# 2 Radioactivity, radiations, particles and interactions

It is the business of the nuclear physicist, having identified the nucleus as the central core of the atom, to enquire what are its component parts. At the first approximation, an answer is given in terms of neutrons and protons, but these, the nucleons, have also come under scrutiny. Moreover, the binding together of nucleons by the internucleon force seems plausibly, since the advent of Yukawa's theory in 1935, to involve mesons at least and the binding of constituents of the nucleon is one of the current problems of the subject. The second approximation for the nuclear physicist therefore establishes a link between nuclear structure and particle physics. This is not even wholly confined to the so-called 'non-strange' particles because 'strange' particle physics has been found to reflect quantitatively on that most historical of nuclear processes, the phenomenon of $\beta$-decay.

The particles of nuclear physics and their properties are listed in Appendix 2. A surprising number of these particles were first characterized without the use of high-energy accelerators as a result of experiments on the cathode and canal rays of the gaseous discharge, as a result of the discovery of radioactivity, and in the world-wide attack on the nature of cosmic radiation. The main events in the chronicle of particle discoveries are given in Table 2.1 and will be reviewed in part in this chapter. As far as radioactivity and cosmic rays are concerned, the particles to which they gave birth have amply repaid their debt, by leading to a new understanding of the nature of the primary phenomena involved.

## 2.1 From electron to muon

### *2.1.1 Electrons*

In 1881 Helmholtz remarked, 'If we assume atoms of chemical elements, we cannot escape from drawing the further inference that electricity, too, positive as well as negative, is divided into definite

TABLE 2.1 Main advances in the growth of nuclear physics

| *Advance* | *Date* | *Physicists* |
|---|---|---|
| Periodic system of the elements | 1868 | Mendeléev |
| Discovery of X-rays | 1895 | Röntgen |
| Discovery of radioactivity | 1896 | Becquerel |
| Discovery of electron | 1897 | J. J. Thomson[a] |
| The quantum hypothesis | 1900 | Planck |
| Mass–energy relation | 1905 | Einstein |
| The expansion chamber | 1911 | Wilson |
| Isotopes suggested | 1911 | Soddy |
| Nuclear hypothesis | 1911 | Rutherford |
| Nuclear atom model | 1913 | Bohr |
| Atomic numbers from X-ray spectra | 1913 | Moseley |
| Positive ray parabolas for neon isotopes | 1913 | J. J. Thomson |
| Transmutation of nitrogen by $\alpha$-particles | 1919 | Rutherford |
| Mass spectrograph | 1919 | Aston |
| Wavelength of material particles | 1924 | de Broglie |
| The wave equation | 1926 | Schrödinger |
| Diffraction of electrons | 1927 | Davisson and Germer; G. P. Thomson |
| Uncertainty principle | 1927 | Heisenberg |
| Wave-mechanical barrier penetration | 1928 | Gamow, Condon, Gurney |
| The cyclotron | 1930 | Lawrence |
| The electrostatic generator | 1931 | Van de Graaff |
| Discovery of deuterium | 1932 | Urey |
| Discovery of the neutron | 1932 | Chadwick |
| Transmutation of lithium by artifically accelerated protons | 1932 | Cockcroft and Walton |
| Discovery of the positron | 1932 | Anderson |
| Hypothesis of the neutrino | 1933 | Pauli |
| Neutrino theory of beta decay | 1934 | Fermi |
| Discovery of artificial radioactivity | 1934 | Curie and Joliot |
| Neutron-induced activity | 1934 | Fermi |
| Hypothesis of heavy quanta (mesons) | 1935 | Yukawa |
| Discovery of the $\mu$-meson (muon) | 1936 | Anderson and Neddermeyer |
| Magnetic resonance principle | 1938 | Rabi |
| Discovery of fission | 1939 | Hahn and Strassmann |
| The principle of phase-stable accelerators | 1945 | McMillan, Veksler |
| Discovery of $\pi$-meson | 1947 | Powell |
| Discovery of strange particles | 1947 | Rochester and Butler |
| Use of space-time diagrams | 1949 | Feynman |
| Production of $\pi^0$-mesons | 1950 | Bjorklund *et al.* |
| Hypothesis of associated production | 1952 | Pais |
| Discovery of hyperfragments | 1953 | Danysz and Pniewski |
| Strangeness | 1953 | Gell-Mann; Nakano and Nishijima |
| Hypothesis of $\overline{K^0}$ and $K_1^0$, $K_2^0$ particles | 1955 | Gell-Mann and Pais |
| Discovery of antiproton | 1955 | Chamberlain *et al.* |
| Non-conservation of parity | 1956 | Lee and Yang; Wu; Garwin |
| Observation of antineutrino | 1956 | Reines and Cowan |

TABLE 2.1 (continued)

| *Advance* | *Date* | *Physicists* |
|---|---|---|
| Prediction of heavy meson | 1957 | Nambu |
| Helicity of neutrino | 1958 | Goldhaber, Grodzins and Sunyar |
| Hypothesis of conserved vector current | 1958 | Feynman and Gell-Mann |
| Discovery of ω-meson | 1961 | Maglic *et al.* |
| Unitary symmetry | 1961 | Gell-Mann; Ne'eman |
| Muon neutrino | 1962 | Danby *et al.* |
| Discovery of $\Omega^-$ | 1964 | Barnes *et al.* |
| Non-conservation of CP | 1964 | Cronin, Fitch and Turlay |
| Hypothesis of charm | 1964–1974 | Bjorken, Glashow and others |
| Evidence for point-like objects in proton | 1968 | SLAC (Stanford) |
| Discovery of neutral currents | 1973 | CERN (Geneva) |
| Discovery of J/ψ particles | 1974 | Richter, Ting |
| Discovery of explicit charm | 1976 | SLAC (Stanford) |

[a] See *Physics Today* July 1966, p. 12.

elementary quanta that behave like atoms of electricity'. This conclusion from the laws of electrolysis related to positive and negative ions; the former appeared always to be associated with matter, but negative charges could be detached from matter and could appear in the free state. They were most convincingly seen as rays emerging from the cathode of a low-pressure discharge tube and experiments with such tubes in magnetic fields led to a determination of the charge to mass ratio $e/m_e$ or *specific charge* of the atom of electricity or *electron* by application of the formula

$$e\boldsymbol{v} \times \boldsymbol{B} = m_e v^2/r \tag{2.1}$$

already discussed in Section 1.2.6 (eqn (1.59)). In relativistic form this equation must be written

$$e\boldsymbol{v} \times \boldsymbol{B} = \gamma m_e v^2/r \quad \text{where} \quad \gamma = (1-\beta^2)^{-1/2}, \quad \beta = v/c \tag{2.2}$$

Knowledge of the value of the specific charge led to the identification of the *beta rays* emitted by radioactive substances as electrons. These particles, which were originally characterized by their negative charge and their penetrating power ($\approx 1$ mm of lead) were soon found to have kinetic energies considerably in excess of the electron energies that had been produced in the gaseous discharge. It was possible even in the early experiments to verify the presence of the relativistic factor $\gamma$ in equation (2.2). Beta particles (Ch. 10) arise in a particular form of nuclear decay; in addition, the radiations from radioactive substances include *internal conversion electrons* which originate from the interaction of nuclear excitations with the surrounding atomic structure.

Electrons behave in all respects as structureless point charges. At energies of a few hundred MeV, when their reduced de Broglie wavelength is about $0{\cdot}5\times10^{-15}$ m, they are important probes of the nuclear charge distribution.

### 2.1.2 Protons and alpha particles

The simplest positive ion was identified in the 'canal' rays that pass through a hole in the cathode of a low-pressure hydrogen discharge. Its charge-to-mass ratio $e/m_p$ was about $\frac{1}{2000}$ of that for the electron and was very close to the ratio of the Faraday $F$ $(=N_A e)$ to the atomic weight of hydrogen $(=N_A m_H)$. This particle is the *proton*, the nucleus of the hydrogen atom.

The proton is the only stable member of the strongly interacting family of fundamental particles, or *hadrons* (Sect. 2.3). It is, therefore, expected as a constituent of complex nuclei. The spontaneous emission of protons from a nucleus however, although not entirely unknown, is a rare phenomenon because alternative processes usually compete successfully. The radiations from radioactive substances do include a heavy-particle component, namely the *alpha rays*, characterized by positive charge and low penetrating power ($\approx 0{\cdot}02$ mm of lead) and these were found to have a specific charge about half that of the proton. Experiments such as that of Rutherford and Royds, in which helium gas was found to appear in a tube into which α-rays were being emitted, disposed of the suggestion that the particle concerned was a hydrogen molecule and confirmed its identity with the helium nucleus, with charge $+2e$ and mass approximately $4m_p$.

The proton, unlike the electron, does not behave as a point charge. The reduced de Broglie wavelength of a proton of energy 1 GeV $(=10^9\,\text{eV})$ is $0{\cdot}12\times10^{-15}$ m and the size of the proton should, therefore, be studied at energies considerably higher than this. In fact, elastic electron–proton scattering experiments at an energy of about 1 GeV (Stanford) first demonstrated the finite size of the proton. Later, when elastic proton–proton collisions were observed in the CERN storage rings for a c.m. energy of 62 GeV the process was found to exhibit a diffraction-like angular distribution indicating a proton radius of about $10^{-15}$ m. Further electron–proton experiments examining *inelastic* processes at energies up to 20 GeV gave clear evidence for some internal structure of the proton (Sect. 2.2.3).

### 2.1.3 The displacement laws; isotopes

The physical nature of the α- and β-particles leads to the laws formulated by Soddy, Russell and Fajans in 1913 to describe the production of different chemical elements as a result of radioactive processes:

(*a*) the loss of an $\alpha$-particle displaces an element two places to the left in the periodic table and lowers its mass by four units;
(*b*) the loss of a $\beta$-particle displaces an element one place to the right in the periodic table but does not essentially alter the atomic mass.

If these rules are applied to the decay of thorium

$$^{232}_{90}\mathrm{Th} \xrightarrow{\alpha} {}^{228}_{88}\mathrm{MsThI} \xrightarrow{\beta} {}^{228}_{89}\mathrm{MsThII} \xrightarrow{\beta} {}^{228}_{90}\mathrm{RdTh} \xrightarrow{\alpha} {}^{224}_{88}\mathrm{ThX} \longrightarrow \qquad (2.3)$$

it is clear that $^{232}$Th and $^{228}$RdTh have the same atomic number (and therefore chemical nature), but a different mass. They are in fact *isotopes* of the element thorium; many elements occur with two or more stable isotopes, and all elements have isotopes if unstable nuclei are counted. Figure 2.1 is a section of a chart on which isotopic constitution of naturally-occurring elements is displayed by plotting charge number $Z$ against neutron number $N = A - Z$, where $A$ is the mass number, equal to the total number of neutrons and protons.

Isotopes were demonstrated objectively by J. J. Thomson (1913) and Aston (1919) using electromagnetic techniques which are now the basis of methods of separating them.

### 2.1.4 *Photons*

The theory of Maxwell is admirably successful in describing the propagation of electromagnetic waves, and accounts for their diffraction and interference. Such phenomena appear over the frequency spectrum from the long waves of radio to the shortest-wavelength radiations from accelerators. The spectrum includes the third and most penetrating of the radioactive radiations, the *gamma rays*, capable of traversing about 10 mm of lead, as well as the X-rays characteristic of atomic inner-shell transitions.

Just as the electron and proton exhibit a duality of nature, in that each may participate in particle-like and wave-like phenomena, so does the duality extend to the electromagnetic spectrum. In the production and absorption of radiation by interaction with matter, quantum theory asserts that the frequency involved is connected with an exchange of energy between the radiation field and initial and final energy levels of the material system (e.g. an atom or a nucleus) (Fig. 2.2) according to the equation

$$h\nu = E_i - E_f \qquad (2.4)$$

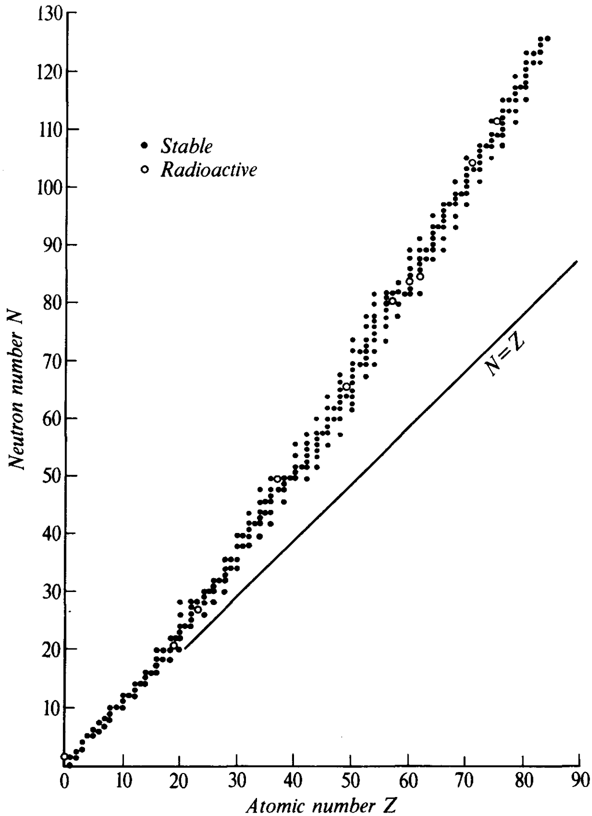


Fig. 2.1 Neutron–proton diagram, sometimes known as a Segrè chart, for the naturally occurring nuclei with $Z < 84$ (Ref. 2.1).

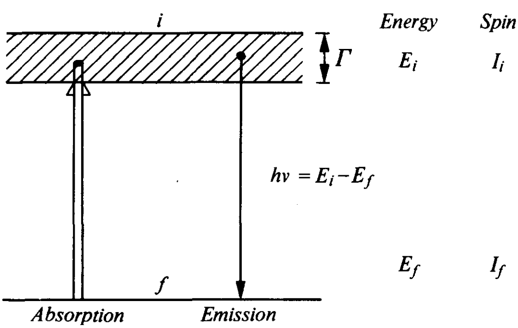


Fig. 2.2 Quantum picture of radiative processes between levels of energy $E_i$, $E_f$. Angular momenta $I_i$, $I_f$ are also indicated. The upper level is assigned an energy width $\Gamma$, which is connected with the lifetime $\tau$ of the level against spontaneous emission by the relation

$$\Gamma\tau = \hbar = 6{\cdot}6 \times 10^{-16}\ \text{eV s}.$$

This replaces the classical picture of radiation interacting with an oscillating charge distribution. The quantum of radiation emitted is known as a *photon* and may be ascribed particle-like properties, although a real photon has zero rest mass and of course travels with the velocity of light. Its momentum is

$$p = h\nu/c \tag{2.5}$$

The concept of the photon simplifies the discussion of many radiative processes. In the case of the Compton scattering of radiation by a free electron for instance (Fig. 2.3), the change of wavelength or of wavenumber $k$ in the scattering may easily be calculated by treating the photon as a particle of four-momentum $p_\mu^1 = (E, \boldsymbol{p}) = (\hbar kc, \hbar \boldsymbol{k}) = (k, \boldsymbol{k})$ putting $\hbar = c = 1$. Conservation of four-momentum gives

$$p_\mu^1 + p_\mu^2 = p_\mu^3 + p_\mu^4 \tag{2.6}$$

where index 2 refers to the struck electron, assumed to be initially at rest, index 3 to the scattered photon of wave vector $k'$, and index 4 to the recoil electron.

To obtain the dependence of $k'$ on $k$ and the scattering angle $\theta$, equation (2.6) is written to permit a suitable scalar product to be taken, i.e.

$$p_\mu^1 + p_\mu^2 - p_\mu^3 = p_\mu^4$$

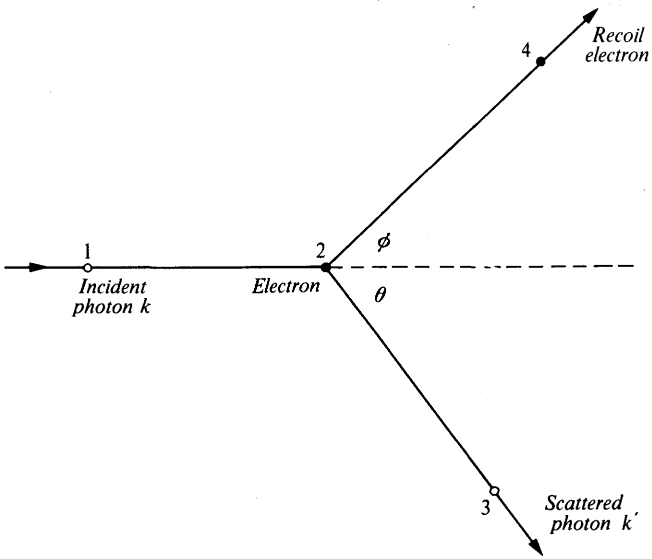


Fig. 2.3 Compton effect. The circular wavenumber $k'$ of the scattered photon is $\leqslant$ the incident wavenumber $k$ for an electron at rest. The electron is assumed to be free.

and then

$$(p_\mu^1+p_\mu^2-p_\mu^3)\cdot(p_\mu^1+p_\mu^2-p_\mu^3)=(p_\mu^4)^2$$

or using equation (1.22)

$$[(E_1+E_2-E_3)^2-(\boldsymbol{p}_1+\boldsymbol{p}_2-\boldsymbol{p}_3)^2]=(p_\mu^4)^2=m_e^2$$

or, in terms of $k$, $m_e$

$$(k+m_e-k')^2-(k^2+k'^2-2kk'\cos\theta)=m_e^2$$

whence

$$1/k'-1/k=(1-\cos\theta)/m_e$$

Inserting $\hbar$ and $c$ to yield the correct dimensions

$$1/k'-1/k=(\hbar/m_ec)(1-\cos\theta)$$

or

$$\lambda'-\lambda=(h/m_ec)(1-\cos\theta) \tag{2.7}$$

The verification of this energy–angle relationship and of the associated expression of the energy of the recoil electron lends support to the photon hypothesis, as of course also do Planck's theory of blackbody radiation and Einstein's theory of the photoelectric effect.

### 2.1.5 *The positron*

Cosmic radiation is a flux of high-energy particles, largely protons, continuously incident on the earth from outer space, together with secondary radiations deriving from interactions of the primary protons in the atmosphere. The radiation at sea level was shown by absorption experiments to contain an easily absorbed or soft component and a penetrating or hard component with an absorption coefficient less than the least expected for gamma radiation; Fig. 2.4

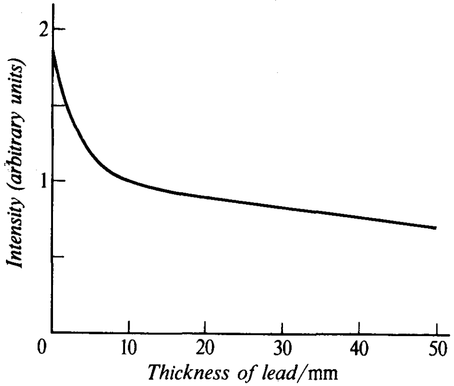


Fig. 2.4 Absorption in lead of cosmic radiation at sea level, showing soft and hard components (based on Auger, P. *et al.*, *J. de Phys.*, **7**, 58, 1936).

gives a typical absorption curve. Cloud chamber photographs taken at random by Anderson (1932) and under conditions of counter control by Blackett and Occhialini (1933) showed that the soft component contained, in addition to electrons, particles of electronic mass but positive charge. This was established by measurements of curvature in a magnetic field, of range and of density of ionization along the track. Figure 2.5 shows the trajectory of one of the positive particles.

Anderson had, in fact, discovered the anti-electron or *positron*, the first example of the fact that particles may have antiparticles of equal mass but opposite charge. The origin of these particles in the cosmic radiation was not fully understood until Bhabha and Heitler in 1937 pointed out that electrons deriving from the primary radiation could give rise to energetic 'bremsstrahlung' quanta as a result of deflections in the electric field of a nucleus (Sect. 3.1.3) and

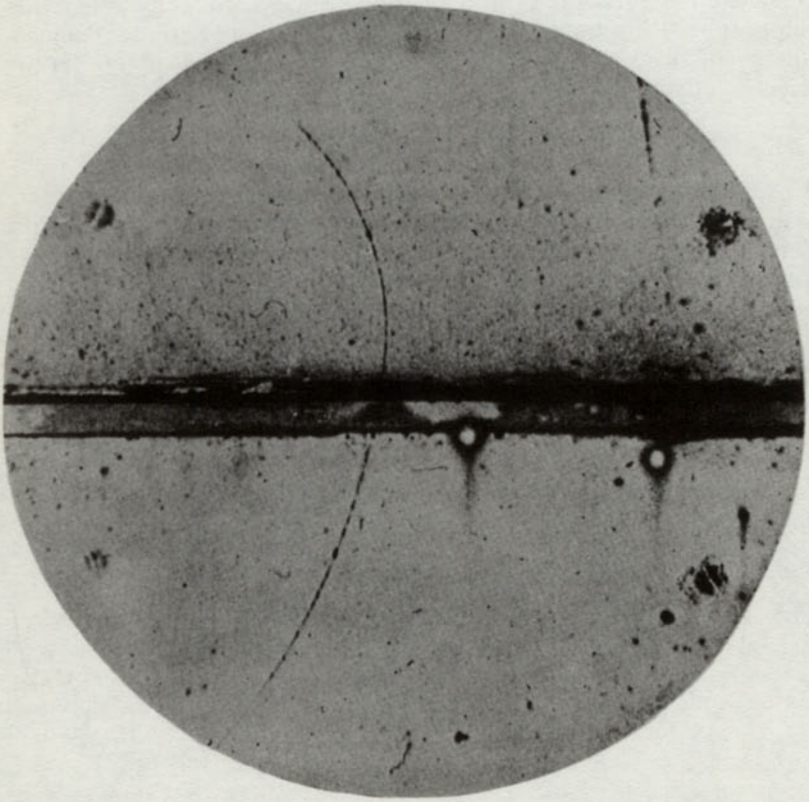

Fig. 2.5 A positron of energy 63 MeV passes through a lead plate and emerges with an energy of 23 MeV (Anderson, C. D., *Phys. Rev.*, **43**, 491, 1933).

that these radiations could subsequently produce electron–positron pairs (Sect. 3.1.4) in further electromagnetic interactions:

$$\gamma \rightarrow e^+ + e^- \tag{2.8}$$

These processes would build up as the radiations passed through the atmosphere into cascade showers, of which Anderson's particle was probably a component.

The possibility of the existence of antiparticles had already been considered theoretically by Dirac who noted that the expression $E^2 = p^2c^2 + m^2c^4$ for the square of the total energy of a particle of mass $m$ led to the conclusion that

$$E = \pm(p^2c^2 + m^2c^4)^{1/2} \tag{2.9}$$

suggesting that electrons might occupy states of negative energy, extending from $-m_ec^2$ to $-\infty$. The difficulty that ordinary electrons should all make transitions to such states was circumvented by the suggestion that normally the states were all occupied, so that the restrictions offered by the Pauli principle would apply. If an electron in a negative energy state were raised by an electromagnetic process to a positive energy level, with an expenditure of energy greater than the minimum of $2m_ec^2$ required, the remaining 'hole' would behave as a normal particle of opposite charge and pair production would have been achieved, i.e. process (2.8).

The positron, as shown in Appendix 2, is a stable particle like the electron, but it may disappear by annihilation with an electron

$$e^- + e^+ \rightarrow 2\gamma \tag{2.10}$$

If the electron and positron are both essentially at rest, the two annihilation quanta, which conserve momentum, have each an energy of $m_ec^2 = 511$ keV. Fast-moving positrons may both radiate and annihilate in flight in a Coulomb field, yielding energetic quanta which contribute to the build-up of the cosmic-ray showers.

### 2.1.6 *The neutron and the neutrino*

In 1919 Rutherford detected the emission of protons from nitrogen bombarded by α-particles. This was the discovery of artificial transmutation, the actual process being the $^{14}N(\alpha, p)^{17}O$ reaction already set out in equation (1.8a). Figure 2.6 reproduces the celebrated cloud chamber picture by Blackett and Lees which gave visual confirmation of this disintegration.

The (α, p) reactions for light nuclei were studied thoroughly in the years following Rutherford's discovery and Rutherford himself was certainly aware of the possibility that some of the products of such reactions might be radioactive and that some might be neutral

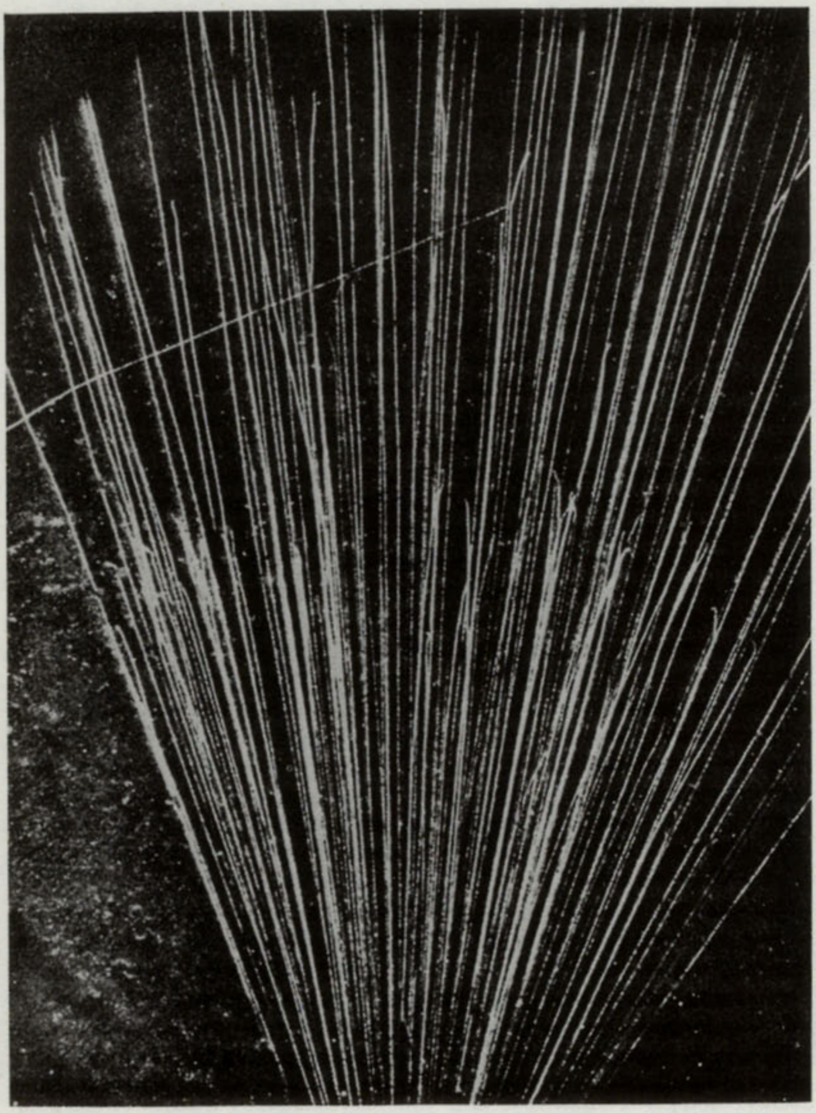

Fig. 2.6 Expansion chamber photograph showing ejection of a proton from a nitrogen nucleus by an $\alpha$-particle (Blackett, P. M. S., and Lees, D. S., *Proc. Roy. Soc.*, **A136,** 325, 1932).

(though here he envisaged a close combination of a proton and electron). The neutral particle or *neutron* was, however, not identified until in 1932 Chadwick established the occurrence of the reaction

$$^{9}\text{Be}+\alpha \rightarrow {}^{12}\text{C}+\text{n} \tag{2.11}$$

($Q$-value now known to be 5·7 MeV).

Reaction (2.11) is similar in nature to the ($\alpha$, p) reactions. It was known for some years before 1932, especially from the work of Bothe and Becker, that bombardment of light elements with $\alpha$-particles could produce a penetrating radiation, assumed then to be gamma radiation connected with the production of excited states of the residual nuclei, e.g. $^{17}$O, formed in the reactions. For beryllium particularly, the penetrating power of the radiation seemed exceptionally great ($\mu_m = 2\times10^{-3}\ \text{m}^2\,\text{kg}^{-1}$ for lead). It is now clear that $\mu_m$ was impossibly low if the radiation were electromagnetic but at the time the effect of pair production in increasing absorption coefficients (see Sect. 3.1.4) was not realized. More significant, however, was the observation by Mme Curie-Joliot and M. Joliot that the radiation from beryllium was able to eject energetic *protons* from hydrogenous material. This they ascribed to a Compton scattering of the supposed electromagnetic radiation by the target protons and from the observed range of the protons the energy of the radiation was calculated to be 35–50 MeV.

This energy seemed larger than might be expected to originate in an $\alpha$-particle reaction with a light element, and the Compton scattering hypothesis was therefore further studied by Chadwick (1932). He found, using a simple ionization chamber and amplifier, that the beryllium radiation could produce recoil ions of many light elements as well as of hydrogen. This was most simply explained by the supposition that the radiation was not electromagnetic, but was a stream of neutral particles (*neutrons*) of mass approximately equal to that of the proton.

The apparatus of Chadwick is shown in Fig. 2.7. In the presence of the source assembly the pulse counting rate in the air-filled ionization chamber increased by a factor of about forty and by a further factor when a sheet of paraffin wax was placed near the entrance to the chamber. The former increase was interpreted as due to the production of recoil nitrogen ions and the latter as due to the detection of recoil protons from the paraffin wax. The initial velocity $u_\text{p}$ of the protons ($3\times10^7\ \text{m s}^{-1}$) was deduced from their measured range, and the initial velocity of the nitrogen recoils $u_\text{N}$ was found to be $4{\cdot}7\times10^6\ \text{m s}^{-1}$ from a separate expansion chamber study of recoil ranges made by Feather.

If the unknown radiation is assumed to consist of particles of mass $M_\text{n}$ and velocity $u_\text{n}$ and if $M_\text{p}$ and $M_\text{N}$ are the masses respectively of

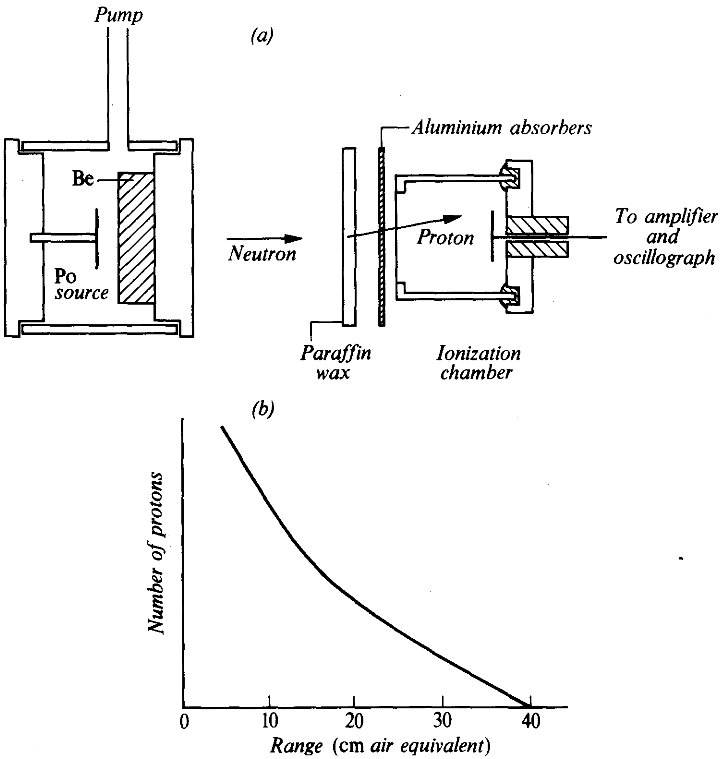


Fig. 2.7 Discovery of the neutron. (*a*) Apparatus, in which neutrons were produced by the (α, n) reaction in a block of beryllium and then ejected protons from a sheet of paraffin wax. (*b*) Number–range curve for protons (Chadwick, J., *Proc. Roy. Soc.*, **A136,** 692, 1932).

the proton and the nitrogen nucleus, then it is easy to show that

$$u_p = 2M_n u_n/(M_n + M_p) \quad \text{and} \quad u_N = 2M_n u_n/(M_n + M_N) \quad (2.12)$$

so that

$$u_p/u_N = 3{\cdot}3 \times 10^7/4{\cdot}7 \times 10^6 = (M_n + M_N)/(M_n + M_p)$$

Substitution of $M_N = 14$ mass units and $M_p = 1$ mass unit gave $M_n = 1{\cdot}16$ mass unit with an error of some 10 per cent. This value was soon refined, by observations on other neutron-producing reactions, to $1{\cdot}005 < M_n < 1{\cdot}008$ atomic mass units. This completed the proof of the existence of a neutral nuclear particle of mass closely similar to that of the proton.

The neutron and proton are known as the *nucleons*, and are essential constituents of a complex nucleus. The masses of the nucleons are close enough for them to be recognizable as an *isobaric doublet* but the neutron is, in fact, slightly the heavier and decays into the proton with the emission of an electron and an (anti-) neutrino

$$\mathrm{n} \rightarrow \mathrm{p} + \mathrm{e}^- + \bar{\nu} \tag{2.13}$$

The neutron was the first unstable elementary particle to be discovered; the probability of such decay is measured by a decay constant $\lambda_n$ and the disappearance of neutıons from an initial assembly by decay with *halflife* $t_{1/2}$ or *mean life* $\tau_n = 1/\lambda_n$ is given by the radioactive-decay law

$$N_t = N_0 \exp -\lambda_n t; \qquad \lambda_n = 1/\tau_n = 0{\cdot}693/t_{1/2} \tag{2.14}$$

The reaction shown in (2.13) is a beta-decay process and is typical of similar processes observed with unstable nuclei in all mass ranges. For reasons that will be discussed later (Ch. 10) Pauli (1931–33) suggested that the further neutral particle shown in (2.13), now called the (anti-) neutrino, should be created in the act of decay. Because of its weak interaction with matter this particle has proved extremely elusive, but in 1959 Reines and Cowan (Sect. 10.4.2) gave objective proof of its existence by observing the inverse of reaction (2.13), namely

$$\bar{\nu} + \mathrm{p} + \mathrm{e}^- \rightarrow \mathrm{n} \tag{2.15}$$

in the form

$$\bar{\nu} + \mathrm{p} \rightarrow \mathrm{n} + \mathrm{e}^+ \tag{2.16}$$

which is equivalent to (2.15) in terms of Dirac's theory of holes.

### *2.1.7 The muon*

The penetrating component of the cosmic radiation at sea level (Fig. 2.4) was shown by expansion chamber photographs to consist of singly charged particles which could pass through lead plates without producing a shower. In 1936–37 Anderson and Neddermeyer presented evidence based on range, momentum and ionization measurements that some of these particles had electronic charge (of both signs) and a mass of about 200 times that of the electron. The high mass accounted for the absence of the radiative effects known for electrons. If, further, it was assumed that the new particles were unstable, disappearing from a flux by decay as well as by scattering, then an anomaly in the absorption coefficient of the penetrating radiation could be explained. Subsequently, decay electrons from the new particles were seen and the mean lifetime was determined by coincidence counter methods to be $2{\cdot}16 \times 10^{-6}$ s.

This new particle is now known as the muon (though originally as the $\mu$-meson) and decays by what is essentially a beta-decay process into an electron, a neutrino and an antineutrino

$$\mu^{\pm} \rightarrow e^{\pm} + \nu + \bar{\nu} \tag{2.17}$$

An example of muon decay is shown in Fig. 2.9.

The observed lifetime ($\tau_0$) of the muon in its rest-frame only permits the particle to traverse large thicknesses of the atmosphere if it is moving with a relativistic velocity. The number of muons from an initial number $N_0$ after traversing a path $l$ (disregarding processes other than decay) is obtained directly from equation (2.14) as

$$N_l = N_0 \exp(-t/\gamma\tau_0) = N_0 \exp(-l/c\gamma\tau_0) \tag{2.18}$$

where as usual $\gamma = (1-\beta^2)^{-1/2}$ and $\gamma\tau_0$ is the Lorentz-transformed lifetime seen by an observer on Earth. For this observer the probability of decay in an atmospheric path d$l$ is

$$p = \mathrm{d}N_l/N_l = -\mathrm{d}l/c\gamma\tau_0 \tag{2.19}$$

An observer travelling with the muon measures the same probability, but now the mean life is indeed $\tau_0$. The difference is that the atmospheric path is Lorentz contracted so that

$$p = -(\mathrm{d}l/\gamma)(1/c\tau_0)$$

as before.

The muon has turned out to behave literally as a heavy electron, and measurement of the anomalous part of its magnetic moment, by observations on the decay of muons circulating in a storage ring at CERN, has confirmed some of the most refined calculations of quantum electrodynamics.

## 2.2 From pion to parton

### *2.2.1 The pions and the deltas*

The discovery of the muon was at first acclaimed as a triumph for the theory of nuclear forces announced by Yukawa in 1935. The force that binds together the components of a complex nucleus is not apparent at distances much greater than the nuclear radius, as was clear from Rutherford's $\alpha$-particle scattering experiments which indicated only Coulomb forces down to a distance of $3 \times 10^{-14}$ m from the centre of a nucleus of gold. To understand an attractive force of an even shorter range Yukawa proposed a potential function

$$U \propto -\exp(-Kr)/r \tag{2.20}$$

with $K$ an adjustable parameter such that $K^{-1}$ is the range of the force. If this length is set equal to the reduced Compton wavelength

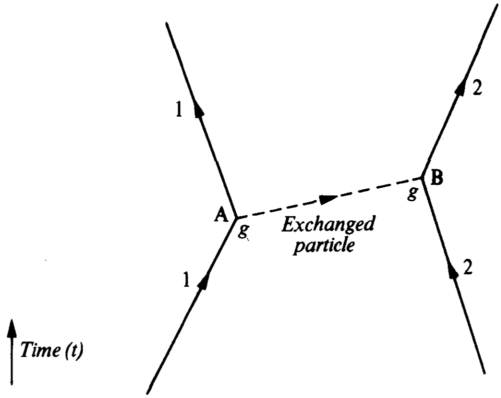


Fig. 2.8 Space–time (Feynman) diagram representing an interaction between two particles (e.g. protons) resulting from exchange of a third particle (e.g. a meson). This is essentially the scattering process shown kinematically in Fig. 1.1 with now an indication of the dynamical process involved. The quantity $g^2$ is a coupling constant (Sect. 2.3).

of a material particle

$$1/K = \hbar/\mu c \tag{2.21}$$

then for $K^{-1} = 2 \times 10^{-15}$ m, $\mu = 200 m_e$, i.e. about equal to the observed mass of the muon. The physical picture of the intervention of this particle is illustrated in the space–time diagram of Fig. 2.8 in which the new particle is emitted spontaneously from a proton (say) at point A and is absorbed a short time later by a second proton (say) at point B. For such a process to happen an energy fluctuation of $\mu c^2$ must occur in the system A and B and according to the Uncertainty Principle $\Delta E . \Delta t \approx \hbar$, this must be restored within a time $\hbar/\mu c^2$. In such a time the exchanged particle could travel a distance $c \times \hbar/\mu c^2$ at velocity $c$ and this should be of the order of the range of the force, in agreement with (2.21). Alternatively, one may retain conservation of momentum and energy at the vertices but the exchanged particle must then have a non-physical mass. It is then said to be *off the mass shell.*

Unfortunately, the particle required by the Yukawa theory must interact strongly with nuclei, with a cross-section of the order of the nuclear area, whereas muons are penetrating particles, sometimes traversing large thicknesses of the atmosphere without loss by nuclear interaction and continuing even through many metres of earth. Finally, slow negative muons can form muonic atoms, in which a muon replaces an electron, and in such an atom the muon can stay in effective contact with the nucleus for a time long enough to permit its normal decay. They must, therefore, interact only weakly with nuclei and cannot be the Yukawa particle.

It was soon apparent that if the primary cosmic radiation (or the first results of its interaction with atmospheric nuclei) did contain a strongly interacting particle, such particles would reach sea level only in small numbers. Mountain-top exposures of the conveniently small nuclear photographic emulsions, were therefore made and in 1947 Lattes, Muirhead, Occhialini and Powell found tracks of charged particles estimated by grain counts and scattering observations to have a mass of 200–300 electron masses. Some of these particles emitted a secondary particle of constant range and mass also about $200m_e$, at the end of their track. Subsequent work with more sensitive emulsions revealed that this secondary particle itself disintegrated at rest, emitting an electron in the way already known for the muon; an example of the whole sequence is shown in Fig. 2.9, and the discoveries are reviewed in detail by Powell (Ref. 2.2).

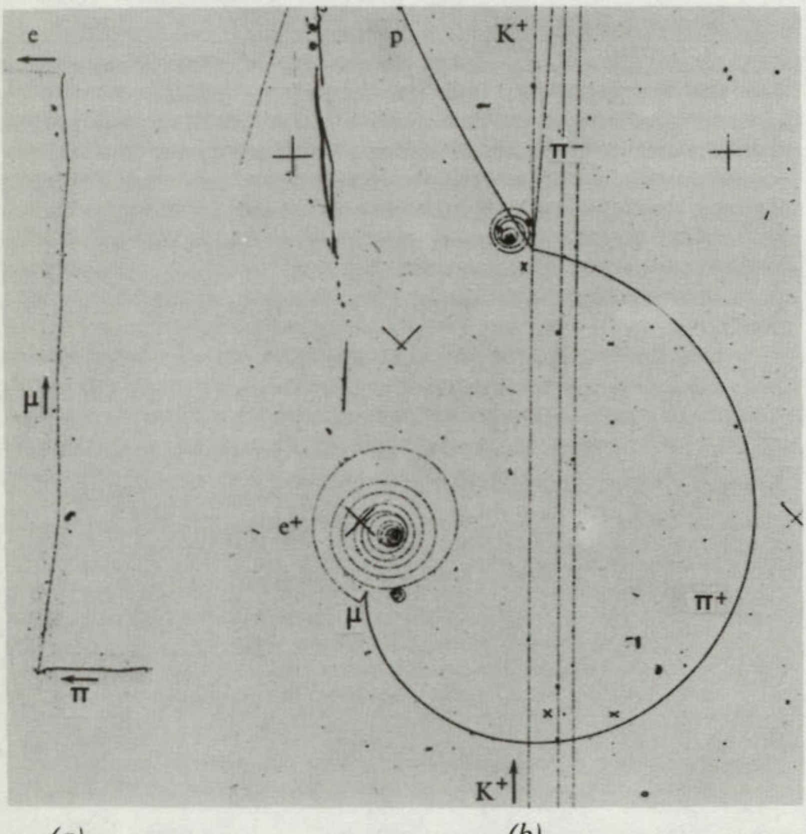


Fig. 2.9 π–μ–e decay seen in (*a*) nuclear emulsion (Powell, C. F., Ref. 2.2) and (*b*) a bubble chamber in a magnetic field (Colley, D. C.).

This remarkable and beautiful series of observations made with equipment of extreme simplicity immediately confirmed and illuminated the emerging theoretical hypothesis that there must be two particles of intermediate mass (mesons) in the cosmic radiation, one being the muon and the other a strongly interacting parent. This latter particle is now known as the $\pi$-meson or pion and it is produced by interactions of the primary cosmic radiation (mainly protons) with nuclei in the atmosphere. The charged pion is now known to have a rest-frame mean lifetime of $2{\cdot}6\times10^{-8}$ s and to decay both in flight and at rest (as shown in Fig. 2.9) into a muon and neutrino

$$\pi \rightarrow \mu + \nu \quad (\text{or } \bar{\nu}) \tag{2.22}$$

the neutrino being invoked because momentum must be conserved in the decay and no other identifiable particle or photon appears to be emitted. The muon may subsequently itself decay

$$\mu \rightarrow e + \nu + \bar{\nu} \tag{2.23}$$

and the $\pi$–$\mu$–e process shown in Fig. 2.9 is complete.

The pion exists in three charge states $\pi^+$, $\pi^-$, $\pi^0$, with the masses shown in Appendix 2, and each of these may be envisaged as the exchanged particle in a nucleon–nucleon interaction as shown in Fig. 2.8. Its appearance in this role, as well as reaction (2.22), suggests that unlike the electron and muon it is not subject to a number-conservation law.

In matter, charged pions slow down to low velocities just as do other particles. Slow $\pi^+$ particles are kept away from nuclei by Coulomb repulsion and finally decay in accordance with process (2.22). Negative pions interact strongly with complex nuclei producing spectacular disintegration 'stars'. Neutral pions decay electromagnetically and very rapidly by the process

$$\pi^0 \rightarrow \gamma + \gamma \tag{2.24}$$

with the occasional alternative of an $(e^+e^-)$ pair instead of one or both of the photons.

The *interaction* of fast charged pions with nucleons has a special significance for nuclear forces and for nuclear structure because of its connection with the Yukawa process. When pion beams from accelerators became available it was possible to determine the energy variation of the total scattering cross-section for the pion–proton collision; the results for positive pions are shown in Fig. 2.10. The outstanding feature of these results is the peak at a pion laboratory momentum of 300 MeV/c, representing a preferred association, or *resonance* of the pion and nucleon at the corresponding centre-of-mass energy. This comes out to be 1236 MeV and although the energy width (120 MeV) of the state shows that it can

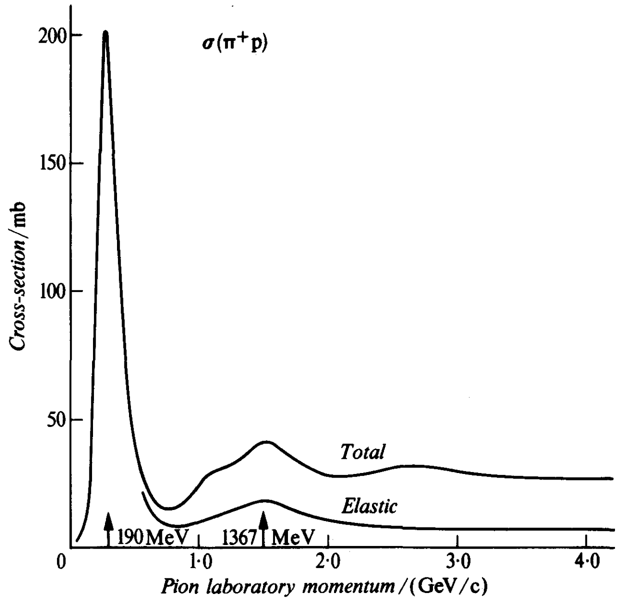


Fig. 2.10 Total and integrated elastic cross-section for scattering of $\pi^+$ by protons.

only have a transitory existence ($\tau \approx 5 \times 10^{-24}$ s using $\Delta E \,.\, \Delta t \approx \hbar$), there is virtue in regarding it as an unstable particle, or excited nucleon; it is known as the delta particle, $\Delta(1236)$. The delta occurs in four charge states $\Delta^{++}$, $\Delta^{+}$, $\Delta^{0}$, $\Delta^{-}$ according to the way in which it is formed from pions ($\pm$) and nucleons (+ and 0 charge). If pions play a part in nuclear structure, then so should the delta.

### *2.2.2 The kaons and the hyperons*

Even before the elucidation of the $\pi$–$\mu$–e decay has been completed, isolated tracks deriving from new types of particle had been seen in cloud chambers exposed to the cosmic radiation at sea level. Rochester and Butler, using a counter-controlled cloud chamber in a magnetic field of 1·4 tesla, concentrated on the components of the showers of penetrating particles that were produced occasionally near the chamber by protons or neutrons. Figure 2.11 shows one of the pictures obtained in 1946–47 in which characteristic 'vee' tracks were found. These were boldly, and correctly, diagnosed as due to the *decay* of a new type of neutral particle produced by a shower-component particle interacting (in the case of Fig. 2.11) with a nucleus in the lead plate mounted in the chamber. From the distances travelled in the chamber by the neutral particle before

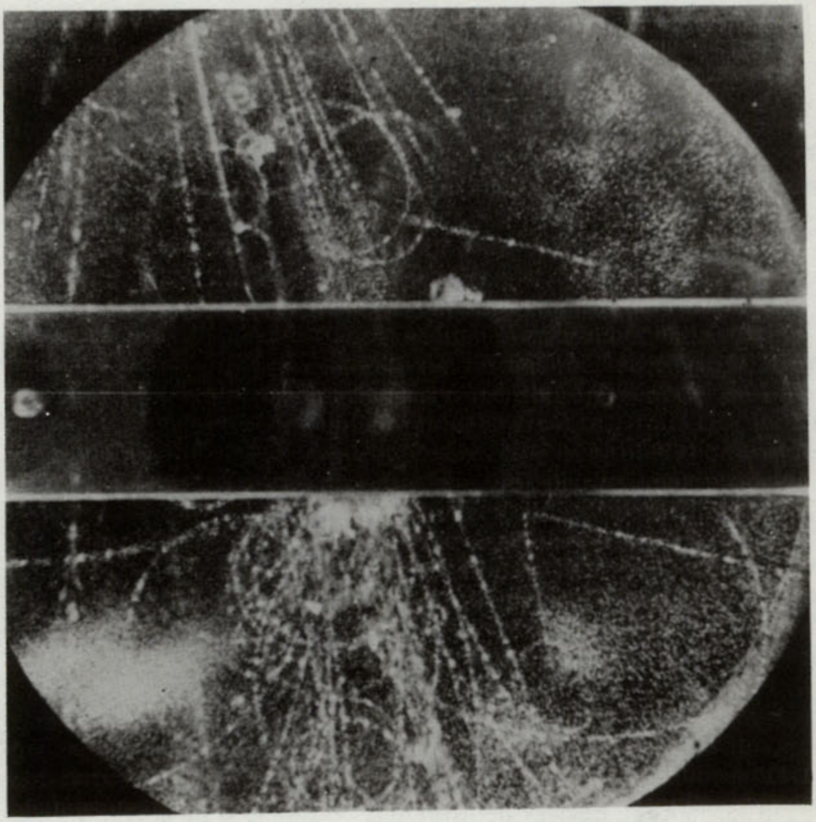

Fig. 2.11 Discovery of strange particles. A K°-meson produced by a cosmic-ray interaction in a lead plate in an expansion chamber decays at bottom right into $\pi^+ + \pi^-$ (Rochester, G. D., and Butler, C. C., *Nature*, **160,** 855, 1947).

decay, a lifetime of $10^{-10}$ s was assessed; from simple assumptions about the decay product a mass $\approx 1000 m_e$ was indicated.

From these results and from similar work at mountain altitudes and finally from accelerator experiments, the neutral 'vee' particles were grouped into two main classes now known as kaons and hyperons. For these the main decay schemes are

$$\text{(kaon)} \quad K^0 \rightarrow \pi^+ + \pi^- \tag{2.25}$$

and

$$\text{(hyperon)} \quad \Lambda^0 \rightarrow p + \pi^- \tag{2.26}$$

Masses and mean lifetimes are shown in Appendix 2.

The table in Appendix 2 includes other particles discovered in later experiments, namely the charged kaons $K^{\pm}$ and the heavier hyperons $\Sigma$, $\Xi$ and $\Omega$, all of which, like the $\Lambda^0$, contain a nucleon.

The *strangeness* of these particles resides in the fact that although their lifetimes are long ($10^{-8}$–$10^{-10}$ s) on a nuclear time scale, e.g. in comparison with that of the $\Delta$, they are nevertheless produced in accelerators and by cosmic radiation, with a cross-section that is a few per cent of the geometrical area of the target nucleus. If, then, reaction (2.26) is considered in reverse

$$\pi^- + p \rightarrow \Lambda^0 \rightarrow \pi^- + p \tag{2.27}$$

one might expect a lifetime comparable with that of the delta.

This difficulty was overcome by Pais who proposed that whereas particles or resonances like the $\Delta$ are indeed formed in analogy with (2.27) the new particles have quantum numbers which require their production in *association*, e.g.

$$\pi^- + p \rightarrow \Lambda^0 + K^0 \tag{2.28}$$

The familiar quantum numbers are not enough to require this process rather than (2.27), but if the kaon and hyperon are ascribed *strangeness* numbers $-1$ and $+1$ respectively and if this quantity strangeness is conserved in the reaction (2.28), then the production of single strange particles from the non-strange $\pi^-p$ system is forbidden. On the other hand, the decay process (2.26) does violate strangeness conservation, and this means that it cannot proceed via an interaction of the fast type allowed for (2.28).

It might be thought that strange particles have little to do with nuclear structure, since nuclei are non-strange. Nuclear beta decay is, however, quantitatively affected by the existence of strange particle decays in a way that will be discussed in Chapter 10. Furthermore, a nuclear neutron may be replaced by a hyperon with consequences of some significance to nuclear structure calculations (Sect. 2.4).

### 2.2.3 *The quark, the parton and the* J/$\psi$

The particles so far described are all objective entities in the sense that they can be produced and characterized and in many cases used to induce reactions. Quarks (Table 2.2) have not yet acquired this status. Their role is a powerful but descriptive one; by their postulated existence as substructures of pions, kaons, nucleons and hyperons they coordinate the grouping of these particles and their associated resonances into multiplets (Ref. 1.1).

The quark hypothesis in its present form is due to Gell-Mann and to Zweig, who postulated the three objects labelled u, d, s in Table 2.2. The u-quark has isobaric spin component (see Sect. 5.6) $T_z = +\frac{1}{2}$ (u = up), the d-quark has $T_z = -\frac{1}{2}$ (d = down) and the s-quark carries strangeness; each has the singular property of non-integral charge. The non-strange quark mass is now thought to be of the order of $\frac{1}{3}$ of the nucleon mass but the quark components of the proton (u+u+d) or of the neutron (u+d+d) are very tightly bound. The binding is supposed, in extension of the quark hypothesis, to result from the exchange of *gluons* between the quarks, just as pions and other particles are exchanged between nucleons to create the internucleon force. No conclusive evidence has yet been found in nature for the existence of fractional charges in a free state, although quark searches continue.

There is, from an entirely different set of phenomena, good evidence for substructure in the proton. It is well known that when Rutherford probed the structure of atoms with α-particles, his conclusions from work with particles of energy much greater than the electron binding energy was that they interacted with a point charge $Ze$ at the centre of the atom. When similar experiments were made on the proton with electrons of several GeV energy from the Stanford linear accelerator both elastic and inelastic scattering involving pion production were observed. The elastic scattering (Sect. 2.1.2) conveyed useful, but expected information on the extent of the proton charge distribution. The inelastic scattering, however, when examined as a function of four-momentum transfer, behaved just as if the scattering was taking place from a point charge or point charges within the proton, in analogy with the Rutherford experiment on the atom. Similar evidence for such localization of interacting centres came from the observation of the production of particles of high transverse momentum (cf. Rutherford large-angle scattering) from the collision of 30 GeV protons in the CERN storage rings. The point charges inferred in both cases are known as *partons*.

It is almost certain that partons are to be identified with the (u, d, s) quarks proposed on the basis of particle systematics. There is, for instance, now sufficient data on neutrino–nucleon scattering

TABLE 2.2 Quark properties

| *Name* | $Q$ | $B$ | $T_z$ | $S$ | $Y$ | $C$ |
|---|---|---|---|---|---|---|
| u (up) | $\frac{2}{3}$ | $\frac{1}{3}$ | $\frac{1}{2}$ | 0 | $\frac{1}{3}$ | 0 |
| d (down) | $-\frac{1}{3}$ | $\frac{1}{3}$ | $-\frac{1}{2}$ | 0 | $\frac{1}{3}$ | 0 |
| s (strange, or sideways) | $-\frac{1}{3}$ | $\frac{1}{3}$ | 0 | $-1$ | $-\frac{2}{3}$ | 0 |
| c (charmed) | $\frac{2}{3}$ | $\frac{1}{3}$ | 0 | 0 | $\frac{1}{3}$ | 1 |

$Q$ = charge/$e$
$B$ = baryon number
$T_z$ = third component of isobaric spin (Sect. 5.6)
$S$ = strangeness number
$Y$ = hypercharge = $2(Q-T_z)-C=S+B$
$C$ = charm number
To each particle shown corresponds an antiparticle with opposite quantum numbers. The quark spin is assumed to be $J=\frac{1}{2}$.

to make a quantitative comparison with inelastic electron–nucleon scattering. The difference between the two should be due to the quark charge and charge numbers $\frac{1}{3}$ and $\frac{2}{3}$ agree with the data. Future experiments on both neutrino and muon scattering by nucleons are expected to confirm this conclusion and to reveal further details of the quark–gluon interaction.

Other properties, beyond those listed in Table 2.2, may be necessary to complete the quark hypothesis. A difficulty relating to the statistics obeyed by quarks (Ref. 1.1) has suggested a new quantum number known as *colour*, which may be carried from quark to quark by the gluons. But the major development in the quark theory has been the introduction, rendered highly plausible since 1974 by the discovery of the J/ψ particles, of a *charmed* quark c. Such a quark had already been discussed for some time by theoreticians because it offered the possibility of explaining, by some appropriate cancellations, the absence of certain anticipated decay processes, especially $K^0 \rightarrow \mu^+ + \mu^-$, which could be effected by a *neutral* current. When the existence of neutral currents was finally verified by the observation in a heavy liquid bubble chamber at CERN of the production of events by muon-neutrinos ($\nu_\mu$) *without* the appearance of a muon, the charm hypothesis received much support (Ref. 2.3). Then in 1974, Ting at Brookhaven and Richter at Stanford, using quite different reaction processes, each reported the production of particles of mass 3·1 GeV which could be formed by, or could decay into, an electron and positron, $e^+ + e^-$. Decay into muon pairs and into pions, kaons and other strongly interacting particles was also established.

These new particles, called J by one group and ψ by the other, were only formed over a relatively sharply defined energy range, so that their lifetime against breakup into pions was about $10^{-20}$ s, at least 1000 times longer than expected for a strongly decaying object of comparable mass, e.g. the Δ(1236). The excitement at this discovery was intense, because, as with the discovery of strangeness, it meant that a new kind of matter with entirely unsuspected properties had been discovered. Both theoretical and experimental progress became extremely rapid, and it is now believed that the J/ψ particles have a $c\bar{c}$ constitution, and that they form a group of states with strong analogies to the ortho- and para-systems of two more mundane spin-$\frac{1}{2}$ particles, e.g. the electron and positron that together form positronium. Many of the predicted states have now been found (Ref. 2.4).

After the J/ψ discovery, effort intensified to observe reactions in which a single charmed quark c would make its presence felt as a constituent of a charmed particle. Charm would then be explicit rather than concealed, as in the J/ψ. In 1976 a narrow state of the $e^+e^-$ system at 1876 MeV was found at Stanford to decay in the way expected for a charmed particle and at about the same time neutrino-induced events with appropriate properties were seen both in nuclear emulsions and in the CERN heavy-liquid bubble chamber. A typical process is

$$\begin{aligned} \nu_\mu + \text{nucleon} &\rightarrow \mu^- + C^+ + \text{hadrons} \\ C^+ &\rightarrow e^+ + \Lambda^0 \quad (\text{or } K^\circ) + \nu_e \end{aligned} \tag{2.29}$$

The signature of the presence of charm in the particle $C^+$ is the production of a strange particle in a leptonic process. (Leptons and hadrons are defined in Sect. 2.3.)

## 2.3 Particle classification and interactions

The general classification of particles, roughly according to mass, is as follows:

(*a*) The photon, i.e. the quantum of radiation, with zero mass.
(*b*) The leptons (light particles), i.e. the electrons, the muons and the neutrinos, although the latter almost certainly have zero mass. Leptons behave as point particles.
(*c*) The mesons (intermediate-mass particles), i.e. particles such as the pion and the kaon but excluding the muon that have masses between that of the electron ($m_e$) and that of the proton ($1836m_e$). Some resonant states that are clearly excited mesons may exceed the latter limit in mass.
(*d*) The baryons (heavy particles), which are subdivided into: (*i*) nucleons, the neutron and proton; (*ii*) hyperons, the particles of mass greater than that of the neutron ($1839m_e$) but which behave as if they contain just one nucleon.

The main types of force known to exist between a pair of particles are compared in Table 2.3*a*. Of these, the gravitational and electromagnetic interactions were familiar in classical physics. Their early recognition was due to the long range of the inverse-square-law force, which ensures that the interaction is sensed by objects of familiar size. Gravitation also has the special feature that it provides a cumulative force, because negative masses do not exist.

The weak interaction describes the production and behaviour of leptons and the decay processes of those strange particles that cannot decay electromagnetically. It is of short range, though how short is not yet certain except that it is very much less than nuclear dimensions. It was not known until the discovery of radioactivity.

The strong interaction, which provides the specifically nuclear forces between nucleons, is also of short range ($\approx 10^{-15}$ m) and was not known until the nucleus was discovered. It affects the behaviour, not only of nucleons, but also of mesons and hyperons, so that it is useful to group all these particles into a strongly interacting class called the *hadrons*. Hadrons, unlike leptons, have an extended structure.

All particles with mass feel gravity and all, if charged, feel electric and magnetic forces. Strongly interacting particles, or complex particles such as nuclei that are held together by the strong interaction, may exhibit small effects due to the weak interaction. The relative strengths of the interactions may be expressed by a rough calculation of the absolute magnitude of the force between two protons at rest, separated by a distance of say $10^{-15}$ m, i.e. within the range of the strong nuclear force; the orders of magnitude are:

| | |
|---|---|
| gravitational force (mass) | $10^{-34}$ N |
| electromagnetic force (charge) | 50 N |
| strong nuclear force | $10^5$ N |

These figures are based on experimentally determined *coupling constants*, which relate to a Yukawa-like description of the forces. Returning to Fig. 2.8, and applying it to the strong interaction between two protons, the square root ($g$) of the coupling constant gives at each vertex A, B the probability amplitude for the emission or absorption of the exchanged particle. The corresponding potential energy, from which the force may be derived, contains the coupling constant $g^2$ itself. Particles that may be exchanged in the interactions are shown in Table 2.3 together with the coupling constants reduced to a suitable dimensionless form.

The important physical quantities to which both strict and conditional conservation laws apply were listed in Table 1.1, Section 1.3. The operation of these laws in processes governed by the interactions of concern to nuclear physics are shown in Table 2.3*b*, the conservations of energy and momentum being omitted because of their universal validity.

TABLE 2.3*a* Interactions between particles

| *Interaction* | *Range* | *Dimensionless coupling constant* | *Exchanged particle* |
|---|---|---|---|
| Gravitational | long | $10^{-39}$ [(a)] | 'graviton' |
| Weak | short ($<10^{-15}$ m) | $1{\cdot}2\ 10^{-5}$ | 'vector boson' |
| Electromagnetic | long | 1/137 | photon |
| Strong | short ($\approx 10^{-15}$ m) | 15 | meson |

[(a)] Using the proton mass as unit.

TABLE 2.3*b* Conservation laws for nuclear interactions

| *Conserved quantity or operation* | *Interaction* | | |
|---|---|---|---|
| | *Weak* | *Electromagnetic* | *Strong* |
| Parity | No | Yes | Yes |
| Isobaric spin | No | No | Yes |
| Charge parity | No | Yes | Yes |
| (Time reversal) | Yes[a] | Yes | Yes |
| Charge $Q$ | Yes | Yes | Yes |
| Baryon number $B$ | Yes | Yes | Yes |
| Lepton number $L$ | Yes | Yes | Yes |
| Strangeness $S$ | No | Yes | Yes |
| Charm $C$ | No | Yes | Yes |

[a] There is a small violation in $K^{\circ}$ decay.

Although the interactions are discussed in this section as separate and distinct fields of force it is likely that a more unified picture will gradually emerge. Already, the behaviour of the weak and electromagnetic interactions shows much more than coincidental similarity (Ch. 10) and theories now exist that identify them, at least at high momentum transfers.

## 2.4 The nucleus and the hypernucleus

A complex nucleus is a many-body system in which attention must be paid to the mutual interaction of a number of particles; the number is, in general, neither very small nor very large, but because of its intermediate nature involves individual properties as well as statistical considerations. From the particles mentioned in Sections 2.1 and 2.2 one may build up:

(*a*) The plasma, a gas of ions and electrons of importance for thermonuclear energy generation. In laboratory plasma experiments the interactions holding the system together are electromagnetic.

(*b*) The neutron star, a condensed degenerate system held together by the gravitational interaction.

(*c*) The typical nucleus, in which protons and neutrons but not electrons exist. The nucleus is too small for gravitational forces to have any major significance, and stability is due to strong interactions between the constituent nucleons, with a disruptive influence due to the Coulomb repulsion of the nuclear protons. The balance between Coulomb and nuclear forces is crucial in determining the stability of a heavy nucleus against deformations and hence the possibility of fission. Because of the nature of the internucleon force it may be claimed that at any given time the nucleus contains some pions and perhaps heavier mesons and, therefore, probably also delta particles.

The distribution of all nuclear constituents, excepting any obeying the Bose–Einstein statistics, between available quantum states is regulated by the Pauli exclusion principle. It is, therefore, of considerable interest that structures known as *hypernuclei* exist in which the control exercised by the exclusion principle has been removed. A hypernucleus is one in which a nuclear neutron has been replaced by a neutral hadron such as the $\Lambda^0$ or $\Sigma^0$; such systems were first seen in events induced by cosmic rays in nuclear emulsions. They have been useful in checking nuclear structure calculations and provide examples of nuclei carrying a strangeness quantum number.

Observable nuclear properties that contribute information on its structure are: ground-state mass and energy of excited states; nuclear radius or potential distribution in all states; intrinsic spin and isobaric spin of all states; parity and electromagnetic moments of all states; matrix elements for decay of all unstable states, and branching ratios for alternative modes; and spectroscopic factors, that govern the participation of the nucleus in reaction processes. These properties will be discussed in Part II of this book.

## 2.5 Summary

A partly historical outline has been given of the nature of the particles that may be concerned in nuclear structure and reactions and of the general types of force that operate between them.

## Examples 2

**2.1** Show that if two consecutive radiations from a long-lived parent have decay constants $\lambda_1$ and $\lambda_2$, the apparent mean life of the second radiation is $1/\lambda_1 + 1/\lambda_2$.

**2.2** A thin $^{210}$Po source of strength 50 μCi is deposited on a small sphere of radius 1 mm and suspended at the centre of an evacuated metal sphere of radius 100 mm by a thread of resistance $10^{13}$ ohms. Find the equilibrium potential difference between the source and the sphere and the time taken for half this value to be reached. ($1\ \text{Ci} = 3{\cdot}7 \times 10^{10}$ disintegrations per second.) [5·9 V, 0·8 s]

**2.3*** Examine the possibility of conservation of four-momentum: (*a*) in the materialization of a photon into an electron pair in free space and in the converse process of single-quantum annihilation; and (*b*) in the emission of a real bremsstrahlung photon by an electron in free space and in the converse process of the absorption of a photon by an electron.