron-sensitive’ emulsion which appears to correspond to the spontaneous decay, at the end of its range, of a particle with a mass of approximately 1,000 $m_e$, into three $\pi$-particles. The interpretation is based on the fact that the total momentum of the three product particles is equal to zero, within the limits of error of the observations, and the total release of energy corresponds to that released by the transformation of the rest-mass of the parent particle. One of the ejected particles is brought to rest in
the emulsion and produces a nuclear disintegration so that it can be identified with confidence as a \( \pi^- \)-particle. A second particle, of much greater energy, can be identified as a \( \pi \)-meson by measurements of scattering and grain-density along the track.

After a considerable lapse of time, during which opinion in the subject has fluctuated, new experimental evidence has been obtained which gives strong support for the observations of Rochester and Butler. Thus Seriff et al. (1950), in experiments with an expansion chamber operated at about 11,000 ft., have observed more than twenty examples of forked tracks, which appear to originate by the decay of a neutral particle \( \tau^0 \) similar to the event observed by Rochester and Butler. In some cases the decay of the \( \tau^0 \)-meson is accompanied by a nuclear disintegration in a lead plate in the chamber. It is then reasonable to assume that the two events are associated, and that the neutral \( \tau^0 \)-meson was created in the disintegration. The authors state that, if this is so, the characteristics of the forks indicate that one or more neutral particles are rarely emitted in the spontaneous decay of the parent neutral particle.

Anderson and his colleagues have also reported a few examples of the second type of \( \tau \)-meson described by Rochester and Butler which has been interpreted to correspond to the decay of a charged meson of mass approximately 700 \( m_e \) into a charged meson of smaller mass and one or more neutral particles.

The observations of Brown et al. have also received support from recent work by Harding (1950) on photographic plates exposed under 3 m. of ice at the Jungfraujoch. Harding has found two events in each of which a particle of mass approximately 1,000 \( m_e \) appears to stop in the emulsion and to decay spontaneously into three charged particles which are emitted in directions which are co-planar. A detailed analysis shows that the features of the tracks are consistent with spontaneous decay into three charged \( \pi \)-particles. It is an important feature of Harding's result that in the one case in which it was possible to measure the total kinetic energy of the secondary particles, the result obtained was closely similar to that of Brown et al., viz. \( \approx 80 \text{ MeV} \). If the secondary particles are indeed all \( \pi \)-particles, this corresponds to a mass of the parent \( \tau \)-meson of the order of 985 ± 20 \( m_e \). Although it is not certain that the \( \tau \)-mesons are all of the same kind, the limited evidence available is consistent with the assumption that some of the processes of decay of the three types can be represented by the equations

\[
\begin{align*}
(1) & \quad \tau^0 \rightarrow \pi^+ + \pi^- + \pi^0 & \text{Rochester and Butler, type 1.} \\
\text{or} & \quad \tau^0 \rightarrow \pi^+ + \pi^- \\
(2) & \quad \tau^+ \rightarrow \pi^+ + \pi^0 + \pi^0 & \text{Rochester and Butler, type 2.} \\
\text{or} & \quad \tau^+ \rightarrow \pi^+ + \pi^0 \\
(3) & \quad \tau^- \rightarrow \pi^+ + \pi^- + \pi^- & \text{Brown et al.}
\end{align*}
\]

For the present, however, the first four of these equations must be regarded as highly speculative.

The work of several experimenters on the nature of the mesons created in the nuclear interactions of protons and \( \pi \)-particles of great energy in the cosmic radiation show that any \( \tau \)-mesons sufficiently stable to be brought to rest in solid materials are produced rarely compared with the \( \pi \)-mesons. The three events of the type observed by Brown et al., and by Harding, have all been observed at an altitude of 11,000 ft., under considerable thicknesses of materials, and it appears
possible that they are commonly produced only with great kinetic energy. In this case it would be possible to observe them only in the presence around the photographic plates of considerable thicknesses of absorbing materials. In the events described by Rochester and Butler and by Seriff et al., the life-time of the particles can hardly be less than $10^{-10}$ sec., and of those described by Brown et al., not less than $10^{-12}$ sec.

9 (ii). Varitrons

The experiments of Alichanian et al. (1948, 49), to which reference has already been made, have been carried out by means of an apparatus operated at an altitude of 10,000 ft., and of the type shown schematically in Figure 39. Charged particles of the cosmic radiation of which the directions of motion are inclined at only small angles to the vertical, pass through the arrays of counters at $C_1$ and $C_2$. By observing which of the individual counters are discharged, the direction of motion of the particle is determined. After emerging from tray $C_2$ a particle passes between the poles of a permanent magnet, giving a field strength of 7,000 gauss, and is deflected so that it leads to the discharge of a counter in tray $C_3$ out of line with its original direction of motion. The deviation in the trajectory can thus be observed and the momentum of the particle determined within limits due to the finite size of the counters.

After passing through the magnetic field the particle passes through sheets of lead between which there are further arrays of counters. It is thus possible to determine the range of the particles from observations on the thickness of lead which they are able to traverse, the uncertainty in the determination being limited by the thickness of the lead plates. In principle the combination of the two observations allows the rest-mass of the particle to be determined, provided the
particle is stopped in its passage through the lead solely as a result of loss of energy by ionization (see § 3 (iv)).

As a result of the finite thickness of the lead plates, the values of the deflections of particles of the same mass which are arrested in a given layer of lead, will be distributed in the way indicated in Figure 40(a). The authors interpret their experimental observations as giving evidence for the existence of such edges in their distribution curves, and conclude that many types of charged mesons exist.

![Figure 40. Characteristic result of Alichanian et al. (1948).](image)

which they refer to as ‘varitrons’, a name chosen to indicate the diversity of the values of the rest-mass of the particles. A typical example of one of their observed distributions is shown in Figure 40(b).

A preliminary report has recently been given by Brode (1949) of experiments similar in principle to those described above, in which the momentum of a particle is deduced from the curvature of its trajectory in a Wilson chamber operated in a magnetic field. Further, the arrest of the particle is studied as it passes through lead plates arranged in a Wilson chamber (see Figure 9(b)). Apart from $\mu^+$ and $\mu^-$ mesons and protons, Brode observed six particles, all positively charged, of which the mass appeared to be about 1,000 $m_e$. Recently, however, he has concluded that these six particles were in fact protons.

The results of the Soviet experiments appear to be in contradiction with those of Franzinetti (1950), Fowler (1950), and other workers whose experiments have
certain advantages already discussed. In experiments with counters it is difficult to be certain that processes, other than those which alone are assumed to be operative, are not in fact making contributions to the discharges of the counters. It is possible, for example, that in Alichanian's experiments, some of the observations are due to particles moving vertically upwards. Such particles are sometimes generated in the nuclear collisions of fast protons and neutrons entering the surface layers of the earth, and are known to exist in appreciable intensity (Camerini et al. 1948).

As a second possible source of confusion in the Soviet experiments, the particles of the dominant downward-moving stream will not invariably be brought to rest by loss of energy through ionization alone. Some of them will be stopped catastrophically as a result of making nuclear collisions. In other cases the electrons emitted during the spontaneous decay of a $\mu^+$-particle may discharge counters at a lower level in the apparatus and thus lead to an over-estimate of the range of the particle. Because of these and other possible processes, the limited statistical weight of the observations obtained hitherto, and the failure of workers in other laboratories to obtain similar results with improved apparatus, it seems reasonable to suggest that the evidence should for the time being be treated with great reserve (see also Daudin 1950).

The experiments of Brode allow a much closer study to be made of the trajectories of the particles and of the physical processes occurring in the apparatus. It is thus possible to exclude most of the ambiguities present in the counter experiments. In this case also, however, the particles are commonly stopped in the lead plates so that some secondary processes which they may produce escape observation.

9 (iii). Summary of Evidence

The question of the existence of other types of mesons, in addition to the $7^-$ and $\mu$-particles is of decisive importance for the development of nuclear physics. The evidence summarized above strongly suggests that other types sufficiently stable to be brought to rest in solid materials without having a high probability of decaying in flight, do exist, but that they are rare compared with the $\pi$-particles. It appears to be a matter of the greatest importance to improve the precision and statistical weight of the observations, in order that the existence of the particles may be put beyond doubt and their properties established, for the present difficulties in developing a satisfactory meson theory may be due to lack of decisive information. It was pointed out at the beginning of the article that the discovery of the $\pi$-meson was made very soon after a sufficient increase in the sensitivity of the photographic method. The possibility must therefore be borne in mind of the existence of other types of particles even more elusive, and with even shorter life-times than the $\pi$- and $7^-$-mesons.

§ 10. PRODUCTION OF MESONS IN THE ATMOSPHERE

As a result of the discoveries of the past four years, it now appears to be possible to give a coherent account of the main processes associated with the passage of cosmic radiation which take place in the atmosphere. It is hardly likely that our present picture will stand in its entirety: it has still to be supported by numerical calculation, many points of detail remain to be elucidated and, in a field of study which has proved rich in yielding fundamental new phenomena,
we may still expect surprises. Nevertheless, it seems reasonable to suppose that many of the most important features of our present views are essentially correct.

10 (i). The Primary Cosmic Radiation

The discoveries of Freier et al. (1948) and of Bradt and Peters (1948) show that in addition to the energetic protons which form the most numerous of the incoming particles, the primary cosmic radiation incident in the high atmosphere contains a large fraction of heavier nuclei. The track of one of these particles, observed in photographic plates exposed at an altitude greater than 100,000 ft., is shown in Plate X. Preliminary results by Bradt and Peters (1950) on the distribution in mass of the particles of the primary radiation, shown in Figure 41, indicate that about 55% of the incoming matter arrives in the form of nuclei more massive than protons.

It has recently been pointed out by Bradt and Peters that the mass spectrum of the primary radiation shows notable gaps, the relative abundance of Li, Be, B and F being particularly low in comparison with neighbouring elements. Apart from its intrinsic interest, this result proves that most of the primary particles have not made a nuclear collision in their journey through space. For otherwise any detailed structure in the form of the mass-spectrum would have been obliterated—see for example Plate XII. Any theory of the origin of the cosmic radiation must explain these features of the primary component.

Because of the magnetic field of the earth, only particles with a certain minimum energy can approach the atmosphere at points with a given magnetic latitude. At latitude 50° N. for example, the protons must have a minimum energy of 1,500 MeV. The energy of heavier particles is limited by similar considerations and depends essentially on the value of \( Z e / M \), where \( Z e \) is the charge and \( M \) the mass. It is a sufficient approximation, for elements of medium atomic weight, to assume that \( Z e / M \) is equal to one half the corresponding value for the proton, and with this assumption the minimum energy of the heavy particles is equal to 500 MeV. per nucleon. The minimum energy of the incoming nuclei therefore increases with their mass. This has the effect that if we confine attention to
particles with energies above a certain value, say $10^{11}$ ev., the heavier particles make a much larger contribution than in the case of the total incoming stream. A more detailed study will depend on the determination of the distribution in energy of the incoming particles, a second point of great interest in its bearing on the problem of the origin of the cosmic radiation.

10 (ii). Disintegrations of Heavy Primary Particles

Because of the large charge carried by the heavy particles, their rate of loss of energy by ionization is very great, and they have a large cross section for interaction with nuclei. As a result they rarely penetrate to depths in the atmosphere below 60,000 ft. Further, the high probability of making a nuclear collision has the consequence that, unlike the particle of which the track is shown in Plate X, relatively few of them reach the end of their range before being disrupted.

The collisions of energetic heavy particles with other nuclei result in a large variety of types of nuclear explosions, (Bradt and Peters 1949) of which a few examples are reproduced in Plates IX and XII. In some cases the incident nucleus appears to be almost completely disrupted into its component nucleons. In others, presumably due to a more distant collision, the disintegration is less complete—see Plate XII. The collisions sometimes lead to the production of showers of $\pi$-mesons similar to those produced by neutrons, protons and $\alpha$-particles moving at relativistic velocities, and because of the large numbers of nucleons involved, the number of mesons in such a shower may be very great.

As a result of processes of this type, showers of fast nucleons moving through the atmosphere contemporaneously, and with energies in the relativistic region, are produced in addition to the primary protons. This stage of the development of the secondary processes is represented in Figure 42 (a).

10 (iii). Origin of the ‘Hard’ and ‘Soft’ Components

The fast individual nucleons can penetrate to much greater depths in the atmosphere than the heavy nuclei. Due, however, to nuclear collisions, their intensity decreases exponentially with the mass of atmosphere penetrated. The particles interact with nuclei and produce disintegrations and showers of fast charged $\pi$-mesons most of which are created with an energy less than 1,000 MeV. Because of their short life-time, these $\pi$-particles, when moving in the atmosphere, commonly decay in flight after moving distances less than 100 metres from their points of creation. By transforming into $\mu$-mesons they give rise to the greater part of the ‘hard’ component of the cosmic radiation.

The nuclear explosions are also accompanied by the emission of neutral $\pi$-mesons of very short life-time. The spontaneous decay of these particles into $\gamma$-radiation, and the subsequent production of the cascade showers of electrons and photons by ‘pair-production’ and ‘bremsstrahlung’, allows us to account for most of the ‘soft’ radiation. Both the ‘hard’ and ‘soft’ components therefore appear to arise in nuclear processes of the same type. The distributions in energy of the charged and neutral $\pi$-particles are closely similar and the number of neutral particles is approximately half that of the charged mesons. The values of total energy carried by the hard and soft components are therefore closely similar, a result in accord with the observations made by Rossi 1948. These processes are represented schematically in Figure 42 (b).

We may assume that many of the particles in a group of fast nucleons, arising from the disintegration of an original heavy ‘primary’ nucleus of great energy,
Mesons will be able to create 'showers' of $\pi$-mesons. If so, we can account for the production of the 'extensive penetrating showers'—groups of many hundreds of $\mu$-mesons accompanied by soft radiation. An original 'primary' nucleus may, in a collision, give rise to many nucleons. The showers of penetrating particles, subsequently produced in the atmosphere by many of these nucleons, will appear to be contemporaneous, for the variation in their instants of arrival at a given depth will be undetectable with the apparatus commonly employed. The extensive penetrating showers may therefore be attributed both to primary heavy nuclei and to primary protons of sufficiently great energy. It will be possible to estimate the relative importance of these two processes when accurate measurements of the distribution in charge and energy of the primary radiation have been made.

There is some evidence that the direct production of charged and neutral $\pi$-particles in the nuclear explosions of great energy is accompanied by the creation of energetic $\tau$-mesons with a frequency of the order of $1\%$ of that of the $\pi$-particles. These $\tau$-mesons, at least in some cases, appear to decay spontaneously into $\pi$-particles with a lifetime of approximately $10^{-10}$ sec.

Because of their very weak interaction with nucleons, those of the $\mu$-mesons with very great energy can penetrate to great depths underground. They can then occasionally interact with nuclei to produce nuclear explosions accompanied by the emission of showers, possibly through the electromagnetic interaction with protons in the nuclei.

The downward flux of charged particles and photons at any depth in the atmosphere is accompanied by a flux of 'neutrinos'—neutral particles, of small rest-mass of which the fate is, at present, unknown.

Figure 42. Schematic representation of processes occurring in the atmosphere.
§11. OUTSTANDING PROBLEMS AND PERSPECTIVES

The experiments carried out during the past three years have established the fact that the n-mesons have properties closely similar to those visualized for the 'heavy quanta'. The particles are created in nucleon–nucleon collisions; they interact with the nucleus of every, or almost every, nucleon with which they collide; when brought to rest in solid materials they commonly interact with the nuclei, even of hydrogen, before they have had time to decay, and this in spite of the short life-time of the particles, viz. $\sim 10^{-8}$ sec. At one time it seemed reasonable to hope, therefore, that it would be possible to modify the original conceptions of Yukawa, and to establish a satisfactory meson theory which would enable a consistent account to be given of the particles and of their relationship to the forces of nuclear cohesion.

With this end in view a great many variations of Yukawa's theory have been developed, in the mathematical formulations of which the meson field has been treated, alternatively, as a scalar quantity (as in the original theory), as a vector, as a pseudo-scalar (spin-dependent terms being added to the terms in the original 'scalar theory' for the forces between two nucleons), and in many other ways. Recent experiments on the generation of $\pi$-mesons by $\gamma$-rays, on the capture of $\pi^0$-particles in gaseous hydrogen, and on the mode of decay of $\pi^0$-particles into two $\gamma$-rays, provide important information which proves that many of the varieties of meson theory are inconsistent with the observations.

In spite of the progress represented by the new discoveries, the question remains, however, whether, in spite of the great stimulus which they have provided for the progress of theory and experiment, the basic features of Yukawa's original ideas are essentially correct. Even if it is a valuable analogy to identify the $\pi$-mesons with the 'heavy quanta' of the nuclear field, there appears to be no place in any formalism, developed hitherto, for the $\mu$-mesons. These particles have a mass of $215\ m_e$; they have a very weak interaction with nucleons, so that they are able to penetrate hundreds of nuclei without disintegrating them; they have half integral spin and decay with the emission of an electron and, probably, two neutrinos; they have a life-time of $2.1 \times 10^{-8}$ sec., and the negative particles when arrested in elements with $Z$ greater than 15 interact with the nuclei before decay and lead to a nuclear transmutation with the emission of a neutrino and a neutron. The great inadequacy of our present theoretical ideas is well illustrated by the fact that there has scarcely been an attempt to account for the existence of these particles and the details of their properties.

These difficulties were already present at a time, a few months ago, when it was commonly believed that we had not to face the additional complication represented by the existence of other types of particles. The recent additional evidence for the existence of $\tau$-mesons strongly suggests, however, that the situation is much more complex than had commonly been visualized: that particles of mass about 1,000 $m_e$ exist, both charged and uncharged, which decay, at least in some cases, with the emission of $\pi$-particles. The most important features of the most common of the different types of particles, of which any theory must attempt to explain the existence and properties, are summarized in Table 4.

We have no reason to believe that the particles included in Table 4 exhaust the list of those most transient forms of matter which we refer to as mesons. We know for example that the neutral $\pi$-particles have a life-time less than $5 \times 10^{-14}$ sec. It would be very difficult to establish the independent existence
of more transient forms of matter, either charged or uncharged, with the present technical resources at our disposal. Without considering such possibilities, it is clear that any theoretical treatment must provide an explanation of the variety of mesons and their properties displayed in Table 4, a variety which appears to us, in the present stage of the development of the subject, as a succession of arbitrary and largely unrelated facts, but which must represent an underlying unity which at present escapes us.

"Experimental science", says Clerk Maxwell, "is continually revealing to us new features of natural processes, and we are thus compelled to search for new forms of thought appropriate to those features". It is possible that decisive

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Table 4. Tentative List of different Types of Mesons and their Properties

<table>
<thead>
<tr>
<th>Type</th>
<th>Reference</th>
<th>Mass in $m_e$</th>
<th>Mean life-time in vacuo</th>
<th>Spin</th>
<th>Mode of decay</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu^+$</td>
<td>Anderson (1938)</td>
<td>212 ± 4</td>
<td>$2.15 \times 10^{-6}$ sec.</td>
<td>(1) $\mu^+ \rightarrow e^+ + \nu + \nu$</td>
<td></td>
</tr>
<tr>
<td>$\mu^-$</td>
<td>Lattes et al. (1947)</td>
<td>212 ± 4</td>
<td>$2.15 \times 10^{-6}$ sec.</td>
<td>(1) $\mu^- \rightarrow \bar{e}^- + \bar{\nu} + \nu$</td>
<td></td>
</tr>
<tr>
<td>$\pi^+$</td>
<td>Lattes et al. (1947)</td>
<td>276 ± 4</td>
<td>$1.6 \times 10^{-8}$ sec.</td>
<td>(0) $\pi^+ \rightarrow \mu^+ + \nu$</td>
<td></td>
</tr>
<tr>
<td>$\pi^-$</td>
<td>Lattes et al. (1947)</td>
<td>278 ± 4</td>
<td>$1.0 \times 10^{-8}$ sec.</td>
<td>(0) $\pi^- \rightarrow \mu^- + \bar{\nu}$</td>
<td></td>
</tr>
<tr>
<td>$\pi^0$</td>
<td>Bjorkland et al. (1950)</td>
<td>~ 270</td>
<td>&lt;5 $\times 10^{-14}$ sec.</td>
<td>(0) $\pi^0 \rightarrow 2\nu$</td>
<td></td>
</tr>
<tr>
<td>$\tau^+$</td>
<td>Rochester and Butler (1948)</td>
<td>~ 900</td>
<td>~ $(2 \times 10^{-10}$ sec.)</td>
<td>? $\tau^+ \rightarrow \pi^+ + \pi^0$</td>
<td></td>
</tr>
<tr>
<td>$\tau^0$</td>
<td>Rochester and Butler (1948)</td>
<td>~ 900</td>
<td>~ $(2 \times 10^{-10}$ sec.)</td>
<td>? $\tau^0 \rightarrow \pi^+ + \pi^-$</td>
<td></td>
</tr>
<tr>
<td>$\tau^+$</td>
<td>Brown et al. (1950)</td>
<td>~1000</td>
<td>&gt;$10^{-12}$ sec.</td>
<td>(0) $\tau^+ \rightarrow \pi^+ + \pi^- + \pi^0$</td>
<td></td>
</tr>
</tbody>
</table>

$\nu$ represents any particle of small rest-mass not a proton.

Features for which the evidence is not yet conclusive, or which are speculative, are shown in brackets. The difference in the values of the life-times of the $\pi^+$ and $\pi^-$-particles is not established.

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information which could provide the stimulus for a radically new approach to the problem of the mesons remains to be discovered. Great interest therefore attaches to the new proton-synchrotrons under construction. The particles generated by the synchro-cyclotrons now in operation are not sufficiently energetic to be able, from the point of view of the conservation laws, to create particles with a mass of the order of $1,000 m_e$. The Birmingham proton-synchrotron is designed, however, to produce protons of energy greater than 1,000 MeV., and these may be able to produce $\tau$-mesons artificially. The machines, based on similar principles under construction at Brockhaven and at Berkeley, are designed to accelerate protons to energies of 3,000 MeV. and 6,000 MeV., respectively.

Even when the new machines have been brought successfully into operation, however, it will still be necessary to turn to natural sources in order to study the nuclear transmutations produced by particles of the greatest energy. Experiments with Wilson chambers operated in magnetic fields, and the development of new methods of determining the energy of fast particles in photographic emulsions, have recently made it possible to make a detailed study of the disintegrations produced by protons and $\pi$-particles with energies in the interval from $10^8$ to $10^{11}$ ev., and occasionally by particles of even greater energy.
As a result of these developments there is to-day no line of division between nuclear physics and the study of cosmic radiation. The latter can be regarded as nuclear physics of the extreme high energy region.

In view of these technical developments, and of the very great resources in men and materials which have been concentrated in the study of these high-energy processes, it appears to be certain that, given peace, the coming years will see further rapid advances in our knowledge of the mesons, those particles which, when free, are ephemeral, but which appear to play a decisive rôle in ensuring the stability of the nuclei and, therefore, of the order of the material world as we know it.

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REFERENCES

The following list does not include references to many important contributions to the subject for which space was not available in the text.

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