e information recorded is equivalent to about thirty CDs per cond. The ATLAS detector has many goals, and has played an portant role in establishing the existence of the Higgs boson d measuring its mass and other properties. ATLAS is expected provide data for the next ten to fifteen years.

5
Hadrons and the quark model

After the discovery of new hadron states in the 1950s and 60s, particle physicists attempted to describe all hadrons as composites of other states. This eventually led to the development of the *quark model* of particles. This model raised a number of big questions, the most important of which was 'Where are the quarks?' After a decade of investigation, that question was answered.

Strange particles

Shortly after the pion was discovered, other particles were found in cosmic ray experiments that, like the muon, had not been predicted by theory. A group at Manchester University was the first to make these discoveries; they referred to the new particles as *V* particles because of the tracks they produced in the detectors.

Two early examples of these events are shown in Figure 5.1. On the left, a neutral particle decays to two charged particles in a cloud chamber; on the right, a charged particle enters the chamber and decays to another charged particle that easily passes through the absorbing plate in the centre of the chamber. This suggests it could be a muon. The kink in the track at the decay point shows that at least one other (neutral) particle has been emitted but it has not been detected directly, because it does not produce ionisation. This is a neutrino. Later experiments using emulsions found evidence for the decay of these *V* particles to three pions in the

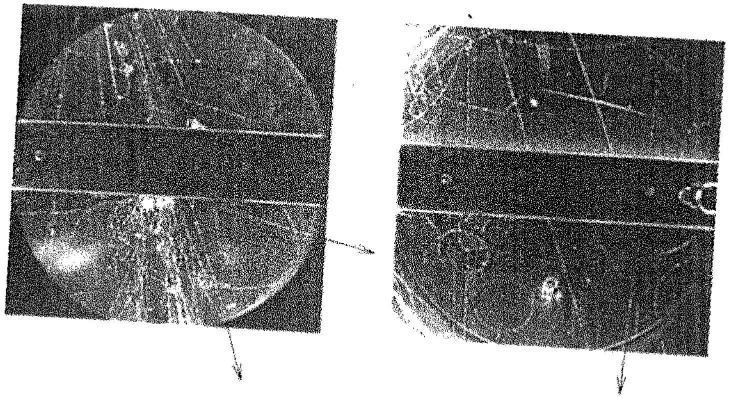

Figure 5.1 Examples of the tracks of *V* particles as seen in a cloud chamber (Rochester, G.D. and Butler, C.C. 1947. *Nature*, **160**, 855; reproduced by permission from *Nature*, Macmillan Publishers Ltd., copyright 1947)

final state. These experiments established the existence of a new particle in three charged forms (positive, negative and neutral) with a mass that was estimated to be approximately 500 MeV/c^2. We now call these *K-mesons* or *kaons*, with the states denoted as K^+, K^- and K^o. K^+ and K^- are anti-particles of each other. The neutral kaon also has an anti-particle, denoted $\bar{K}^o$, although at this point in our story there is nothing to distinguish it from the K^o.

In the early 1950s, further particles were discovered, all heavier than a nucleon, now collectively referred to as *hyperons*. Hyperons, like nucleons, are part of the baryon group of particles. Like the nucleons, they experience the nuclear strong interaction and so are also members of the larger family of hadrons. There are three distinct types of hyperon, denoted by Greek letters: lambda particles (Λ), which only have a neutral form; sigma particles (Σ), which exist in three charged forms (Σ^+, Σ^- and Σ^0) and

particles (Ξ), which exist in two charged forms, Ξ^- and Ξ^0. ach of the hyperons also has an anti-particle.

All the hyperons are unstable and decay to a nucleon (or in .he case of the Σ^0 to a Λ), plus one or more other particles. Decays that do not result in another baryon in the final state are not observed. To particle physicists this is a clear indication that a law of nature is forbidding these decays. The operation of such a law was already apparent from the observed decays of nucleons. For example, the proton does not decay to a positron and a pion, although there appears to be nothing to forbid it. To codify these observations, baryons are assigned a quantum number, the *baryon number*. This number is an example of an *internal* quantum number, as it does not depend on the space-time properties of the particle. Electric charge is also an internal quantum number.

Baryon number is conserved in all interactions; the total baryon number (obtained by adding the individual baryon numbers of the particles) before the interaction is the same as the total baryon number after the interaction, just as in the conservation of electric charge. In practice, the baryon number is defined to be +1 for all the baryons, −1 for their anti-particles and 0 for all other particles. For example, in nuclear beta decay, where a nucleon of one type changes to a nucleon of another type, the total number of baryons is conserved. Likewise, the most likely decay of the lambda particle is to a proton and a negatively charged pion (that is, $\Lambda \rightarrow p + \pi^-$) and baryon number is also unchanged. After the anti-proton was discovered, it was observed that when a proton and an anti-proton annihilate, it is always to a system of particles whose total baryon number is 0 (that is, $p + \bar{p} \rightarrow \pi^+ + \pi^- + \pi^0$). Baryon number differentiates the neutron from the anti-neutron.

One of the most intriguing properties of these new states concerned their decay properties. Although they were produced by the strong interaction at about the same rate at which pions are produced, their lifetimes were far longer than would be expected if they also decayed via this interaction. For example, the lifetime of the charged kaons is about 10^{-8} seconds, characteristic of a weak interaction. Charged pions decay via the weak interaction because there are no lighter mesons to which they could decay via the strong interaction. However, there was no obvious reason why kaons should not decay to two pions via the strong interactions, which would give them a much shorter lifetime of 10^{-23} seconds.

When it came to baryon number, it appeared that a new rule was operating. Gell-Mann coined the name 'strangeness' (S) for this new quantum number because of these particles' unexpected behaviour. The assigned values of the strangeness quantum numbers are $S = +1$ for the K^+ and K^0, $S = -1$ for the Λ and Σ hyperons and $S = -2$ for the Ξ hyperons, with their anti-particles having the opposite sign of S. All other particles are assigned the value $S = 0$. (This choice of values for the strangeness quantum numbers is an historical accident. With hindsight, using numbers with the opposite signs would have been more logical.) The strangeness quantum number distinguishes the K^0 from its anti-particle, the $\overline{K}^0$, and leads to the differences in their properties.

Once strangeness numbers were assigned, selection rules were postulated: strangeness is conserved in strong and electromagnetic interactions but in weak interactions it could change, though by at most one unit. When S does change in the weak interaction, particle physicists talk of strangeness being violated. The rules and assignments attached to strangeness are consistent with all the observed decays: for example, the negative Ξ decays to a Λ particle and a negative pion ($\Xi^- \to \Lambda + \pi^-$), with a change of strangeness of one unit and not to a neutron and a pion ($\Xi^- \not\to n + \pi^-$), which would require a change of strangeness of two units. The rules also explained another observation: strange particles, as they are called, are only produced in pairs in the strong interactions of pions and nucleons, one with positive strangeness and the other with negative strangeness, a phenomenon called *associated production*. Thus, positive kaons are produced in association with sigma hyperons ($\pi^+ + p \to K^+ + \Sigma^+$) but not with protons ($\pi^+ + p \not\to K^+ + p$).

While these rules for strangeness seem almost obvious to particle physicists today, it took five years to deduce them from the various production and decay data. Important steps included the prediction, made by Gell Mann in 1955, of the existence of the neutral states of the sigma and xi (Σ^0 and Ξ^0) from the known properties of their observed charged partners and their experimental discovery four years later. Incidentally, because there is a lighter neutral hyperon with $S = -1$, the lambda, the neutral sigma decays preferentially to a lambda particle and a photon by the electromagnetic interaction, rather than to a nucleon by the weak interaction. For all the other hyperons, there are no lighter states with the same strangeness quantum number and so they are forced to decay via the weak interaction. The lifetime of the neutral sigma is therefore much shorter than that of other hyperons.

Resonances

The hadrons I have discussed so far are analogous to the ground states of atoms or nuclei. Just as they can have excited states, excited states of hadrons also exist. These are unstable and in general decay via the strong interaction to their ground states, with characteristic lifetimes, unless something prevents this from occurring. The first resonance was discovered by Fermi and his group, working in Chicago in the early 1950s. Using a newly-built cyclotron, Fermi was able to produce beams of charged pions with a maximum energy of a couple of hundred MeV and to scatter them from protons in the form of a liquid hydrogen target. The results of an equivalent modern experiment are shown

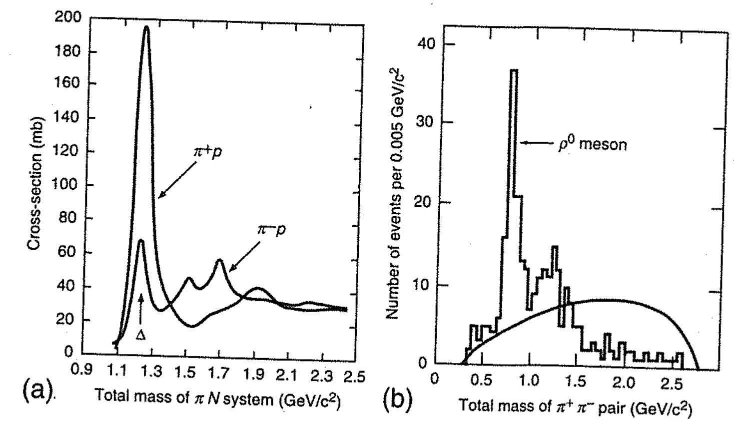

Figure 5.2 (a) Pion-nucleon cross-section as a function of the total effective mass of the πN system
(b) Plot of the number of events where the total effective mass of the two pions produced in the reaction $\pi^- + p \rightarrow p + \pi^+ + \pi^-$ has a specific value

in Figure 5.2a. This shows the 'total cross-section' as a function of the total effective mass of the pion-nucleon system, which includes the energy of their motion. (The total cross-section is the effective area of the target 'seen' by a particle in the beam and is proportional to the probability of any interaction. It is measured in millibarns (mb), where 1 barn is 10^{-28} m^2. There is a very pronounced peak in both the cross-sections where the interaction is particularly strong, indicative of the formation and subsequent decay of a resonance, which we now call the delta.

How do we know that this particle decays via the strong interaction when its expected lifetime would be around 10^{-23} seconds, far too short a time interval to be measured directly by even the best electronic methods? The plot is not unlike the spectral lines exhibited by excited atoms and nuclei. In those

cases, the width of a line is measured in units of energy and denoted by ΔE, where Δ means 'small' and indicates that the width of the state is a relatively small quantity compared to its mass. The width is related to the lifetime, t, of the excited state, whose decay has given rise to the line, drawing upon Heisenberg's uncertainty principle. Specifically, the product of width of the resonance ΔE and t cannot be less than $\hbar/2$. The value of ΔE in the pion-nucleon case can be found from the plot and is about 100 MeV. So the lifetime is about 10^{-23} seconds, which indicates a particle decaying via the strong interaction. It is more usual to quote the width rather than the lifetime for a resonance if it decays by the strong interaction, because the width is easily measured.

The delta resonance, denoted by Δ (which has nothing to do with the use of this symbol in the uncertainty principle!), exists in four charged forms, represented as Δ^{++}, Δ^{+}, Δ^{0}, Δ^{-}, where for example the superscript '++' means a positive electric charge of two units. Subsequent analysis of its decay products found that the Δ has a spin of $\frac{3}{2}$, in units of $\hbar$, the first particle discovered to have a spin greater than one.

Searching for resonances by looking for enhancements in the final states produced in collisions of two particles has been a standard technique ever since Fermi's original experiment and has led to the identification of numerous hadron resonances. The 'golden age' of resonance discovery occurred during the mid- to late 1960s, as computers began to handle the large quantities of data being produced from a new generation of accelerators. As another example, this time for a meson resonance, Figure 5.2(b) shows the total effective mass of the two pions produced from a pion and a proton ($\pi^- + p \rightarrow n + \pi^+ + \pi^-$). The curve shows the expected distribution of events if no resonance was produced. There is clear evidence for an enhancement at a mass of 760 MeV/c^2, which in this case is due to the production and decay to a resonance called the rho (ρ) meson, with a spin of 1.

Composite models and the Eightfold Way

With the rapid proliferation of new particles, including resonances, it was natural to seek a unifying model that would explain these states and their quantum numbers. Several people tried to interpret the known hadrons in terms of a smaller number of elementary states. This was not new. Before the discovery of strange particles, Fermi and the Chinese-American theorist Chen-Ning Yang had proposed a model of the pion as a composite bound state of a nucleon and an anti-nucleon. Although they could explain some of the properties of the pion, their model attracted very little interest until the discovery of strange particles. At that point the Japanese theorist Shoichi Sakata extended the idea to include these particles by taking as his fundamental set of states the nucleons and the lambda, together with their anti-particles. For example, in his model a kaon is a composite of a lambda particle and an anti-nucleon, referred to as $K = (\Lambda\bar{N})$, with the nucleon chosen to give the correct charge on the kaon. One prediction of Sakata's model was that there should be eight light mesons, although at that time only seven were known (three charged pions, two kaons and the kaons' anti-particles). When, in 1961, another neutral state, later called the eta (η) meson, was discovered, it confirmed Sakata's prediction.

The model was less convincing when it came to explaining baryons. When Sakata developed his approach, most physicists believed that theories should put all hadrons on an equal footing – 'particle democracy' – a view that had arisen partly as a result of the failure to produce a quantum field theory for the strong interaction. Sakata's model was not democratic; some baryons were singled out as being special. For example, in the model a sigma hyperon is a composite of a lambda, a nucleon and an anti-nucleon, $\Sigma = (\Lambda N\bar{N})$. But the sigma and lambda are both hyperons with similar properties and there seemed to be no reason why Sakata's choice should be preferred. (The objection that all particles were not being treated equally was rather ironic, because Sakata and his group wholeheartedly embraced Marxist philosophy.)

Around the same time, in 1960 and 1961, Gell-Mann and the Israeli theorist Yuval Ne'eman made a significant breakthrough in understanding the observed spectrum of hadrons. They considered the strangeness and charge quantum numbers of the spin-$\frac{1}{2}$ baryons. When plotted on the diagram shown in Figure 5.3a, they saw that the eight states of this *multiplet* form a hexagon. If the same is done for the spin-0 mesons, the pions and the kaons, as shown in Figure 5.3b, a hexagon also emerges, except at that time a particle was missing from its centre. For consistency across these two patterns, there would have to be an additional neutral meson. The η particle, which was found not long after Gell-Mann and Ne'eman constructed these diagrams, fits the bill. Throughout his career, Gell-Mann has had a knack for producing memorable names for theories and phenomena. In this case he named these patterns of eight the *Eightfold Way*, an allusion to the Eightfold Path of Buddhism.

Gell-Mann and Ne'eman's mathematical theory led them to expect that baryon multiplets could also be positioned naturally in a diagram, in this case in a regular decuplet pattern of ten constituents. At the time this plot was first made, there were nine baryon resonances, all with spin values of $\frac{3}{2}$, of which the delta was one. These are plotted in Figure 5.3c. Again they predicted the internal quantum numbers for the missing particle in the diagram. Gell-Mann also predicted its mass, since he had recognised that mass increased by about 150 MeV/c^2 every time the strangeness quantum number decreased by one. These properties indicated that the missing particle was a negatively charged baryon, which he named the omega-minus (Ω^-), with $S = -3$ and a mass of 1680 MeV/c^2. Gell-Mann's leap is often likened to the gaps that Mendeleev built into his periodic table of the chemical

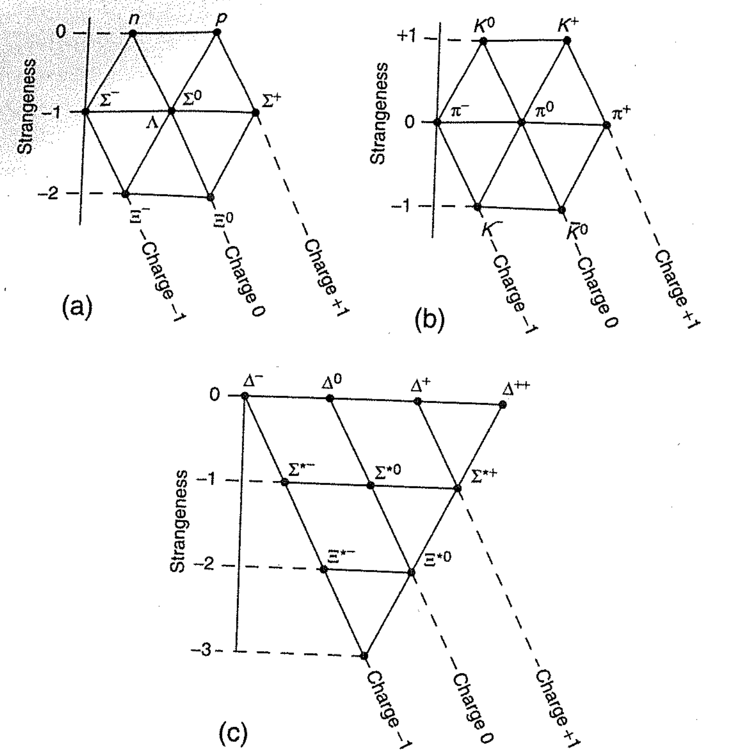

Figure 5.3 Some observed multiplets of hadrons

elements – gaps that were later filled when gallium, germanium and scandium were discovered.

In the Gell-Mann–Ne'eman decuplet diagram, all states except the omega-minus decay via the strong interaction or, in the case of the neutral sigma state, via the electromagnetic interaction, with characteristic decay times. In each case there is a ground-state baryon with the same value of S, so that strangeness can be

conserved in the decay. For the omega-minus, however, there is no ground-state baryon with $S = -3$. Neither is there any lighter multi-particle state with $S = -3$ that would be allowed by conservation of energy, so the decay has to be via the weak interaction. Because of the selection rule that strangeness can only change by at most one unit at a time, the omega-minus was predicted to give rise to a multi-stage process of decays.

To test these ideas, an experimental team at Brookhaven National Laboratory in New York State used a hydrogen bubble chamber to look for a particle with the predicted quantum numbers and decay signature of the omega-minus. They found a match at almost exactly the predicted mass. The particle's production and decay is recorded in the remarkable picture in Figure 5.4, which shows an incoming negatively-charged kaon interacting with a proton and producing an omega-minus and a positively charged kaon. The Brookhaven team was confident the charges of the particles were correctly assigned, because the bubble chamber was in a uniform magnetic field that curved the tracks of charged particles. Because this is a strong interaction that conserves strangeness, they deduced that the other particle produced was a neutral kaon. The production process ($K^- + p \to \Omega^- + K^+ + K^0$) is shown in the right-hand diagram. The neutral kaon does not leave an ionisation trail as do charged particles, so it is shown as a dotted line. The omega-minus travels a short distance and then decays via the weak interaction (that is, $\Omega^- \to \Xi^0 + \pi^-$), where the strangeness quantum number changes by one. Similarly, the neutral xi is shown as a dotted line. Next, the neutral xi decays to two neutral particles, one a lambda and the other a neutral pion, neither of which leave a trail. They are detected by the weak decay of the lambda to a proton and a charged pion ($\Lambda \to p + \pi^-$) and the fact that the neutral pion decays to two photons, both of which produce electron-positron pairs. In these reactions and decays, electric charge and baryon number are also conserved. This figure gives a sense of the skill

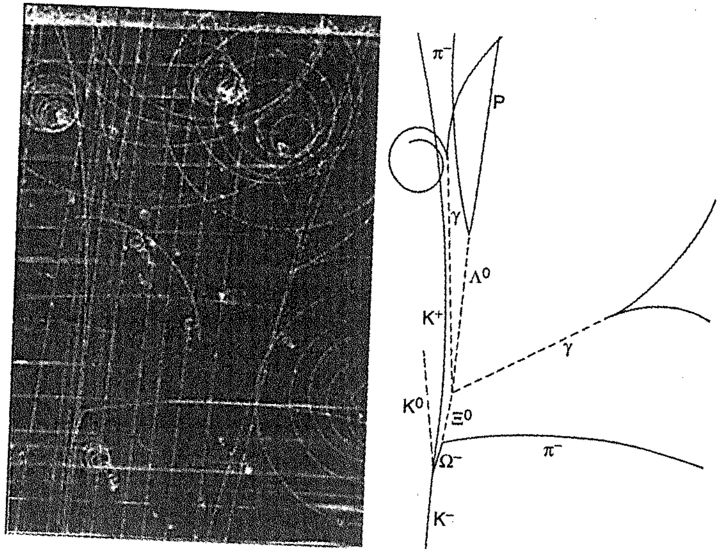

Figure 5.4 Characteristic pattern of tracks in a hydrogen bubble chamber from the production and decay of an Ω^- resonance

required to identify complex events when scanning thousands of bubble chamber photographs.

The quark model

Inspired by the Eightfold Way, in 1964 Gell-Mann and the young American theorist George Zweig simultaneously and independently realised that the observed pattern of particle multiplets would arise naturally if all the known hadrons were composites of three varieties of still smaller entities. Although they arrived at this conclusion by very different paths, their results were the same. Zweig called these constituents *aces*; Gell-Mann called them *quarks*, quoting the phrase 'Three Quarks for Muster

Mark!' from James Joyce's seldom read (and largely unreadable) book *Finnegan's Wake*. It has been said that the quarks refer to the three children of the main character in the book, who is sometimes called Mr Mark and is therefore presumably associated with the proton. Gell-Mann simply said he liked the sound of the word, which reminded him of a duck. The three quarks are the up (u) and down (d) and a new 'strange' quark, denoted by s. The collective properties of each quark type are said to define its 'flavour'. As suggested by its name, the strange quark was assigned a strangeness quantum number of $S = -1$, with the other two quarks having $S = 0$.

In the quark model, baryons are assumed to be clusters of three quarks qqq, bound together by the strong interaction, where initially q is any of the quarks u, d or s. Immediately, some unexpected properties of quarks emerge. First, they have non-integer electric charges and baryon numbers. The electric charges are $\frac{2}{3}$ for the u quark and $-\frac{1}{3}$ for the d and s quarks (in units of the magnitude of the charge on the electron) and the baryon numbers are $\frac{1}{3}$ for all three quarks. The finding for the electric charge was totally unexpected and seemed directly to contradict the results of classic experiments performed between 1910 and 1913 by the American physicist Arthur Millikan. He had shown that the smallest electric charge was that carried by a single electron and that other particle charges were integer multiples of this charge. But if we ignore this objection for the present, it is straightforward to work out the internal quantum numbers of all possible combinations of these three quarks. The result is shown in Table 2, which shows the possible baryon quark clusters in terms of their strangeness (S) and electric charge (Q). In the case of the decuplet of states with spin $\frac{3}{2}$, there is again an exact match between the ten predicted states and those observed experimentally. The same is true for the octet of states with spin $\frac{1}{2}$, provided we exclude clusters where all three quarks are the same.

Table 2 Predicted quark multiples for hadron clusters involving u, d, and s quarks

Baryons	S	Q			Mesons	S	Q	
uuu	0	2	Δ^{++}		$u\bar{s}$	1	1	K^+
uud	0	1	Δ^+	p	$d\bar{s}$	1	0	K^0
udd	0	0	Δ^0	n	$u\bar{d}$	0	1	π^+
ddd	0	−1	Δ^-		$u\bar{u}$, $d\bar{d}$, $s\bar{s}$	0	0	π^0, η^0, η'^0
uus	−1	1	Σ^{*+}	Σ^+	$d\bar{u}$	0	−1	π^-
uds	−1	0	Σ^{*0}	Σ^0, Λ	$s\bar{u}$	−1	−1	K^-
dds	−1	−1	Σ^{*-}	Σ^-	$s\bar{d}$	−1	0	$\bar{K}^0$
uss	−2	0	Ξ^{*0}	Ξ^0				
dss	−2	−1	Ξ^{*-}	Ξ^-				
sss	−3	−1	Ω^-					

Mesons in the quark model are composite states of a quark and an anti-quark $q\bar{q}$, where q can be any of the quarks u, d or s. It is then simple to construct all possible meson states, as with the baryons. In this case, nine states (a nonet) are predicted, a contradiction of Gell-Mann's elegant Eightfold Way. However, the ninth state, called eta-primed (η'), was later discovered and the nonet was confirmed.

An equally impressive and significant fact about these predictions, both for mesons and baryons, is that there are no known states that do not follow from the simple hypotheses of the quark model. For example, there are no known mesons with strangeness quantum number $S = -2$ or baryons with $S = +1$.

What about spin? If baryons are made of three quarks, it follows that quarks must be fermions. Since spins can be added or

subtracted provided the sum is not negative, three quarks, each with spin $\frac{1}{2}$, can have a total spin of $\frac{1}{2}$ (where two add and the third subtracts) or $\frac{3}{2}$ (where all the spins add). Baryons with spin-$\frac{1}{2}$ correspond to particles of the octet, which in the context of the quark model is the ground state multiplet, with the lowest possible energies for a given quark content. Baryons with spin $\frac{3}{2}$ correspond to the decuplet of resonances. Two observed particles with the structure *uds* appear in the spin-$\frac{1}{2}$ octet because, unlike the cases where at least two quarks are of the same type, the exclusion principle does not restrict the composite particle when each of the three quarks is a different flavour. For the baryon, there are two ways that the spins of the three quarks can give an overall value of $\frac{1}{2}$. In the first of these, the spin of a pair can be 0, which when combined with the spin of the third quark gives spin $\frac{1}{2}$ overall; in the second, the spin of the first pair can be 1, which when combined with the spin of the third quark can yield spin $\frac{1}{2}$ or $\frac{3}{2}$ overall.

For mesons, the total spin of a quark and an anti-quark (which also has spin $\frac{1}{2}$) can be 0 (where the two spins subtract) or 1 (where they add). The former corresponds to the ground state nonet and the latter to a nonet of resonances with spin 1, of which the rho meson shown in Figure 5.2b is an example. All the other members of the spin-1 resonance multiplet have been seen experimentally. Again, no states are predicted that do not occur in nature and no states are observed that are not predicted by the simple quark model.

By analogy with the electrons in atoms, quarks can have orbital angular momenta in addition to their spin. This would increase their energies (as it does with electrons in atoms) and lead to heavier hadron resonances with a range of higher spins, such as those seen in the pion-nucleon cross-sections of Figure 5.2a. Whenever spectroscopic predictions for resonances with higher spins have been tested, they have been confirmed by experiment.

Despite its early successes, the quark hypothesis was initially viewed with considerable scepticism because of the failure to observe free quarks. Most physicists looked upon quarks as a convenient mathematical description, rather than as actual physical particles. From his writings at the time, Gell-Mann himself was strongly inclined towards this view, although he downplayed this in later years. On the other hand, Zweig, who had taken a more intuitive approach in arriving at a theory of quarks, openly stated his belief that they were real particles. He paid a high price for his stance. When he submitted a paper to the leading American journal, it met with so much opposition from referees that he eventually withdrew it in exasperation. It was not fully published until sixteen years later. Gell-Mann, anticipating such problems, had prudently submitted his paper to a less prestigious journal.

The simple quark model seems to explain the world of particles extremely well. A baryon with the structure $qqqq\bar{q}$ would, for example, have the same internal quantum numbers as one with the structure qqq because the quantum numbers of the extra quark–anti-quark pair would cancel out. Similarly, mesons with structures of the form $q\bar{q}q\bar{q}$ would have the same internal quantum numbers as those with the structure $q\bar{q}$. Occasionally, experiments have claimed evidence for hadrons with these more complex structures but the observations have never been verified. Scientists conclude that only the particles of the simple quark model exist, although this does not answer the question of why the model works so well.

Colour

In the early years of the quark model, one of the simplest ways to rebut it was to note that quarks had not been seen. Doubters also had another line of attack: there was a conundrum embedded in the proposed structures of the model. For a wide range of states,

the quark model explains the observed internal quantum numbers such as strangeness and the dynamic quantum number that is spin, but we have not considered the consequence of combining them. This is done by applying the exclusion principle, which states that in a collection of fermions, no two particles of the same type can have the same set of quantum numbers. Since quarks are fermions, the principle applies to them.

The problem this raises is most easily seen by considering the spin-$\frac{3}{2}$ baryons shown in Table 2. For example, the omega-minus baryon is a cluster of three s quarks, because this is the only combination that gives $S = -3$. Thus all three quarks have the same internal quantum numbers. But because the omega-minus has spin $\frac{3}{2}$, the quark spins must be oriented in the same direction, so that they add. So, all three quarks are identical and the exclusion principle is violated. This is not just a peculiarity of the Ω^- but is true for all baryons. For example, the doubly-charged delta resonance (Δ^{++}) is composed of three u quarks with aligned spins. Like the Ω^-, this state should not exist!

This is why when discussing spin-$\frac{1}{2}$ baryons, I excluded configurations where all three quarks were of the same type. To obtain the correct spin for the baryon, two of the quarks must have their spins aligned and the third quark spin must be in the opposite direction. Excluding these configurations is equivalent to allowing only those configurations where all three quarks have their spins aligned; that is, only allowing states that violate the exclusion principle. However, there is overwhelming evidence for the exclusion principle from atomic physics, so another solution had to be sought.

It did not take long before the American physicist Oscar 'Wally' Greenberg found the solution by resorting to the old device of particle physicists: invent a new quantum number. He called it, rather whimsically, *colour*, and hypothesised that quarks exist in three distinct colour states, which we now call red, blue and green, following the three primary colours of light.

Similarly, he assigned 'anti-colours' – anti-red, anti-blue and anti-green – to anti-quarks. Needless to say, colour in this context has absolutely nothing to do with the colours we experience visually. Greenberg further suggested that the quarks in hadrons are in different colour states: baryons would contain one red, one blue and one green quark. Then, because the three quarks would not be truly identical, the exclusion principle would not be violated! Pursuing the analogy with 'real' colour, combining the three primary colours of light yields white light, so the observed baryons are referred to as being 'colourless'; mesons consist of combinations of a coloured quark and an anti-quark carrying an anti-colour, so their observed states are also colourless. Greenberg's proposal that observable states have to be colourless is called *colour confinement*. It immediately explains why clusters of quarks such as $qqq\bar{q}$ and qq and other particles with fractional charges, are not observed experimentally. However, colour does not explain why states such $qqqq\bar{q}$ do not seem to exist.

What is colour, other than a convenient device to restore agreement with the exclusion principle? In 1972, the German theorist Harald Fritzsch, with his Swiss collaborator Heinrich Leutwyler and also Gell-Mann, hypothesised that colour plays the role in the strong interaction that electric charge plays in the electromagnetic interaction. As with the 'like charges repel, unlike charges attract' rule for electric charge, a colour 'charge' and its anti-colour would attract, yielding stable clusters of pairs of quarks, in which one has a definite colour and the other its anti-colour: these are the mesons. At the same time, states consisting of quarks with three distinct colours would also exist because of the mutual attraction of the three quarks of different colours: these are the baryons.

By the mid-1960s, particle physicists agreed that the simple quark model, incorporating the new quantum number of colour, gave a good account of the observed spectrum of hadrons, including both their ground states and their resonances.

When strangeness was introduced to explain the production and decay data for the kaons and hyperons, other predictions were made that were later verified by experiment, even though the reason for the existence of strangeness remained unclear. Colour, however, had been introduced purely to avoid violating the exclusion principle and so it was essential that it be tested in another context. In the next chapter we will see how the answers to these perplexing questions about quarks were resolved.