The Elementary Particles

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1 Introduction

Just twenty years ago, in 1947, the list of sub-atomic or 'elementary' particles, that were known or believed to exist, was quite short (Table 1) and of deceptive simplicity. The two heavy particles, the neutron and proton, were known to be the constituents of atomic nuclei, interacting together with a force that was very strong compared with the well-understood electromagnetic interactions that are responsible for non-nuclear atomic and molecular phenomena. The nuclear force also differs from the electromagnetic force in the range of interaction. The electromagnetic force is of long range but the neutrons and protons only interact at distances closer than 10^{-13}cm.; that is, the nuclear force is of short range. The only other strongly interacting particles, called the π mesons, were considered to be the quanta of the field producing the nuclear forces just as photons are the quanta of the electromagnetic field. It can be shown that the range of the interaction produced by the exchange of a particle of mass M is $R = \hbar/Mc$, where $\hbar$ is $h/2\pi$, and h is Planck's constant; c is the velocity of light. For the π meson mass, $R =$ *ca.* 10^{-13}cm., as observed. The long-range character of the Coulomb force is consistent with this expression, if it is remembered that the exchanged photon has zero mass. The strongly interacting particles, which are collectively called the hadrons, can be distinguished sharply from the lighter particles, or leptons, comprising the electron e^-, the positron e^+, the μ^+ and

Table 1 *The elementary particles known in* 1947

Particle[a]	*Mass* (Mev/c^2)	I[b]	I_3[b]	Y[b]	J^P[c]	*Weak-decay*	*Mean lifetime (sec.)*	*Antiparticle*[a]
Photon γ	0	–	–	–	1	Stable	–	Photon γ
Neutrino v^d	0	–	–	–	$\frac{1}{2}^+$	Stable	–	Antineutrino v^{-d}
Electron e^-	0·51	–	–	–	$\frac{1}{2}^+$	Stable	–	Positron e^+
μ-Meson μ^-	105·7	–	–	–	$\frac{1}{2}^+$	$e \mp v + \bar{v}$	10^{-6}	μ-Meson μ^+
π-Meson π^0	135	1	0	0	0^-	$\gamma+\gamma^e$	10^{-16}	π-Meson π^0
π-Meson π^+	140	1	$\frac{1}{2}$	0	0^-	$\mu^+ + v$	10^{-8}	π-Meson π^-
Proton p	938·2	$\frac{1}{2}$	$+\frac{1}{2}$	1	$\frac{1}{2}^+$	Stable	–	Antiproton ^{d} $\bar{p}$
Neutron n	939·2	$\frac{1}{2}$	$-\frac{1}{2}$	1	$\frac{1}{2}^+$	$p+e^-+\bar{v}$	10^3	Antineutron $\bar{n}^d$

[a] The superscript ± denotes that the particles possess charge ±; [b] The isotopic spin I, the third component I_3, and the hypercharge Y are defined in the text. Y and I_3 for an antiparticle are of equal magnitude to but of opposite sign from those quantities for the corresponding particle; [c] J is the internal angular momentum, or spin, measured in units of $\hbar$. $P = +$ for even and $-$ for odd parity particles; [d] These particles had not been discovered in 1947 but were believed to exist. They have been detected subsequently; [e] This decay is electromagnetic.

μ^- mesons and the neutrino, v, because these do not share in the strong nuclear interaction. Of the particles shown in Table 1, only the photon, the electron, the proton, and the neutrino (and the corresponding antiparticles) are completely stable. The remainder ultimately decay into the stable particles. For example, a free neutron decays into a proton, an electron, and a neutrino, with a mean life of 17 minutes, while a μ^- meson decays into an electron, a neutrino, and an antineutrino, with a mean life of 10^{-6} sec. The spontaneous decay times of these particles are all longer than 10^{-16} sec., which may be compared with the time required for a typical strong interaction which is of the order 10^{-23} sec., so that as far as the strong interactions alone are concerned all the particles of Table 1 can be considered to be stable. Some force must be responsible for these slow decays, and this force must be extremely weak, compared with the strong interactions, in view of the long life-times of the particles on the nuclear time scale. We shall call this force the weak nuclear interaction. One further interaction is known and is very familiar to us, that due to gravity, but this is many times weaker than the weak nuclear interaction and plays no important role in elementary-particle interactions (see Table 2). The importance of gravitational phenomena in the macroscopic world arises from its long-range inverse-square law, in contrast to both the weak and strong interactions, which vanish when the particles concerned are separated by distances much in excess of 10^{-13}cm.

Table 2 *The interactions*

	Strengths	*Range*
Strong nuclear interaction	1—10	10^{-13}cm.
Electromagnetic interaction	$e^2/\hbar c = 1/137$	Long-range inverse-square law
Weak nuclear interaction	10^{-12}	10^{-14}cm.
Gravitational interaction	10^{-38}	Long-range inverse-square law

In 1927, P. A. M. Dirac was able to show, by combining quantum mechanics with the theory of special relativity that, for every particle another should exist, of the same mass and angular momentum, but of opposite charge, known as its anti-particle. In particular he predicted that the electron should possess a positive counterpart (the positron) which was subsequently discovered by C. D. Anderson in 1933. On this basis, it was confidently believed that the proton, neutron, and neutrino would possess corresponding antiparticles, and indeed negatively charged antiprotons were observed for the first time in the summer of 1954.

Table 1 illustrates further interesting features. It can be seen that the neutron and proton have nearly the same mass, and also that the π^0 meson has nearly the mass of the π^+ and π^- mesons. From the study of the atomic nuclei, it had become apparent that the neutron and proton both took part in the nuclear interactions in the same way and this suggested that the neutron and proton were two charge states of the same particle, called the nucleon. The small mass difference between the neutron and the proton was attributed to the different action of the electromagnetic field on the charged proton and on the neutral neutron. In the same way, the three π mesons could be considered to be different states of one particle, and again, the difference in mass between the $\pi^{\pm}$ mesons and the π^0 meson could be attributed to electromagnetic effects. These remarks will be elaborated below.

2 Discovery of the 'Strange Particles'

The relatively simple picture presented by Table 1 was soon disturbed by the discovery of further particles, known as 'strange particles', in cosmic radiation by C. Butler and G. D. Rochester. The characteristics of the new particles were finally determined a few years after the initial discovery, when the large accelerators first at Brookhaven (1952) and later at Berkeley (1954) and at C.E.R.N., Geneva (1959), came into operation. These machines accelerate protons by electric and magnetic fields to energies of up 30 Gev (1 Gev = 1000 Mev; 1 Mev = 10^6ev). The high-energy proton beam can be directed at a target so that nuclear interactions take place between the incident protons and the nuclei of the target atoms. Just as an electron deflected by the Coulomb field of a charged particle will radiate light (photons), so during the scattering of protons by the strong interaction, particles that take part in the strong interaction may be produced. For example, the result of a collision between two protons might be a proton, a neutron, and a π^+ meson:

$$\mathrm{p} + \mathrm{p} \rightarrow \mathrm{p} + \mathrm{n} + \pi^+ \qquad (1)$$

Another possible reaction, if sufficient energy were available, would be the creation of an antiproton ($\bar{\mathrm{p}}$) by

$$\mathrm{p} + \mathrm{p} \rightarrow \mathrm{p} + \mathrm{p} + \bar{\mathrm{p}} + \mathrm{p} \qquad (2)$$

Apart from the primary proton beam, by focusing of the products of these collisions secondary beams of various particles can be produced. These secondary beams can also be made to interact with a target and it is by examining the products of such collisions that most of the new particles have been discovered.

So far, some thirty particles have been discovered that are stable under the strong interaction, but which decay slowly under the weak interaction. The properties of these particles are summarised in Table 3. The new particles are also found to be grouped into multiplets, each member of which possesses the same internal angular momentum or 'spin' and approximately the same mass, but differ in charge. Those with a mass near 500 Mev/c^2 and of zero spin are called the K mesons, K^+ and K^0, and the corresponding antiparticles are the $\bar{\mathrm{K}}$ and $\bar{\mathrm{K}}^0$ mesons, while a further meson, the η, is found, with a mass of 548 Mev/c^2, also having zero spin. The particles in Table 3 with mass greater than the nucleon are known as hyperons and comprise the Λ^0 at 1115 Mev/c^2, the Σ^+, Σ^-, and Σ^0 at 1190 Mev/c^2, the Ξ^- and Ξ^0 at 1320 Mev/c^2, and the Ω^- at 1675 Mev/c^2. Each of these particles possesses a corresponding antiparticle.

The particles stable under the strong interactions can generally travel a sufficient distance to be detected directly in a photographic emulsion or in a

Table 3 *The particles stable under the strong interactions discovered since* 1947

Particle[a]	*Mass* (Mev/c^2)	I^a	$I_3{}^b$	Y^b	J^{Pc}	*Principle weak-decay*	*Mean life-time*	*Anti-particle*[a]
		Mesons ($B = 0$)						
K^+	493·8	$\frac{1}{2}$	$\frac{1}{2}$	1	0^-	$\left\{\begin{array}{l}\mu^+ + \nu\\ \pi^+ + \pi^0\end{array}\right.$	10^{-8}	$\overline{K}^-$
K^0	497·7	$\frac{1}{2}$	$-\frac{1}{2}$	1	0^-	$\left\{\begin{array}{l}\pi + \pi\\ \pi + \pi + \pi\end{array}\right.$	10^{-8}	$\overline{K}^0$
η^0	548·7	0	0	0	0^-	$\gamma + \gamma^e$	?	η^0
		Baryons ($B = 1$)						
Λ^0	1115	0	0	0	$\frac{1}{2}^+$	$N + \pi$	10^{-10}	Λ^0
Σ^+	1189	1	1	0	$\frac{1}{2}^+$	$N + \pi$	10^{-10}	$\overline{\Sigma}^-$
Σ^0	1192	1	0	0	$\frac{1}{2}^+$	$\Lambda^0 + \gamma^e$	10^{-14}	Σ^0
Σ^-	1197	1	-1	0	$\frac{1}{2}^+$	$N + \pi$	10^{-10}	Σ^+
Ξ^0	1314	$\frac{1}{2}$	$\frac{1}{2}$	-1	$\frac{1}{2}^+$	$\Lambda^0 + \pi^0$	10^{-10}	$\overline{\Xi}^0$
Ξ^-	1321	$\frac{1}{2}$	$-\frac{1}{2}$	-1	$\frac{1}{2}^+$	$\Lambda^0 + \pi^-$	10^{-10}	$\overline{\Xi}^+$
Ω^-	1675	0	0	-2	$\frac{3}{2}^+$	$\left\{\begin{array}{l}\Xi + \pi\\ \Lambda + \overline{K}\end{array}\right.$	10^{-10}	$\overline{\Omega}^+$

See footnotes to Table 1.

bubble chamber, before decaying under the weak interaction, but in the last few years it has been realised that other particles exist that are not stable under the strong interaction and which decay too rapidly to be observed directly, as they possess mean life-times of the order 10^{-22} sec. For instance, it is observed that if π mesons are scattered from protons, then at certain well-defined energies a great increase in the flux of scattered particles takes place. This may be interpreted by supposing that these 'resonance' energies are the energies at which the π meson and proton combine to form an unstable compound particle, called the N*, that subsequently decays rapidly into a proton and π meson again.

$$p + \pi \rightarrow N^* \rightarrow p + \pi \tag{3}$$

Resonance phenomena of this kind have been seen and studied in scattering processes between atoms or ions, and between nuclei, corresponding to the formation of excited molecular or nuclear states respectively. In experiments of a different type, the resonant particle may be produced along with other particles and its presence can be detected by examining the correlations among the end products of the reaction. The ρ meson, which decays into two π mesons, can be studied in this way through the reaction

$$\pi + p \rightarrow \rho + p \rightarrow \pi + \pi + p \tag{4}$$

In this general way, a great number of particles, unstable under the strong interactions, have been discovered (some of these are shown in Table 4). It is now quite clear that the name 'elementary' is undeserved and in fact that we are

Table 4 *Some of the lighter particles unstable under the strong interactions*

Particle[a]	*Mass* (Mev/c^2)	I^b	Y^b	J^{Pc}	*Principle strong decays*
		Mesons ($B = 0$)			
ρ	769	1	0	1^-	$\pi+\pi$
ω	783	0	0	1^-	$\pi+\pi+\pi$
K*	891	$\frac{1}{2}$	1	1^-	$K+\pi$
X^0	959	0	0	0^-	$\pi+\pi+\eta$
ϕ	1020	0	0	0^-	$K+\bar{K}$
f	1253	0	0	2^+	$\pi+\pi$
		Baryons ($B = 1$)			
$N^*_{\frac{3}{2}}(1236)$	1236	$\frac{3}{2}$	1	$\frac{3}{2}^+$	$N+\pi$
$Y^*_1(1385)$	1385	1	0	$\frac{3}{2}^+$	$\Lambda+\pi$
$N^*_{\frac{1}{2}}(1518)$	1518	$\frac{1}{2}$	1	$\frac{3}{2}^-$	$N+\pi$
$Y^*_0(1520)$	1520	0	0	$\frac{3}{2}^-$	$\Sigma+\pi$
$\Xi^*(1530)$	1530	$\frac{1}{2}$	-1	$\frac{3}{2}^+$	$\Xi+\pi$
$N^*_{\frac{1}{2}}(1688)$	1688	$\frac{1}{2}$	1	$\frac{5}{2}^+$	$N+\pi$

[a] The ($2I + 1$) charge states of each multiplet have not been listed separately. A complete list of all particles known is given by A. H. Rosenfeld, A. B. Gallieri, W. H. Barkas, P. L. Bastien J. Kirz and M. Ross, *Rev. Mod. Phys.*, 1965, 37, 633. [b,c] See footnotes (*b*) and (*c*) of Table 1

looking at a mass spectrum of particles comparable with the energy spectrum of atoms or molecules, and it is quite possible that there is an infinite number of such excited states. As in the case of the atomic spectrum, the full description of the system of particles requires two steps: first, the states must be classified by assigning appropriate quantum numbers, and secondly the underlying dynamical explanation must be sought.

Before considering the classification of the particles, we note that, with one exception, the list of leptons in Table 1 has not increased. This is consistent with the idea that the mass spectrum is a consequence of the strong interactions, in which the leptons play no part. The single exception is that it is not known from a study of neutrino interactions that there are two kinds of neutrino, one associated with the electron and one with the μ meson. It is still a complete puzzle why the μ meson, which has the same properties as the electron but is of greater mass, exists at all.

3 The Classification of Elementary Particles

All reactions whether caused by the electromagnetic, the weak, or the strong interactions obey the fundamental laws of conservation of energy, momentum, angular momentum, and of electrical charge. Both in classical and quantum mechanics, these laws (with the exception of conservation of charge) arise from certain symmetries of space and time. In fact, conservation of energy is a necessary consequence of the application of the invariance of laws of physics to time displacements, conservation of momentum follows from invariance under spatial displacements, and conservation of angular momentum corresponds to invariance under rotations of the co-ordinate systems. It can be checked experimentally that reactions between elementary particles conserve angular momentum if each particle is assigned a definite intrinsic angular momentum or spin J. According to the general principles of quantum mechanics all angular momenta must be of the form $n\hbar$ where n is an integer or half-integer. In quantum theory, the wave function of a particle must either be even or odd under reflection of the co-ordinate system, in which the position vector of the particle $\mathbf{r}$ becomes $-\mathbf{r}$. States for which the wave function is even are said to be of parity $P = +1$ and those in which the wave function is odd of parity $P = -1$. If a system is composed of several parts, the total parity is found by multiplying together the parities of the separate parts. It can be shown that the total parity of a molecular system, bound by coulomb forces, is conserved. Reactions involving the strong interactions (but not the weak) are also found to conserve parity, but only if it is assumed that each particle has a definite internal parity associated with it, in addition to the ordinary parity of the wave function familiar in atomic and molecular physics. For example, the nucleon is found to have parity $P = +1$, while the anti-nucleon and the π mesons have parity $P = -1$.

So far we have associated three numbers, J, P, and Q (the charge) with each particle. Of these the conservation law of charge is particularly simple; each particle in a reaction has a definite charge whether positive or negative, and in a reaction such as

$$\bar{\pi} + \mathrm{p} \rightarrow \bar{\mathrm{K}}^0 + \Lambda^0 \qquad (5)$$

the algebraic sum of the charges on each side of the equation must be the same. Are there any further such 'additive' quantum numbers? A study of all known reactions, whether strong or weak, shows that if we define the baryon number B of each baryon (the collective name given to nucleons, hyperons, and other heavier particles possessing half-odd integer spin in units of $\hbar$; $J = \frac{1}{2}\hbar, \frac{3}{2}\hbar, \ldots$) to be $+1$, and that of each antibaryon to be -1, and that of all other particles to be zero, then the total baryon number is conserved: for example, the initial and final systems in eqns. (1), (3), (4), and (5) have $B = 1$, while in eqn. (2) $B = 2$. A reaction such as

$$\pi^+ + \mathrm{p} \rightarrow \mathrm{p} + \mathrm{p} \qquad (6)$$

where $B = 1$ on the left-hand side and $B = 2$ on the right-hand side is never observed.

A less obvious quantity, conserved in the strong interactions only, is the hyperchange Y, which is defined as twice the average charge (in units of e, the charge on the electron) in any charge multiplet. The average charge of the neutron–proton multiplet is $\frac{1}{2}$e, so the nucleon multiplet is said to have hypercharge $Y = 1$. The K^+, K^0 multiplet similarly has $Y = 1$, but the Λ^0 and the $\Sigma^+, \Sigma^-, \Sigma^0$ hyperons possess $Y = 0$ and the Ξ^-, Ξ^0 multiplet $Y = -1$. Conservation of Y was originally introduced to explain the puzzling fact that hyperons were always produced in association with K mesons in π meson-proton reactions such as that of eqn. (5). As a consequence of the definition, the hypercharge of an antiparticle is always equal in magnitude but opposite in sign to that of the corresponding particle.

We have suggested that, as far as the strong interactions are concerned, all the particles in a charge multiplet (in which each particle possessing the same J, P, and Y are of approximately the same mass) are just different states of the same particle, the different states being labelled by the charge Q. If such a multiplet contains $(2I + 1)$ particles, then I is called the isotopic spin and is also a characterising quantum number (non-additive) associated with each member of the multiplet.

To summarise, each particle can be classified by specifying J, P, B, Y, Q, and I and of these B, Y, and Q are additive quantum numbers, while J adds like an ordinary angular momentum and P obeys a multiplicative rule. The significance and addition rule of the isotopic spin I will now be discussed. An alternative to Y, often used, is the 'strangeness' S, defined by $S = B - Y$.

4 Internal Symmetry Schemes

A. The Isotopic Spin.—Studies of nuclear forces in the early 1930's suggested that if the Coulomb attraction between protons were ignored, the proton–proton neutron–proton, and neutron–neutron forces were identical in corresponding states. W. A Heisenberg showed that this fact could be expressed by a conservation law or symmetry principle. It is supposed that there is an abstract three-dimensional space, called isotopic space, and that the nucleons are associated in this space with a vector quantity, the isotopic spin vector, with components I_1, I_2, and I_3. It is further postulated that I_1, I_2, and I_3 obey the same algebraic relations (the commutation relations) as do the components of the ordinary angular momentum vector in ordinary space. Physical processes are now assumed to be invariant under rotations in this abstract three-dimensional space and this implies that systems of nucleons are described by wave-functions which correspond to definite values of the magnitude of the isotopic spin vector and of its third component I_3, just as invariance to rotation in ordinary space implies that systems must possess a definite value of the total angular momentum and a definite value of the component of angular momentum along a given direction. For a given value of total isotopic spin I [which must be a multiple of $(\frac{1}{2})$] the multiplicity of different states with different I_3 is $(2I + 1)$, so that as the nucleon exists in two states it can be assigned the value $I = \frac{1}{2}$ with $I_3 = \frac{1}{2}$ for the proton and $I_3 = -\frac{1}{2}$ for the neutron. For systems of nucleons the allowed states are found by adding the isotopic spins by use of the same rules by which angular momentum is added in quantum mechanics. The invariance condition then requires that the total isotopic spin (and the third component) found in this way is conserved in any nuclear reaction.

It is now important to notice a fundamental difference between conservation of angular momentum and of isotopic spin. The former law is always exactly satisfied in all reactions, whatever the mechanism, as it arises from the structure of space itself. In the latter case, the law is satisfied by the strong nuclear interaction only to the extent that the Coulomb forces between protons can be neglected. It is more accurate for systems with small numbers of protons and less accurate for systems with large numbers. Nevertheless, because the Coulomb forces are so small compared with the nuclear forces, the idealisation in which isotopic spin is exactly conserved in strong interactions (and in which the mass differences between particles within multiplets is ignored) is most useful.

The extension of this concept to the other elementary particles has been extraordinarily successful. The π mesons form a triplet with $I = 1$, the K^+, K^0 mesons a doublet with $I = \frac{1}{2}$, and so on (see Tables). The value of I_3 is not independent of the quantum numbers that we have previously introduced; in fact $I_3 = Q - \frac{1}{2}Y$. The mass differences within any multiplet are of a magnitude that is consistent with their being of electromagnetic origin, breaking the complete isotopic spin symmetry slightly. With the assignments shown in the Tables the hypothesis that the strong interactions conserve isotopic spin may be tested by noting that all processes that violate this principle occur extremely slowly on the nuclear time scale and can be explained as the result of either the weak or the electromagnetic interactions. This hypothesis also predicts explicit relationships between reaction rates for different members of a multiplet, which after correction for Coulomb forces, appear to be accurately satisfied.

B. Higher Symmetry Schemes.—The successful grouping into isotopic spin multiplets posed the question as to whether further groupings could be achieved. The algebra satisfied by the isotopic spin components (and the ordinary angular momentum components) allows one of these components, I_3, to be an additive quantum number. There is a further additive quantum number, the hypercharge Y, involved in the strong interactions, so a natural extension is to examine algebras for which both I_3 and Y can be additive quantum numbers. The most successful algebra achieving this is known as SU_3, and contains in addition to I_1, I_2, I_3 five further independent quantities, one of which can be identified with Y. We have seen that the isotopic spin algebra (known as SU_2) contains multiplets containing $(2I + 1)$ particles where I is a multiple of $(\frac{1}{2})$, but the corresponding SU_3 multiplets have not quite such a simple structure. The lowest multiplets possible are those containing 1, 3, 6, 8, 10, 15, and 27 different states. If these are to be associated with particles, each particle in a multiplet must have the same values of J, P, and B. In addition the isotopic spin multiplets contained within each SU_3 multiplet are not arbitrary, but are determined. For example, the eight-dimensional multiplet, or octet, contains an isotopic spin singlet with $I = 0$, $Y = 0$, a doublet with $I = \frac{1}{2}$, $Y = 0$, a doublet with $Y = 1$, $I = \frac{1}{2}$, and a triplet with $I = 1$, $Y = 0$, The eight baryons, Λ^0; n, p; Ξ^-, Ξ^0; and Σ^+, Σ^-, Σ^0 fall exactly into this pattern (and the corresponding antiparticles can also be fitted just as well in an octet pattern). These states are shown in Figure 1, plotted in a 'weight' diagram against the allowed values of I_3 and Y. If the strong interactions were exactly invariant under transformations in the abstract SU_3, space then each particle in a multiplet would have exactly the same mass, apart from the small splitting among the isotopic spin multiplets caused by the electro-

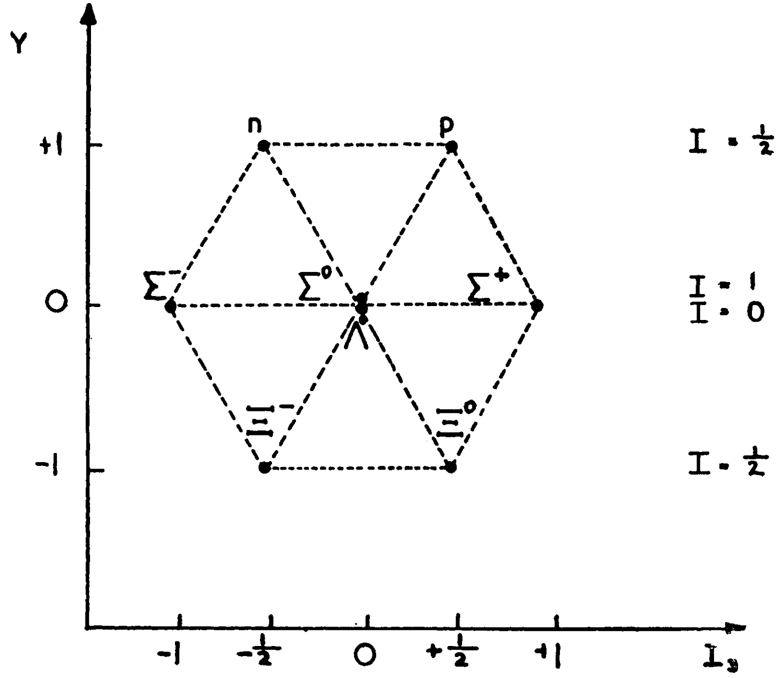

Fig. 1 *The baryon* SU$_3$ *octet.*

magnetic interaction, and also many relations between the reaction rates for collisions between the various particles could be predicted. Examinations of the baryon masses show that they lie between 938 and 1132 Mev/c^2, so that some interaction of medium strength must be present which produces a sizable departure from strict SU$_3$, invariance. By consideration of the simplest possibilities for the SU$_3$ properties of this medium-strength interaction, a mass formula giving the masses in terms of I_3 and Y has been developed. The most convincing evidence for this scheme came in 1962. At that time nine baryon resonances with $J = \frac{3}{2}$ and $P = +1$ were known, consisting of an isotopic spin quartet, $I = \frac{3}{2}$ with $Y = 1$, a triplet with $I = 1$ and $Y = 0$, and doublet with $I = \frac{1}{2}$, $Y = 1$ (Figure 2). These would fit into a ten-dimensional multiplet, if one further particle could be found with $Y = -2$ and $I = 0$, and on the basis of the mass formula, this was predicted to have a mass of about 1680 Mev/c^2. The subsequent discovery of this particle, Ω^-, with a mass of 1676 Mev/c^2 must be considered to be a triumph of the theory.

The mesons also fit neatly into the SU$_3$ multiplets. The nine mesons with $J = 0$ and $P = -1$ divide into an SU$_3$ octet (Figure 3) and an SU$_3$ singlet (the single particle is X^0 of Table 4) and so do the nine mesons with $J = 1$ and $P = -1$ (Figure 4); the physical ω, ϕ particles appear to be mixtures of the

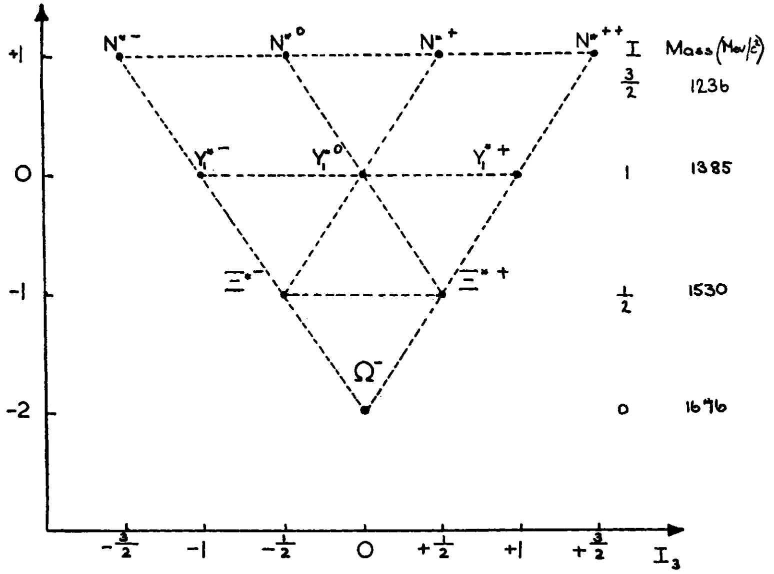

Fig. 2 *The* SU$_3$ *decouplet of baryon resonances.*

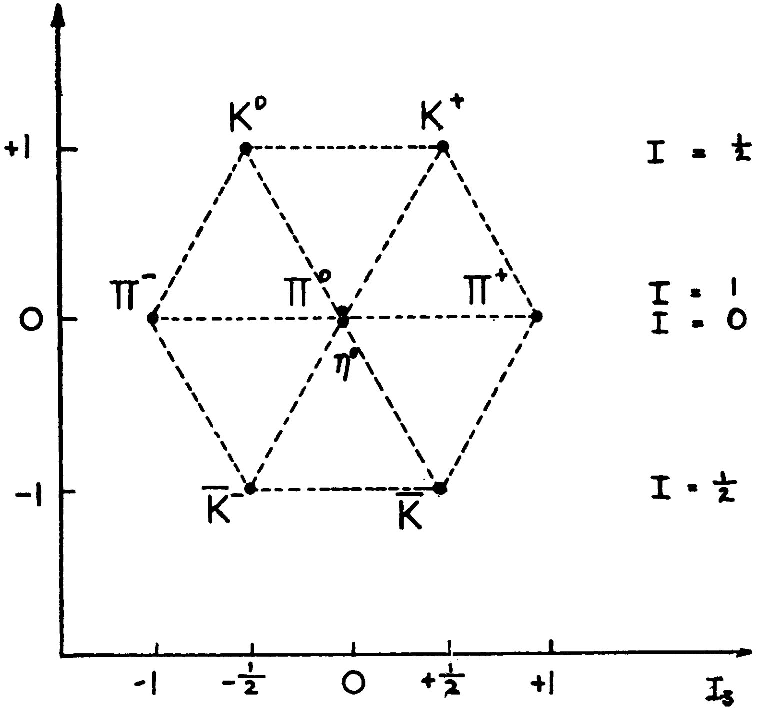

Fig. 3 *The* SU$_3$ *octet of mesons stable under the strong interactions.*

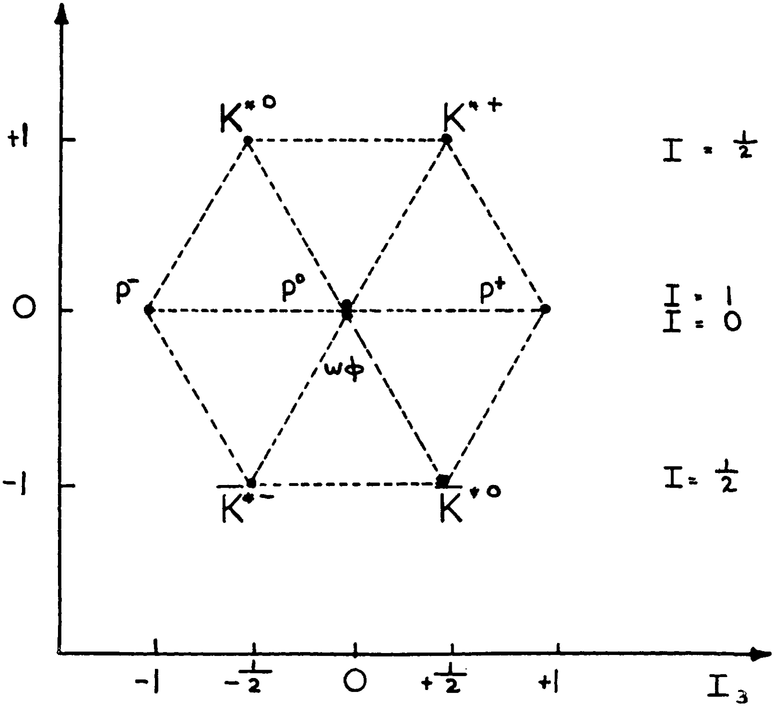

Fig. 4 *The* SU$_3$ *octet of mesons with J* = 1.

singlet state with $Y = 0$ and $I = 0$ and the octet state with the same quantum numbers.

Mathematically the wave functions for particles of any isotopic spin can be formed by combining the wave functions of a suitable number of doublets with isotopic spin $I = \frac{1}{2}$ and $I_3 = \pm\frac{1}{2}$. In the same way all SU$_3$ wave functions can be built by combining triplets. The basic SU$_3$ triplets are composed of an isotopic doublet together with an isotopic spin singlet. The rules for adding SU$_3$ states show that an octet is to be built from three basic triplets, and because $B = 1$ for the baryons and the baryon charges are integral in e, this requires that the quantum numbers of the basic triplet states q_i must be: q_1 with $B = \frac{1}{3}$, $Y = \frac{1}{3}$, $Q = \frac{2}{3}e$; q_2 with $B = \frac{1}{3}$, $Y = \frac{1}{3}$, $Q = -\frac{1}{3}e$; and q_3 with $B = \frac{1}{3}$, $Y = -\frac{2}{3}$, $Q = -\frac{1}{3}e$. A daring speculation of M. Gell-Mann was that one way of accounting for the observed symmetries would be to postulate the existence of three real particles called the quarks,* q_i, of spin $J = \frac{1}{2}$ and $P = +1$, with the basic SU$_3$ triplet quantum numbers q. Antiquarks q_i would also exist with $J = \frac{1}{2}$, $P = -1$ and with the opposite signs of B, Y, and Q. All elementary particles would then

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*'Three quarks for Muster Mark!
Sure he hasn't got much of a bark'; James Joyce, 'Finnigans Wake', Faber and Faber, 1939, p. 383.

be composed of quarks and antiquarks bound together by some basic interaction. The baryon octet would exist of three bound quarks, the meson octets would consist of a bound quark and an antiquark, and so on. Further groupings of particles result from considering the spin and orbital angular momentum of parts of the quark wave functions. Similar results can be obtained by considering higher algebras than SU_3, in particular by considering SU_6 which combines ordinary spin with SU_3. From three quarks with zero orbital angular momentum, each of spin $\frac{1}{2}$, states can be built with total spin either of $J = \frac{1}{2}$ or $J = \frac{3}{2}$. The spin $J = \frac{1}{2}$ states form an SU_3 octet and the $J = \frac{3}{2}$ states an SU_3 decouplet so that the existence of the baryon octet, and the decouplet of spin $J = \frac{3}{2}$ resonances, finds an explanation. The quark–antiquark states with zero orbital angular momentum give rise to states with $J = 1$ or $J = 0$; in each case the SU_3 part of the wave function corresponds to an octet plus a singlet, so the existence of nine mesons with $J = 0$ and nine with $J = 1$, is again explained. Many other particles must be connected with excited states of non-zero orbital angular momentum of the quark systems, but this identification is not yet complete. The mass differences between the various isotopic spin multiplets, within an SU_3 multiplet, can also be explained on this model. It is only necessary to suppose that the quark q_3 possesses a different mass from the quarks q_1 and q_2 to account for the mass splitting within octets. By considering basic interactions between quarks that depend on spin or on the SU_3 operators, the different masses of the different octets and decouplets may perhaps also be explained.

5 The Search for Quarks

If quarks have a real existence as the basic building bricks out of which the elementary particles are constructed, then it should be possible to detect them, because in contrast to all other particles, they possess a charge which is a fraction of the charge on the electron. It seems certain that quarks are not among the particles produced by the giant accelerators, and this implies that they must be extremely heavy, with a mass greater than 4 Gev/c^2. Searches for quarks in cosmic rays have proved to be negative so far, and, although these searches are continuing, it is natural to consider other physicochemical methods for quark detection. Consider the fate of a quark produced by very high-energy cosmic rays in our atmosphere; cosmic ray events are observed in which the primary particle responsible possessed an energy of thousands of Gev, so that quarks of great mass should be produced from time to time. The quarks of charge $-\frac{1}{3}e$ will ultimately be captured by atoms into a Bohr orbit. Because of the great mass of the quark this orbit will be inside the nucleus of the atom. The nucleus will then possess a fractional charge (in units of e), and will remain so for all time, because any mechanism such as β decay which changes the charge of a nucleus can only change it in units of e. The chemical properties of an atom with a fractionally charged nucleus are not yet known in detail; but they will not be very different from the normal atom, because the number of electrons attached to the 'quarked' atom will be the same as for a normal atom.

The positively charged quarks must eventually capture an electron and subsequently the electron–quark combination will behave like a highly reactive electropositive hydrogen atom. For a quark with charge $+\frac{1}{3}e$ this hydrogen-like atom will possess an ionisation potential of 1·51 ev, and it could exist in water as a hydrated ion and would be evaporated as a positive ion. For the quark with charge $+\frac{2}{3}e$, the ionisation potential is 6·04 ev and this could be evaporated mainly in association with an electron or negative ion, and would therefore be manifested as a negatively charged object. In the very interesting experimental work of Chupka *et al.*,[1] which we closely follow in this section, large samples of various materials were passed in gaseous form through an electric field strong enough to detach fractionally charged particles and to concentrate then on a platinum filament. The concentrated specimen could either be examined with a mass spectrometer, or alternatively connected to an apparatus that measured the concentration of negatively charged particles by accelerating them through a field of 15 kv on to an electron multiplier. In this way when the ions were evaporated by heating the filament, the concentration could be measured as a function of time. This concentration decreases exponentially, the decay constant depending on the species. All known negative ions are evaporated in the form of neutral atoms, so the accelerating field of the detector has no effect on the rate of evaporation and if the field is reversed, and then restored, the concentration of negative ions continues to follow the same exponential curve (see Figure 5). Positive ions evaporate in the positively charged state, so that evaporation ceases while the field is reversed. An example of this behaviour is also shown in Figure 5. As quarked atoms never can be neutralised they will behave like positive ions in this respect, and should be easily detected.

The production rate of quarks by cosmic rays is expected to be inversely proportional to their mass, so a measurement of quark concentration also provides a measure of this mass. The first material in which quarked atoms might be found is the atmosphere, and Chupka *et al.* sampled large quantities of air containing *ca.* 10^{33} molecules. In addition, in case the quarked atoms adhered to dust particles, the material collected by the air filters of the laboratory was also examined, the amount corresponding to about 10^{32} air molecules. Some anomalous behaviour was found, but unfortunately this was not repeatable and it was concluded that if the quark mass was less than 10 Gev/c^2 then the concentration must be less than 1 quark in 10^{33} nucleons. The experiments were repeated in sea water and on meteorite material, but no definite evidence for the existence of quarks has been obtained. Another line of attack is to repeat Millikan's famous oil-drop experiment. It is interesting to note that Millikan himself reported 'one uncertain and unduplicated observation . . . giving a value of charge on the drop some 30% lower than the final value of e'.

The quest for the quark has now spread outside the Earth to the solar atmosphere. It has been argued[2] that $-\frac{1}{3}e$ quarks in the galaxy would be found preferentially attached to carbon, nitrogen, and oxygen atoms in the stellar atmospheres. These quarked atoms should show distinctive and easily calculated

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[1] W. A. Chupka, J. P. Schiffer, and C. M. Stevas, *Phys. Rev. Letters*, 1966, **17**, 60.

[2] Y. B. Zel'dovich, L. B. Okun', and S. B. Pikel'ner, *Uspekhi Fiz. Nauk*, 1965, **87**, 113.

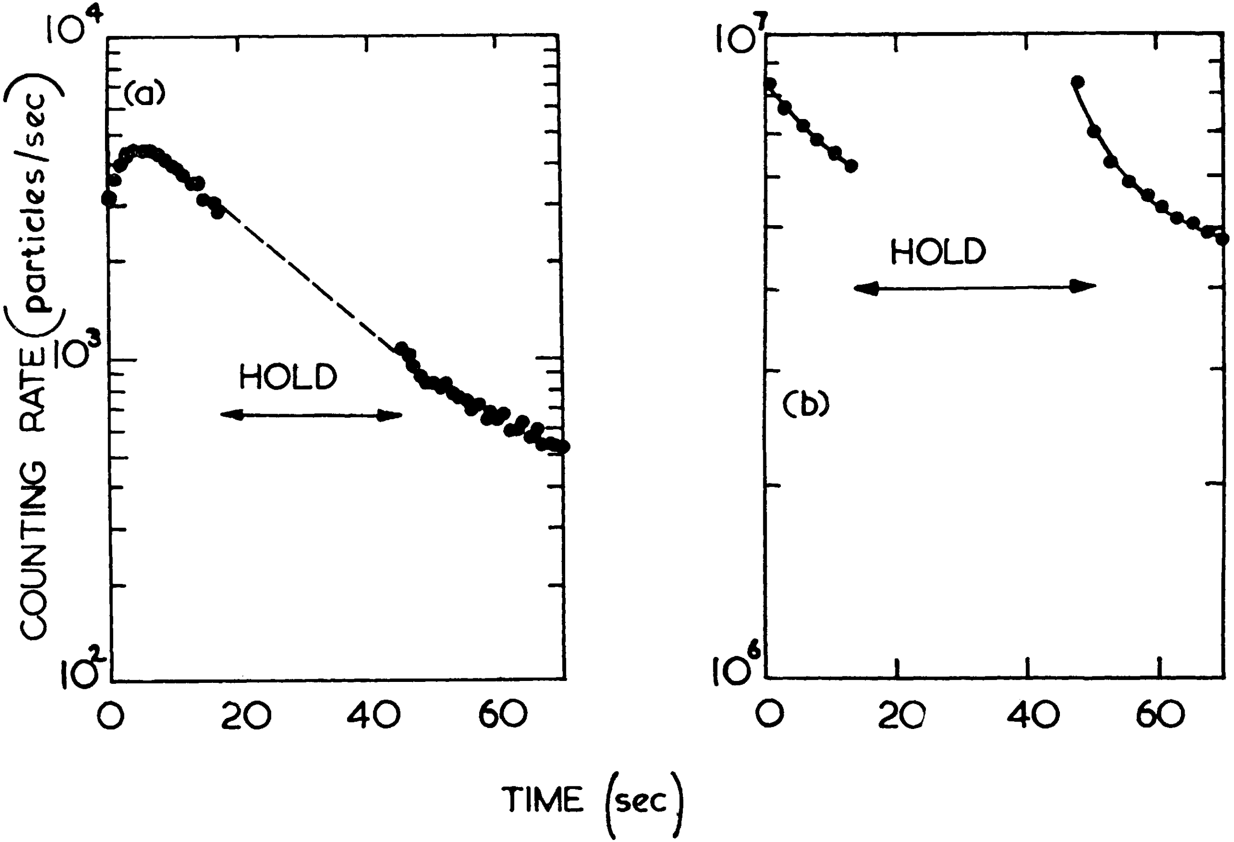

Fig. 5 *(a) The evaporation rate of a sample containing negative ions. The rate is determined by the evaporation of neutralised particles and is unaffected by reversing during the 'hold' period. (b) A corresponding result for a positive-ion species. The evaporation is inhibited during the reversed field 'hold' period.*

electronic spectra. A recent search in the ultraviolet region[3] has proved negative but the limits on the quark concentration are not very stringent.

6 Bootstraps

At the beginning of this Review, the original idea of field theory was noted in which nuclear forces are considered to be due to the exchange of π mesons. This requires that a nucleon should be able to convert into a nucleon plus a π meson and *vice versa*, and similarly that a meson should be able to convert into a nucleon–antinucleon pair and *vice versa*:

$$\mathrm{N} \rightleftharpoons \mathrm{N} + \pi;\ \pi \rightleftharpoons \bar{\mathrm{N}} + \mathrm{N} \tag{7}$$

These elementary processes are virtual because energy and momentum conservation cannot be satisfied simultaneously, but real scattering occurs through a sequence of elementary processes, such as

$$\pi + \mathrm{N} \rightarrow \mathrm{N} \rightarrow \pi + \mathrm{N} \tag{8}$$

Another way of looking at the elementary reactions of eqn. (7) is to consider that the nucleon partly consists of a nucleon and a π meson (and partly of all other combinations of particles into which it can convert). Similarly every particle can be considered to be composed of combinations of other particles, the most important contribution coming from the combination of lightest mass. For example, the ρ meson would be predominantly composed of two π mesons, the $\mathrm{N}^*\frac{3}{2}$ resonance of a nucleon, and a π meson, and so on. Sets of mathematical equations, based on rather general principles such as conservation of probability and relativistic invariance, can be written embodying these ideas which express the relationships between the masses of particles and scattering amplitudes for processes like eqn. (8). It is the hope of the 'bootstrap' school of theorists that these equations have a unique solution determining the observed masses.

As there are probably an infinite number of these equations relating all possible particles and scattering processes, some rather drastic approximations must be made, but such calculations as can be done are quite encouraging. For example, the N* resonance can consistently be described as π meson–nucleon bound state. The most extensive calculations, by G. F. Chew and his colleagues at Berkeley, on the system of the two π mesons have occupied some six years and still have not produced conclusive results, but some encouraging ideas have emerged. For example, one prediction is that particles can be grouped into families so that for each family the masses are a smooth function of the spin of the particles. These mass–spin plots are known as Regge trajectories, and it does seem that the known particles do lie on such curves. Further, the existence of these trajectories has been shown to imply certain behaviours of scattering processes at very high energies, which also appear to be satisfied.

How can the bootstrap model be reconciled with the quark model? How far can the N* be described both as a meson–nucleon state and also as a bound

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[3] O. Singanoglu, B. Skutruk, and R. Tousey, *Phys. Rev. Letters*, 1966, **17**, 785.

state of three quarks? These questions are far from being resolved and it may well be that the two models are incompatible. This does not, of course, mean that the higher symmetries cannot be incorporated into the bootstrap theory, but that these symmetries are not consequences of the existence of real quarks bound together in some potential.

In this Review only the strong interactions have been discussed, because these are responsible for the proliferation of elementary particles. The weak interaction and their connection with the strong interactions have been also extensively studied with some success and the interested reader might consult ref. 4 for further study.

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[4] C. E. Swartz, 'The Fundamental Particles', Addison-Wesley, London, 1965; R. D. Hill, 'Tracking Down Particles', Benjamin, New York, 1963.