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The particle physicist's view of Nature

1.1 Introduction

It is more than a century since the discovery by J. J. Thomson of the electron. The electron is still thought to be a structureless point particle, and one of the elementary particles of Nature. Other particles that were subsequently discovered and at first thought to be elementary, like the proton and the neutron, have since been found to have a complex structure.

What then are the ultimate constituents of matter? How are they categorised? How do they interact with each other? What, indeed, should we ask of a mathematical theory of elementary particles? Since the discovery of the electron, and more particularly in the last sixty years, there has been an immense amount of experimental and theoretical effort to determine answers to these questions. The present Standard Model of particle physics stems from that effort.

The Standard Model asserts that the material in the Universe is made up of elementary fermions interacting through fields, of which they are the sources. The particles associated with the interaction fields are bosons.

Four types of interaction field, set out in Table 1.1., have been distinguished in Nature. On the scales of particle physics, gravitational forces are insignificant. The Standard Model excludes from consideration the gravitational field. The quanta of the electromagnetic interaction field between electrically charged fermions are the massless photons. The quanta of the weak interaction fields between fermions are the charged W^+ and W^- bosons and the neutral Z boson, discovered at CERN in 1983. Since these carry mass, the weak interaction is short ranged: by the uncertainty principle, a particle of mass M can exist as part of an intermediate state for a time $\hbar/Mc^2$, and in this time the particle can travel a distance no greater than $\hbar c/Mc$. Since $M_w \approx 80\,\mathrm{GeV}/c^2$ and $M_z \approx 90\,\mathrm{GeV}/c^2$, the weak interaction has a range $\approx 10^{-3}$ fm.

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Table 1.1. *Types of interaction field*

Interaction field	Boson	Spin
Gravitational field	'Gravitons' postulated	2
Weak field	W^+, W^-, Z particles	1
Electromagnetic field	Photons	1
Strong field	'Gluons' postulated	1

The quanta of the strong interaction field, the gluons, have zero mass and, like photons, might be expected to have infinite range. However, unlike the electromagnetic field, the gluon fields are *confining*, a property we shall be discussing at length in the later chapters of this book.

The elementary fermions of the Standard Model are of two types: *leptons* and *quarks*. All have spin $\frac{1}{2}$, in units of $\hbar$, and in isolation would be described by the Dirac equation, which we discuss in Chapters 5, 6 and 7. Leptons interact only through the electromagnetic interaction (if they are charged) and the weak interaction. Quarks interact through the electromagnetic and weak interactions and also through the strong interaction.

1.2 The construction of the Standard Model

Any theory of elementary particles must be consistent with special relativity. The combination of quantum mechanics, electromagnetism and special relativity led Dirac to the equation now universally known as the *Dirac equation* and, on quantising the fields, to quantum field theory. Quantum field theory had as its first triumph quantum electrodynamics, QED for short, which describes the interaction of the electron with the electromagnetic field. The success of a post-1945 generation of physicists, Feynman, Schwinger, Tomonaga, Dyson and others, in handling the infinities that arise in the theory led to a spectacular agreement between QED and experiment, which we describe in Chapter 8.

The Standard Model, like the QED it contains, is a theory of interacting fields. Our emphasis will be on the beauty and simplicity of the theory, and this can be understood at a certain 'classical' level, treating the boson fields as true classical fields, and the fermion fields as completely anticommuting. To make a judgement of the success of the model in describing the data, it is necessary to quantise the fields, but to keep this book concise and accessible, results beyond the lowest orders of perturbation theory will only be quoted.

The construction of the Standard Model has been guided by principles of symmetry. The mathematics of symmetry is provided by group theory; groups of

Table 1.2. *Leptons*

	Mass (MeV/c^2)	Mean life (s)	Electric charge
Electron e^-	0.5110	∞	$-e$
Electron neutrino ν_e	$< 3 \times 10^{-6}$		0
Muon μ^-	105.658	2.197×10^{-6}	$-e$
Muon neutrino ν_μ			0
Tau τ^-	1777	$(291.0 \pm 1.5) \times 10^{-15}$	$-e$
Tau neutrino ν_τ			0

For neutrino masses see Chapter 20.

particular significance in the formulation of the Model are described in Appendix B. The connection between symmetries and physics is deep. *Noether's theorem* states, essentially, that for every continuous symmetry of Nature there is a corresponding conservation law. For example, it follows from the presumed homogeneity of space and time that the Lagrangian of a closed system is invariant under uniform translations of the system in space and in time. Such transformations are therefore symmetry operations on the system. It may be shown that they lead, respectively, to the laws of conservation of momentum and conservation of energy. Symmetries, and symmetry breaking, will play a large part in this book.

In the following sections of this chapter, we remind the reader of some of the salient discoveries of particle physics that the Standard Model must incorporate. In Chapter 2 we begin on the mathematical formalism we shall need in the construction of the Standard Model.

1.3 Leptons

The known leptons are listed in Table 1.2.. The Dirac equation for a charged massive fermion predicts, correctly, the existence of an *antiparticle* of the same mass and spin, but opposite charge, and opposite magnetic moment relative to the direction of the spin. The Dirac equation for a neutrino ν allows the existence of an antineutrino $\bar{\nu}$.

Of the charged leptons, only the electron e^- carrying charge $-e$ and its antiparticle e^+, are stable. The muon μ^- and tau τ^- and their antiparticles, the μ^+ and τ^+, differ from the electron and positron only in their masses and their finite lifetimes. They appear to be elementary particles. The experimental situation regarding small neutrino masses has not yet been clarified. There is good experimental evidence that the e, μ and τ have different neutrinos ν_e, ν_μ and ν_τ associated with them.

It is believed to be true of all interactions that they preserve electric charge. It seems that in its interactions a lepton can change only to another of the same type,

Table 1.3. *Properties of quarks*

Quark	Electric charge (e)	Mass ($\times c^{-2}$)
Up u	2/3	1.5 to 4 MeV
Down d	−1/3	4 to 8 MeV
Charmed c	2/3	1.15 to 1.35 GeV
Strange s	−1/3	80 to 130 MeV
Top t	2/3	169 to 174 GeV
Bottom b	−1/3	4.1 to 4.4 GeV

and a lepton and an antilepton of the same type can only be created or destroyed together. These laws are exemplified in the decay

$$\mu^- \to \nu_\mu + e^- + \bar{\nu}_e.$$

Apart from neutrino oscillations (see Chapters 19–21). This *conservation of lepton number*, antileptons being counted negatively, which holds for each separate type of lepton, along with the conservation of electric charge, will be apparent in the Standard Model.

1.4 Quarks and systems of quarks

The known quarks are listed in Table 1.3.. In the Standard Model, quarks, like leptons, are spin $\frac{1}{2}$ Dirac fermions, but the electric charges they carry are 2e/3, −e/3. Quarks carry quark number, antiquarks being counted negatively. The net quark number of an isolated system has never been observed to change. However, the number of different types or *flavours* of quark are not separately conserved: changes are possible through the weak interaction.

A difficulty with the experimental investigation of quarks is that an isolated quark has never been observed. Quarks are always confined in compound systems that extend over distances of about 1 fm. The most elementary quark systems are *baryons* which have net quark number three, and *mesons* which have net quark number zero. In particular, the proton and neutron are baryons. Mesons are essentially a quark and an antiquark, bound transiently by the strong interaction field. The term *hadron* is used generically for a quark system.

The proton basically contains two *up* quarks and one *down* quark (uud), and the neutron two down quarks and one up (udd). The proton is the only stable baryon. The neutron is a little more massive than the proton, by about 1.3 MeV$/c^2$, and in free space it decays to a proton through the weak interaction: $n \to p + e^- + \bar{\nu}_e$, with a mean life of about 15 minutes.

All mesons are unstable. The lightest mesons are the π-mesons or 'pions'. The electrically charged π^+ and π^- are made up of $(\mathrm{u}\bar{\mathrm{d}})$ and $(\bar{\mathrm{u}}\mathrm{d})$ pairs, respectively, and the neutral π^0 is either $\mathrm{u}\bar{\mathrm{u}}$ or $\mathrm{d}\bar{\mathrm{d}}$, with equal probabilities; it is a coherent superposition $(\mathrm{u}\bar{\mathrm{u}} - \mathrm{d}\bar{\mathrm{d}})/\sqrt{2}$ of the two states. The π^+ and π^- have a mass of $139.57\,\mathrm{MeV}/c^2$ and the π^0 is a little lighter, $134.98\,\mathrm{MeV}/c^2$. The next lightest meson is the η ($\approx 547\,\mathrm{MeV}/c^2$), which is the combination $(\mathrm{u}\bar{\mathrm{u}} + \mathrm{d}\bar{\mathrm{d}})/\sqrt{2}$ of quark–antiquark pairs orthogonal to the π^0, with some $\mathrm{s}\bar{\mathrm{s}}$ component.

1.5 Spectroscopy of systems of light quarks

As will be discussed in Chapter 16, the masses of the u and d quarks are quite small, of the order of a few MeV/c^2, closer to the electron mass than to a meson or baryon mass. A u or d quark confined within a distance $\approx$ 1 fm has, by the uncertainty principle, a momentum $p \approx \hbar/(1\mathrm{fm}) \approx 200\,\mathrm{MeV}/c$, and hence its energy is $E \approx pc \approx 200\,\mathrm{MeV}$, almost independent of the quark mass. All quarks have the same strong interactions. As a consequence, the physics of light quark systems is almost independent of the quark masses. There is an approximate $SU(2)$ isospin symmetry (Section 16.6), which is evident in the Standard Model.

The symmetry is not exact because of the different quark masses and different quark charges. The symmetry breaking due to quark mass differences prevails over the electromagnetic. In all cases where two particles differ only in that a d quark is substituted for a u quark, the particle with the d quark is more massive. For example, the neutron is more massive than the proton, even though the mass, $\sim 2\,\mathrm{MeV}/c^2$, associated with the electrical energy of the charged proton is far greater than that associated with the (overall neutral) charge distribution of the neutron. We conclude that the d quark is heavier than the u quark.

The evidence for the existence of quarks came first from nucleon spectroscopy. The proton and neutron have many excited states that appear as resonances in photon–nucleon scattering and in pion–nucleon scattering (Fig. 1.1). Hadron states containing light quarks can be classified using the concept of isospin. The u and d quarks are regarded as a doublet of states $|\mathrm{u}\rangle$ and $|\mathrm{d}\rangle$, with $I = 1/2$ and $I_3 = +1/2$, –1/2, respectively. The total isospin of a baryon made up of three u or d quarks is then $I = 3/2$ or $I = 1/2$. The isospin 3/2 states make up multiplets of four states almost degenerate in energy but having charges $2e$(uuu), e(uud), 0(udd), $-e$(ddd). The $I = 1/2$ states make up doublets, like the proton and neutron, having charges e(uud) and 0(udd). The electric charge assignments of the quarks were made to comprehend this baryon charge structure.

Energy level diagrams of the $I = 3/2$ and $I = 1/2$ states up to excitation energies of 1 GeV are shown in Fig. 1.2. The energy differences between states in a multiplet are only of the order of 1 MeV and cannot be shown on the scale of the figure. The

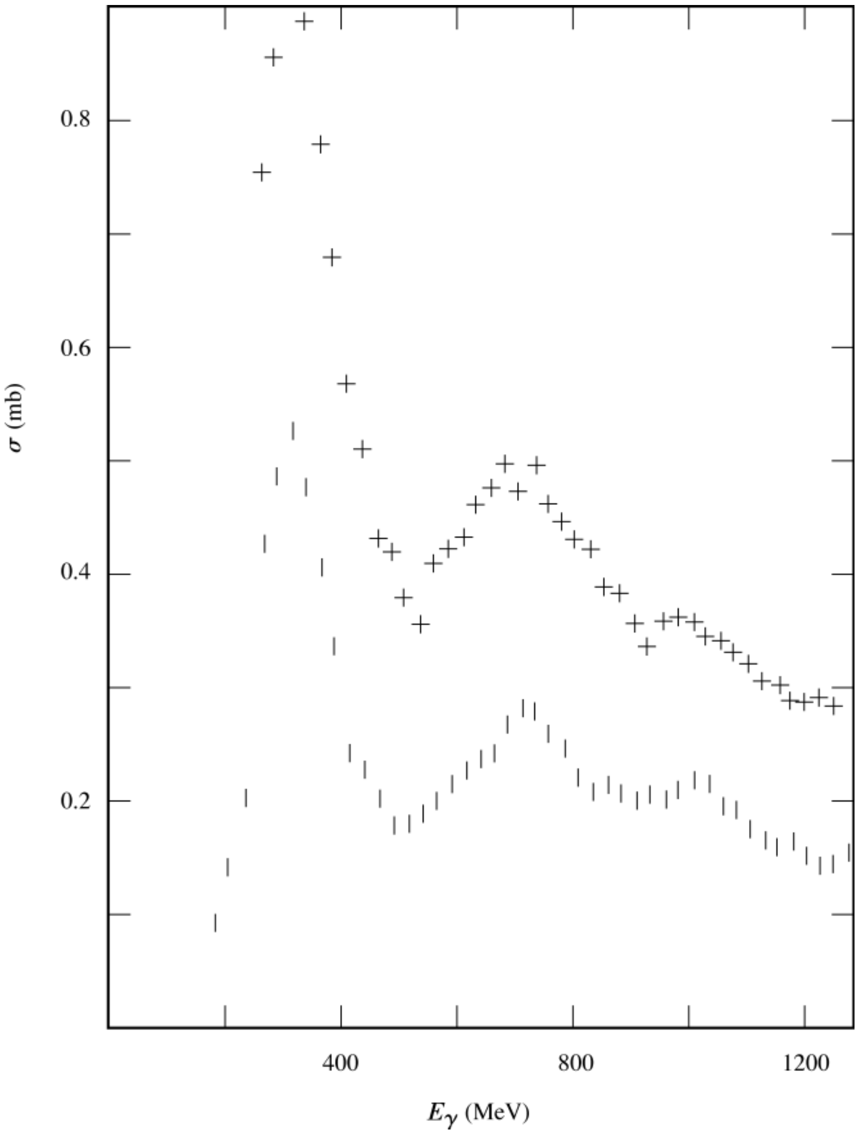

Figure 1.1 The photon cross-section for hadron production by photons on protons (dashes) and deuterons (crosses). The difference between these cross-sections is approximately the cross-section for hadron production by photons on neutrons. (After Armstrong *et al.* (1972).)

widths Γ of the excited states are however quite large, of the order of 100 MeV, corresponding to mean lives $\tau = \hbar/\Gamma \sim 10^{-23}$s. The excited states are all energetic enough to decay through the strong interaction, as for example $\Delta^{++} \to p + \pi^+$ (Fig. 1.3).

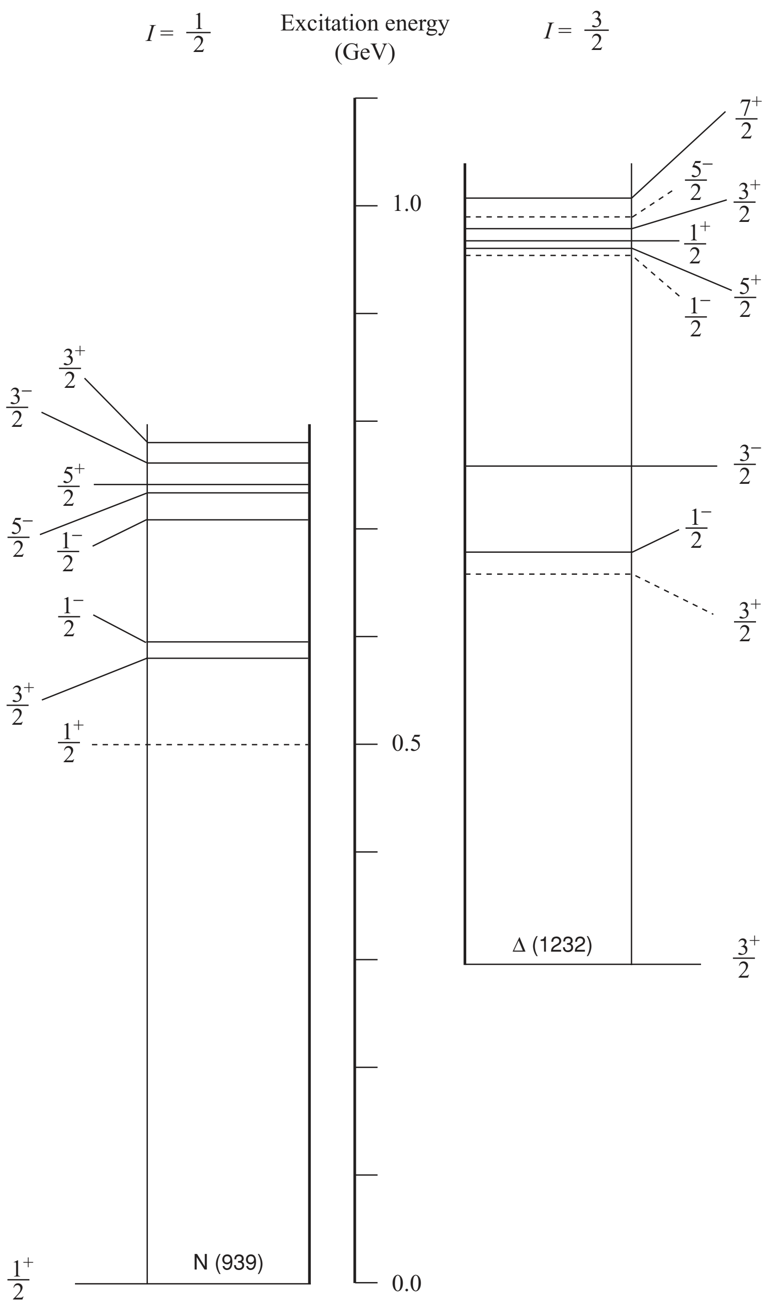

Figure 1.2 An energy-level diagram for the nucleon and its excited states. The levels fall into two classes: isotopic doublets ($I = 1/2$) and isotopic quartets ($I = 3/2$). The states are labelled by their total angular momenta and parities J^P. The nucleon doublet N(939) is the ground state of the system, the Δ(1232) is the lowest lying quartet. Within the quark model (see text) these two states are the lowest that can be formed with no quark orbital angular momentum ($L = 0$). The other states designated by unbroken lines have clear interpretations: they are all the next most simple states with $L = 1$ (negative parity) and $L = 2$ (positive parity). The broken lines show states that have no clear interpretation within the simple three-quark model. They are perhaps associated with excited states of the gluon fields.

Table 1.4. *Isospin quantum numbers of light quarks*

Quark	Isospin I	I_3
u	1/2	1/2
ū	1/2	−1/2
d	1/2	−1/2
d̄	1/2	1/2
s	0	0
s̄	0	0

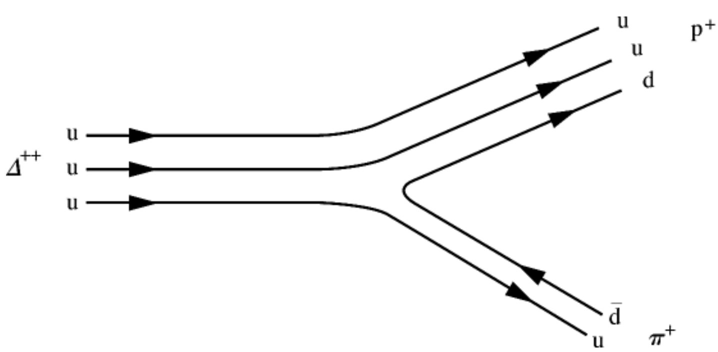

Figure 1.3 A quark model diagram of the decay $\Delta^{++} \to p + \pi^+$. The gluon field is not represented in this diagram, but it would be responsible for holding the quark systems together and for the creation of the $d\bar{d}$ pair.

The rich spectrum of the baryon states can largely be described and understood on the basis of a simple 'shell' model of three confined quarks. The lowest states have orbital angular momentum $L = 0$ and positive parity. The states in the next group have $L = 1$ and negative parity, and so on. However, the model has the curious feature that, to fit the data, the states are completely symmetric in the interchange of any two quarks. For example, the Δ^{++}(uuu), which belongs to the lowest $I =$ 3/2 multiplet, has $J^{\mathrm{p}} = 3/2^+$. If $L = 0$ the three quark spins must be aligned ↑↑↑ in a symmetric state to give $J = 3/2$, and the lowest energy spatial state must be totally symmetric. Symmetry under interchange is not allowed for an assembly of identical fermions! However, there is no doubt that the model demands symmetry, and with symmetry it works very well. The resolution of this problem will be left to later in this chapter. There are only a few states (broken lines in Fig. 1.2) that cannot be understood within the simple shell model.

Mesons made up of light u and d quarks and their antiquarks also have a rich spectrum of states that can be classified by their isospin. Antiquarks have an I_3 of opposite sign to that of their corresponding quark (Table 1.4.). By the rules for the addition of isospin, quark–antiquark pairs have $I = 0$ or $I = 1$. The $I = 0$ states

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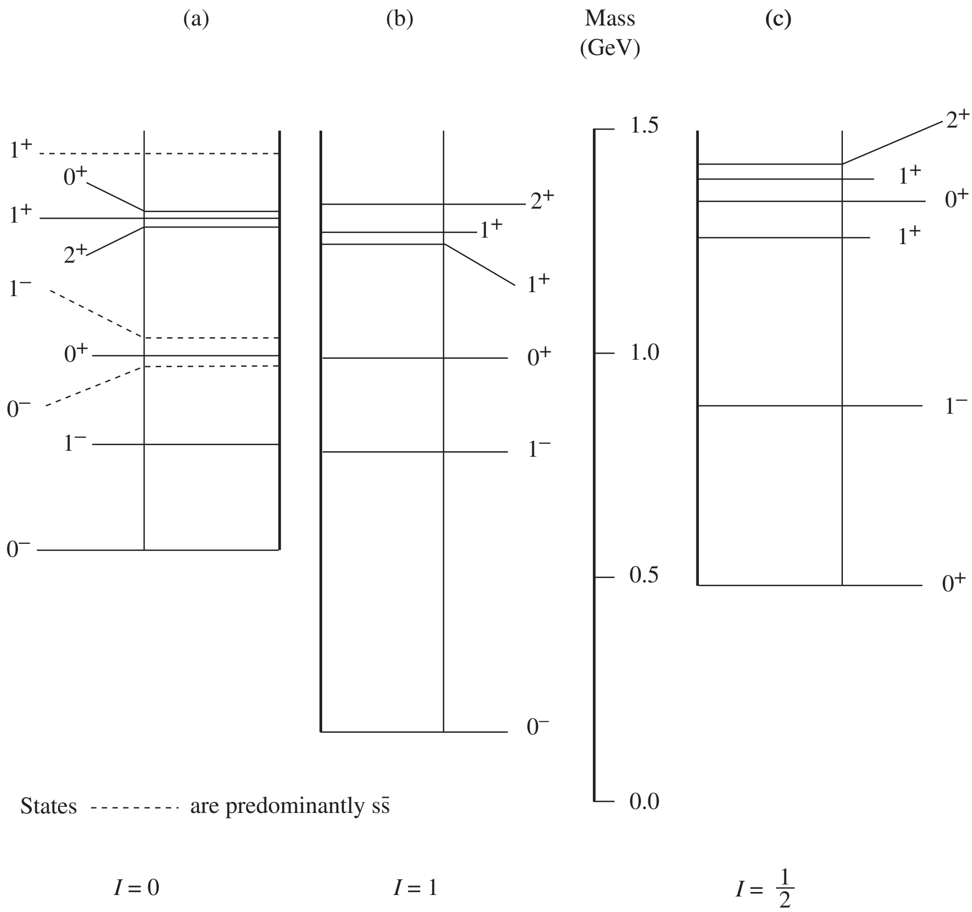

Figure 1.4 States of the quark–antiquark system u$\bar{\text{u}}$, u$\bar{\text{d}}$, d$\bar{\text{u}}$, d$\bar{\text{d}}$ form isotopic triplets $(l = 1)$: u$\bar{\text{d}}$, $(\text{u}\bar{\text{u}} - \text{d}\bar{\text{d}})/\sqrt{2}$, d$\bar{\text{u}}$; and also isotopic singlets $(I = 0)$: $(\text{u}\bar{\text{u}} + \text{d}\bar{\text{d}})/\sqrt{2}$. Figure 1.4(a) is an energy-level diagram of the lowest energy isosinglets, including states --- which are interpreted as s$\bar{\text{s}}$ states. Figure 1.4(b) is an energy-level diagram of the lowest energy isotriplets. Figure 1.4(c) is an energy-level diagram of the lowest energy K mesons. The K mesons are quark–antiquark systems u$\bar{\text{s}}$ and d$\bar{\text{s}}$; they are isotopic doublets, as are their antiparticle states s$\bar{\text{u}}$ and s$\bar{\text{d}}$. Their higher energies relative to the states in Fig. 1.4(b) are largely due to the higher mass of the s over the u and d quarks. The large relative displacement of the 0^+ state is a feature with, as yet, no clear interpretation.

are singlets with charge 0, like the η (Fig. 1.4(a)). The $I = 1$ states make up triplets carrying charge $+e$, 0, $-e$, which are almost degenerate in energy, like the triplet π^+, π^0, π^-.

The spectrum of $I = 1$ states with energies up to 1.5 GeV is shown in Fig. 1.4(b). As in the baryon case the splitting between states in the same isotopic multiplet is only a few MeV; the widths of the excited states are like the widths of the excited baryon states, of the order of 100 MeV. In the lowest multiplet (the pions), the quark–antiquark pair is in an $L = 0$ state with spins coupled to zero. Hence $J^{\mathrm{P}} = 0^-$, since a fermion and antifermion have opposite relative parity (Section 6.4). In the first excited state the spins are coupled to 1 and $J^{\mathrm{P}} = 1^-$. These are the ρ mesons. With $L = 1$ and spins coupled to $S = 1$ one can construct states 2^+, 1^+, 0^+, and with $L = 1$ and spins coupled to $S = 0$ a state 1^+. All these states can be identified in Fig. 1.4(b).

1.6 More quarks

'Strange' mesons and baryons were discovered in the late 1940s, soon after the discovery of the pions. It is apparent that as well as the u and d quarks there exists a so-called *strange* quark s, and strange particles contain one or more s quarks. An s quark can replace a u or d quark in any baryon or meson to make the strange baryons and strange mesons. The electric charges show that the s quark, like the d, has charge $-e/3$, and the spectra can be understood if the s is assigned isospin $I = 0$.

The lowest mass strange mesons are the $I = 1/2$ doublet, K^-(s$\bar{\mathrm{u}}$, mass 494 MeV) and $\bar{\mathrm{K}}^{\mathrm{o}}$(s$\bar{\mathrm{d}}$, mass 498 MeV). Their antiparticles make up another doublet, the K^+(u$\bar{\mathrm{s}}$) and K^{o}(d$\bar{\mathrm{s}}$).

The effect of quark replacement on the meson spectrum is illustrated in Fig. 1.4. Each level in the spectrum of Fig. 1.4(b) has a member (d$\bar{\mathrm{u}}$) with charge $-e$. Figure 1.4(c) shows the spectrum of strange (s$\bar{\mathrm{u}}$) mesons. There is a correspondence in angular momentum and parity between states in the two spectra. The energy differences are a consequence of the s quark having a much larger mass, of the order of 200 MeV.

The excess of mass of the s quark over the u and d quarks makes the s quark in any strange particle unstable to decay by the weak interaction.

Besides the u, d and s quarks there are considerably heavier quarks: the *charmed* quark c (mass $\approx 1.3\ \mathrm{GeV}/c^2$, charge $2e/3$), the *bottom* quark b (mass $\approx 4.3\ \mathrm{GeV}/c^2$, charge $-e/3$), and the *top* quark t (mass $\approx 180\ \mathrm{GeV}/c^2$, charge $2e/3$). The quark masses are most remarkable, being even more disparate than the lepton masses. The experimental investigation of the elusive top quark is still in its infancy, but it seems that three quarks of any of the six known flavours can be bound to form a system of states of a baryon (or three antiquarks to form antibaryon states), and any quark–antiquark pair can bind into mesonic states.

The c and b quarks were discovered in $\mathrm{e}^+\mathrm{e}^-$ colliding beam machines. Very prominent narrow resonances were observed in the $\mathrm{e}^+\mathrm{e}^-$ annihilation cross-sections. Their widths, of less than 15 MeV, distinguished the meson states responsible from those made up of u, d or s quarks. There are two groups of resonant states.