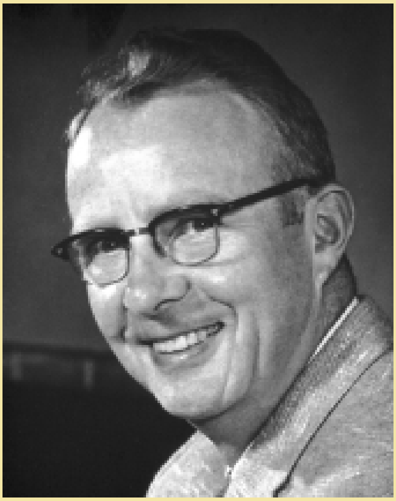
8 The Particle Zoo

8.1 Introduction

Around 1960 the situation in particle physics was very confusing. Elementary particles[a] such as the photon, electron, muon and neutrino were known, but in addition many more particles were being discovered and almost any experiment added more to the list. The main property that these new particles had in common was that they were strongly interacting, meaning that they would interact strongly with protons and neutrons. In this they were different from photons, electrons, muons and neutrinos. A muon may actually traverse a nucleus without disturbing it, and a neutrino, being electrically neutral, may go through huge amounts of matter without any interaction. In other words, in some vague way these new particles seemed to belong to the same group of particles as the proton and neutron. In those days proton and neutron were mysterious as well, they seemed to be complicated compound states. At some point a classification scheme for all these particles including proton and neutron was introduced, and once that was done the situation clarified considerably. In that era theoretical particle physics was dominated by Gell-Mann, who contributed enormously to that process of systematization and clarification. The result of this massive amount of experimental and theoretical work was the introduction of quarks, and the understanding that all those 'new' particles as well as the proton

[a] We call a particle elementary if we do not know of a further substructure.



Luis Alvarez (1911–1988). After Glaser came up with the idea of a bubble chamber Alvarez was quick to realize the potentialities of such an instrument. With considerable energy he put himself to the task of building bubble chambers, and to use them for physics purposes. With his group of very talented engineers and physicists (the distinction was not always clear) at Berkeley he started constructing a then relatively large hydrogen bubble chamber (10 inch = 25 cm long), with which a large amount of physics was done. They discovered many of the particles mentioned in this section. Alvarez received the 1968 physics Nobel prize.

In a subsequent daring step the Berkeley group went on to construct a much larger hydrogen bubble chamber ($72 \times 20 \times 15$ inch = $183 \times 51 \times 84$ cm) for the then large sum of $2.5 million. The problems were huge: liquid hydrogen (or deuterium) had to be kept at a temperature of -250°C, and the magnet surrounding the bubble chamber was very large (100 tons, using some 2 Megawatts to power it).

The first very significant result obtained with the 72-inch chamber was due to Pevsner and his group at Johns Hopkins University. The chamber (filled with deuterium) was exposed to a beam of pions from the Bevatron (a 6-GeV accelerator in Berkeley) and photographs were taken and sent to Johns Hopkins. The result was the discovery of the η, which particle completed the octet of mesons as described in this Chapter.

The relation of Alvarez with the then director of LBL (Lawrence Berkeley National Laboratory), Edwin MacMillan, deteriorated to the point that it interfered with the physics done. So it goes.

Scanning table at CERN in 1972. These devices were used at all institutions engaging in particle research. Rolls of film would be recorded during some run at one of the big accelerator laboratories and then scanned and analyzed at the various university laboratories. Up to a million of such pictures were recorded, and one can see the huge and rather dull work associated with that. The physicist became more of a manager rather than an experimenter. The scanning was usually done by girls who often did not know anything about the subject.

This kind of physics, while a necessity for progress, tended to make particle physics dull and uninteresting. At the scanning table the data was recorded on magnetic tapes for further processing by computers, and things became interesting again after computers processed the data and summarized the results in graphs and histograms. Then patterns could be found and new particles discovered. The new particles, all of them highly unstable, would decay in a very short time, and they were established through analysis of the decay products. For example, Pevsner and his group at Johns Hopkins University obtained films from the 72-inch hydrogen bubble chamber at Berkeley exposed to a pion beam. The pions colliding with protons in the bubble chamber gave rise to events with many particles coming out. Pevsner and co. then searched for combinations involving three pions, and tried to figure out if the three pion configurations were consistent with the decay of a single particle (the η). The curvature of the tracks (due to a magnetic field in the bubble chamber) allowed the determination of the particle energies, and from them the mass of the η (about 550 MeV). Not all three-pion systems are due to η decay, so this was actually a lot harder than it seems.

and neutron were various bound states of quarks. So this is what this Chapter is about: bound states of quarks. There are many of them, and they form what we may call the particle zoo. They are particles, but not elementary particles. Some of them have been mentioned before, namely pions and kaons.

It must be well understood that although hypothetical particles called quarks could theoretically be used to understand all these states as bound states of these quarks, there was nonetheless at that stage no evidence that the quarks were actually real particles, with a well-defined mass. That changed completely after 1967, when experiments at SLAC showed that inside protons and neutrons there were point-like things. This will be discussed in Chapter 11.

8.2 Bound States

Thus at this point the big complication was that for some reason, even now not yet completely understood, the quarks cannot occur by themselves, free. They occur only in bound states. That was difficulty number one. Furthermore, the way that the quarks are bound differs quite a lot of what is seen in other known bound states such as atoms and nuclei, and it took quite some time before this was understood. That was difficulty number two, which we shall describe now.

In a hydrogen atom the constituents (one proton and one electron) are still easily recognized. The binding energy is relatively low, so that the total energy of the atom is very close to the sum of the energies contained in the masses of the electron and the proton.

To be precise, the masses of the electron and the proton are about 0.511 MeV and 938.272 MeV respectively, and the binding energy is -13.6 eV = -0.0000136 MeV. The binding energy is negative, you must add energy to tear the atom apart. Clearly the binding energy is next to nothing compared to the mass energies, and the mass of the hydrogen atom is in good approximation equal to the sum of the electron and proton masses.

For nuclei the story is quite similar, except that the binding energy is much larger. However, it is still small compared to the masses of the protons and the neutrons in the nucleus.

For helium, for example, the nucleus contains 2 protons and 2 neutrons, and using the mass values 938.272 and 939.563 MeV gives 3755.67 MeV for the mass energy of the helium nucleus. For the helium nucleus the binding energy (equal to minus the energy needed to tear that nucleus apart into its constituent protons and neutrons) is -28 MeV. Thus the binding energy is about 0.7% of the total energy. The nuclear binding energy is slightly different from nucleus to nucleus, and is usually quoted in terms of binding energy per nucleon. For helium that is $-28/4 \approx -7$ MeV.

Thus it is quite easy to count how many protons plus neutrons there are in a given nucleus, simply by measuring its mass. That makes it easy to realize that nuclei are bound states of protons and neutrons. But with bound quark states that is a very different matter.

Bound states of quarks are complicated structures. The reason is that the gluons, responsible for the strong interactions between the quarks, also interact with themselves, and there are big globs of gluons that keep the quarks bound. While the gluons themselves are massless, they do have energy, and the gluon globs are quite energetic and thus contribute to the mass of the bound state. The quarks are embedded in gluons. The masses of the quarks are only a small part of the mass of the bound states. For example, the proton has two up quarks and one down quark, which accounts for about 15 MeV of the mass of the proton, 938.27 MeV. Thus the gluon blob contains some 923 MeV! It is very hard to even speak of binding energy in those circumstances. Moreover, it is not possible to separate the proton into its quark constituents. As the quarks are moved apart more and more gluon matter builds up between the quarks, requiring energy, and that energy keeps on increasing no matter how far the quarks are separated. This kind of binding mechanism is totally unknown elsewhere, and that made it so hard to recognize the real state of affairs.

It is obviously not easy to determine the quark masses in these circumstances. A certain amount of not too clear theory goes into that, and consequently there are quite large uncertainties here, in particular for the up and down quark. However, information on the mass difference between the up and down quark mass can be guessed from the mass difference between proton (*uud*) and neutron (*udd*), 1.291 MeV. Proton and neutron are very similar in their quark-gluon structure, and the main difference is in electric charge. The energy related to the electric force must be taken into account, and the up-down quark mass difference is estimated to be somewhere between 1.5 and 4 MeV.

Matters change when heavier quarks are involved. Bound states containing heavy quarks were discovered after 1967, so these states did not play any role in the question of hypothetical versus real quarks. The heavy quarks are the charmed, bottom and top quark, with masses of approximately 1.3, 4.5 and 175 GeV (1 GeV = 1000 MeV). These masses are quite large compared to the energy contained in the gluon blobs, and it is easy to guess how many of these heavy quarks are contained in any bound state. In 1974 the first bound state involving heavy quarks was discovered and identified as a new particle simultaneously at SLAC (Stanford) and BNL (Long Island). The people at SLAC called it a ψ, those at Brookhaven a J, and till today we are saddled with this dual name. This J/ψ particle, with a mass of about 3000 MeV, was later established to be a bound state of a charmed quark and an $\overline{\text{charmed quark}}$.[b] The mass of the J/ψ is 3096 MeV, as compared to the sum of the quark masses of about 2600 MeV. Apparently there is here about 500 MeV in the gluon

[b]Reminder: the bar indicates the antiparticle.

blob. The amount of energy in the glue of the quark bound states varies from case to case, and is generally in the range of 120 to 1000 MeV.

The foregoing makes clear that it was quite difficult to recognize the observed particles (those involving up, down, and strange quarks only) as bound states of varying numbers of quarks and antiquarks.

8.3 The Structure of Quark Bound States

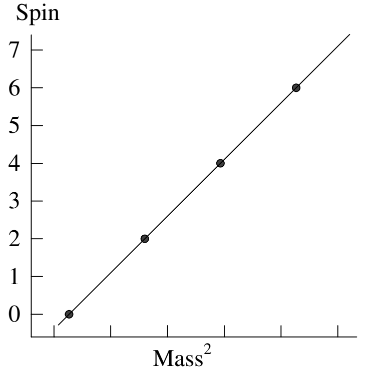
Today a proton is understood as a glob of gluons with three quarks swimming in it. One might ask if such gluon blobs could also exist without any quarks in them, and in fact that has been suggested. Extended experimental searches have not produced convincing evidence for such particles, tentatively called glue-balls. Somehow the quarks seem to be a necessary ingredient.

The branch of physics that is about gluons and their interactions with themselves and with quarks is called quantum chromo-dynamics (QCD). It is a very complicated subject, and it will not be discussed in any serious way in this book. The complications arise because, as mentioned above, the various types of gluons interact with each other in a complicated way. It is due to this that one can have large blobs of gluons that seem to resemble wads of chewing gum. The analogy goes even further: when considering a two-quark bound state one may try to take it apart. What happens is that, when separating the quarks, a string of glue appears to form between the two quarks. As if trying to tear a piece of chewing gum apart. The difference is that the chewing gum will break at some point, while the gluon glob just keeps on stretching. The peculiar thing about it is that the force with which the two quarks are held together apparently remains roughly the same, no matter how much they have been pulled apart. That at least is more or less what most particle physicists think today, although the evidence for this precise constant behaviour is not very substantial. In any case, one can apparently never get the two quarks separated. A lot of experimentation and theory has gone into that, but these gluon strings remain difficult objects. They are an approximate description of a complex situation. People have idealized and abstracted these strings of glue to string-like objects that have no quarks and are not glue either, and that has given rise to string theory, studied widely. However, there is no evidence of any kind that Nature uses strings other than in the approximate sense of gluon matter between quarks relatively far apart.

Let us now describe the above in more detail. In the past, when quantum mechanics was introduced, the first important system to which the theory was applied was the hydrogen atom. One started from the known electric attractive force between electron and proton. This force, the Coulomb force, is known to fall sharply as the distance is increased, and to be precise it falls quadratically with that distance. So if the electron and proton are at some distance there will be an attractive force, and then moving the electron out to twice that distance the force becomes four times smaller.

Now, using this Coulomb force law, quantum mechanics predicts the various bound states for an electron and a proton, and these bound states are the excited states of hydrogen. They correspond to the electron circling in higher orbits. If now an electron circulating in a higher orbit around the proton drops to a lower orbit it will emit a photon. The energy of that photon is precisely equal to the difference in the energy of those two bound states. Thus by observing the energy of the photons emitted by hydrogen after being put in an excited state (this can be done by bombarding the hydrogen atom with electrons) one may precisely establish the energies of the excited states, that is the bound states with the electrons in higher orbits. The experimentally observed optical spectrum of hydrogen agreed very well with the energies of the bound states found when using the Coulomb force law in the quantum mechanical calculations. Conversely, if one had not known about the Coulomb force law, one could have deduced that law by observing the spectrum and then trying to find which force law would reproduce the observed spectrum of photon energies. That is the procedure which one tried to apply in connection with the quark bound states.

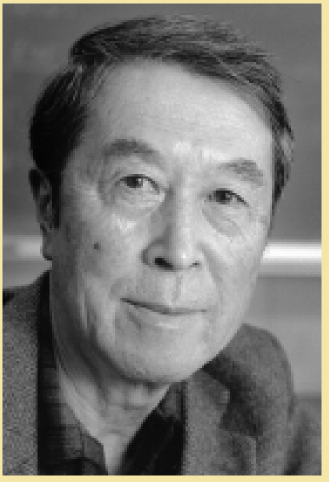
There is some (scanty) evidence that associated with a given bound state of quarks there were higher mass bound states, with higher spins. Making a plot of these bound states, plotting spin versus the square of the mass, something like a straight line seemed to appear.



Such a line is called a Regge trajectory (after the Italian physicist T. Regge). Using the procedure sketched above such a spectrum of bound states of two quarks can be understood as due to a force that would be independent of the distance between these quarks. That force was interpreted as due to a string-like configuration of quarks and gluons.

In time the Regge trajectories thus became the cradle of string theory. Nowadays the Regge trajectories have largely disappeared, not in the least because these higher spin bound states are hard to find experimentally. At the peak of the Regge fashion (around 1970) theoretical physicists produced many papers[c] containing families of Regge trajectories, with the various (hypothetically straight) lines often based on one or two points only!

[c]Just like these days on the subject of strings.



Yoichiro Nambu (1921). Nambu interpreted the success of the Regge idea in terms of a force between quarks. He also had a large influence on the development of quantum chromodynamics; together with a collaborator, Han, he essentially introduced quark color charges. Not only that, they then also introduced what we now call gluons. Their work was yet a far cry from the rather elegant theory of quark and gluon interactions (quantum chromodynamics) that is today contained in the Standard Model, but the basis for a considerable part of the theory was undoubtedly in their paper.

Another important contribution by Nambu (together with Jona-Lasinio) is the idea of a neutral field in the vacuum. While such a field would not be observable by direct experimentation, it could explain a number of observed facts. This idea became the basis of the work of Brout, Englert and Higgs (see Chapter 10) that was of fundamental importance in connection with gauge theories.

Somewhere in the nineties I had an unexpected encounter with Nambu. I had developed some equation that contained a relationship between the top quark mass and the Higgs particle mass, both particles then still to be discovered. If the top is sufficiently heavy that relation becomes very simple: the Higgs is twice as heavy as the top. At that point, at Fermilab, I ran into Nambu who not only had arrived at the same equation, but in addition came up with the idea that the Higgs might thus be a bound state of a top and an antitop quark (which indeed would put the Higgs mass at about twice the top mass). We went together to question the experimenters about the state of affairs, but then, as now, there was no answer. We are still waiting for the Higgs.

It is for our purposes quite pointless to describe the multitude of bound states observed. The discussion will be restricted to bound states of the light quarks, that is the up, down and strange quarks, and even more narrowly to some subset of these bound states, namely the states of lowest mass. Those states were experimentally discovered in the period 1948–1965. Mainly quark-antiquark bound states, called mesons, and three-quark bound states, called baryons will be reviewed. Bound states containing heavy quarks (charm, bottom and top) will be discussed briefly after that.

8.4 Spin of a Bound State

A bound state is just another particle, just as an atom may be considered a particle. Any particle has a spin that may be considered as an internal state of rotation. It is really like a spinning tennis ball. However, on the particle level there are quantum effects, meaning here that only certain amounts of rotation, of spin, are possible. All spins must be integer or half-integer multiples of a certain basic quantity. That basic quantity will be taken as the unit, so spins can take the values 0, $\frac{1}{2}$, 1, $\frac{3}{2}$, 2, $\frac{5}{2}$, etc. The spin of a bound state is equal to or between the sum and difference of the spins[d] of its constituents plus an integer amount. The extra integer amount can be seen as a rotation of the constituents around each other. Negative spin does not occur, to us spin is simply the amount of rotation, and that can be zero but not less than zero. So this is the picture: the total amount of rotation is the internal rotation of the quarks themselves (the spin of the quarks) plus the spin due to these quarks rotating around each other. It is a simplified picture, because the gluon matter may (and does) rotate as well, but altogether one obtains the result described, as if ignoring the gluon glob.

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[d] However always integer or half-integer if the sum is integer or half-integer.

8.5 Mesons

Mesons are defined as bound states of one quark and one antiquark. Both quark and antiquark have spin $\frac{1}{2}$. The spin of a meson can be 0, 1, 2, etc. We start with low mass spin zero particles.

Considering only bound states of up, down and strange quarks there are nine possibilities. These possibilities are listed below. The first line lists the quark antiquark combinations, the second line the symbols of the experimentally found particles that appear to correspond to these combinations. As usual, the bar indicates an antiquark, thus for example $\overline{u}$ is the antiup quark or $\overline{\text{up quark}}$.

$d\overline{s}$	$u\overline{s}$	$d\overline{u}$	$u\overline{d}$	$s\overline{u}$	$s\overline{d}$	$d\overline{d}$	$u\overline{u}$	$s\overline{s}$
K^0	K^+	π^-	π^+	K^-	$\overline{K}^0$	π^0	η	η'

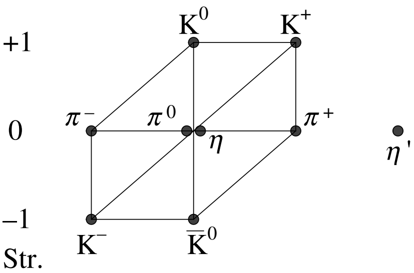
The color charge of the quarks (see Chapter 2) plays no role in this discussion; the bound states are color neutral. This means that if there is for example a red quark, there is also an anti(red quark). The bound state will be a mixture of the possible color combinations red–antired, green–antigreen and blue–antiblue.

The pions (π) and kaons (K) have been mentioned before, in Chapter 6. These particles were copiously produced at the first big machines (CERN, BNL), and became the subject of intense experimentation. All particles shown on the second line were discovered before it was realized that they were bound states of a quark and an antiquark, and the names shown are those given in the pre-quark era. The electric charges of these particles are as shown, if not indicated (η and η') they are zero.

The table is strictly speaking not correct, because the π^0, η and η' are not precisely the bound states listed above them, but certain mixtures. For example, the π^0 is a mixture of $d\overline{d}$ and $u\overline{u}$. There is no need to worry about that here.

In 1961 all these particles were classified in a particular manner, best shown in a figure. This most remarkable figure, introduced by Gell-Mann in his paper entitled "The eightfold way", immediately took hold in particle physics. As we will see it is suggestive of a construction built up from triangles, and that is indeed what led to the introduction of quarks in 1964. The nine particles are grouped into an octet (8 particles) and a singlet.

particle	mass (MeV)	lifetime (seconds)
π^+, π^-	140	2.6×10^{-8}
π^0	135	8.4×10^{-17}
K^+, K^-	494	1.2×10^{-8}
K_S	498	0.89×10^{-10}
K_L	498	5.2×10^{-8}
η	548	5.6×10^{-19}
η'	958	3.3×102^{-21}

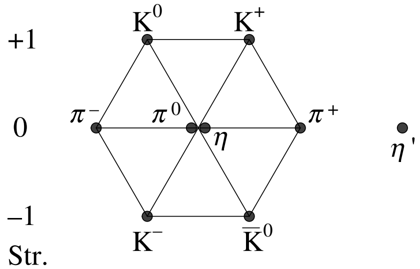


Spin 0 Meson Octet and Singlet

In this figure the particles are arranged by strangeness and charge; for our purposes the strangeness of a particle is determined by the number of strange quarks in that particle. For every strange quark count -1, and $+1$ for its antiparticle, the strange quark. For example, K^- has one s quark, and thus has strangeness -1. The strangeness is the same for particles on the same horizontal line; charge is the same for particles on the same vertical line. The classification into octet and singlet is related to the behaviour of the bound states under exchange of the quarks. The η' is supposedly an equal mixture[e] of $u\bar{u}$, $d\bar{d}$ and $s\bar{s}$. It remains the same thing if the quarks are interchanged, for example, if the d and $\bar{d}$ are interchanged with s and $\bar{s}$. Particles in the octet interchange with each other, for example that same quark interchange ($d \leftrightarrow s$ and $\bar{d} \leftrightarrow \bar{s}$) exchanges K^0 and $\bar{K}^0$.

[e] There is some further mixing, but that is of no relevance here.

Customarily one draws this figure in a slightly more symmetrical way. The charges of particles on the same diagonal line (upper left to lower right) are then the same.



Spin 0 Meson Octet and Singlet

If the quarks had all the same mass, all particles in the octet would presumably have the same mass. However, the mass of the strange quark (the strange quark has the same mass) is higher than those of the up and down quarks, and thus the kaons, containing one strange quark or antiquark are heavier than the pions. The η and η' also contain a strange quark and an anti(strange quark) and are even heavier. As indicated in the table all of these particles are unstable.

K_S and K_L are certain mixtures of K^0 and $\overline{K}^0$. If you are confused by all this mixing business you are in good company: it took quite some time before all this was unraveled and understood. Now we know, but it is never really easy. Luckily there is rarely any need to go into details, at least not within the framework of this book.

The charged pions and kaons decay with relatively long lifetimes (of the order of a few one-hundredths of a micro-second), such that they actually make tracks that can be observed and measured. The neutral pion decays very fast, but by very refined methods it has nonetheless been possible to establish a path over a small distance prior to decay. The distance covered is of the order of a micron (one micron is a millionth of a meter). The neutral pion decays almost always into two photons.

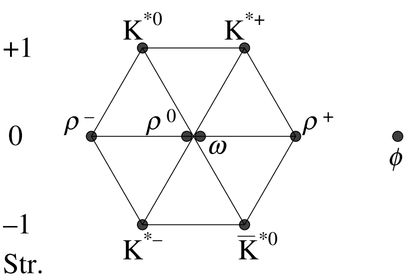
The η, discovered by Pevsner and his group in bubble chamber data around 1960, is very unstable, and decays so fast after production that no track can be seen in the usual detection instruments. Such particles are established purely on the basis of the mass-shell relation as described before. The η decays mainly into two photons or three pions, and by carefully measuring the momentum and energy of the pions (or the photons) one establishes the mass of the η from the total energy and momentum of the decay products. The particle is established by the fact that in many events the same mass value results.

The above mentioned states are bound states where the spins of the quark and the antiquark point in opposite directions. Also there is no motion of the quarks around each other, which makes for relatively simple bound states. Almost as simple are the bound states without relative motion, but where the quark spins point in the same direction. Then the total spin is 1. Here is the corresponding set of spin 1 particles as observed.

$d\bar{s}$	$u\bar{s}$	$d\bar{u}$	$u\bar{d}$	$s\bar{u}$	$s\bar{d}$	$d\bar{d}$	$u\bar{u}$	$s\bar{s}$
K^{*0}	K^{*+}	ρ^-	ρ^+	K^{*-}	$\overline{K}^{*0}$	ρ^0	ω	ϕ

The spin 1 particles may also be arranged into an octet and a singlet. Here the lifetimes are not given, as they are very short.

particle	mass (MeV)
ρ^+, ρ^-	770
ρ^0	770
K^{*+}, K^{*-}	892
K^{*0}, $\overline{K}^{*0}$	892
ω	782
ϕ	1020



Spin 1 Meson Octet and Singlet

8.6 Baryons

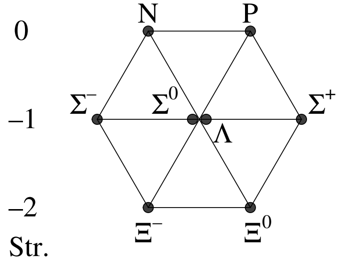
The particles to be described here are called baryons, and they are bound states of three quarks. The situation with respect to spin is more complicated than in the meson case, and will not be described in any depth. The best known particles can be separated into two groups, containing respectively eight particles of spin $\frac{1}{2}$ (two quarks with spin up and one with spin down) and ten particles of spin $\frac{3}{2}$ (spins of all three quarks in the same direction). The group of eight particles fits nicely into an octet like in the meson case, the group of ten (decuplet) fits into a new type of figure. There are no singlets.

In the case of mesons the antiparticles are in the same octet as the particles. Thus K^- and K^+ are each other's antiparticle, but they are in the same octet.

The baryons are bound states of three quarks, for example the proton has two up and one down quark. The antibaryons contain antiquarks, thus the antiproton contains two anti(up quarks) and one anti(down quark). The antibaryons thus form an octet and a decuplet by themselves. With the rule that particles of less strangeness appear lower in the figures it follows that in the case of the antibaryons the figures must be drawn upside down. This because the particles containing an anti(strange quark) have strangeness +1 and must be placed above the other particles that have zero or negative strangeness. Thus the Ω^-, three strange quarks, has strangeness -3 and charge -1, while the $\overline{\Omega^-}$, three anti(strange quarks), has strangeness $+3$ and electric charge $+1$. The antibaryons have the same mass and lifetime as the baryons. But let us now return to the baryon octet and show the list and the corresponding figure.

The proton is of course stable, or you would not be reading this. The neutron lives very long, about 10 minutes, due to the fact that the energy difference between proton and neutron is quite small (about 1.3 MeV). A little binding energy in a nucleus goes a long way to compensate this and that makes the bound neutrons stable. Most nuclei up to uranium, containing many

particle	mass (MeV)	lifetime (seconds)
P(roton)	938.3	stable
N(eutron)	939.6	887
Σ^-	1197.4	1.5×10^{-10}
Σ^0	1192.6	7.4×10^{-20}
Σ^+	1189.4	0.8×10^{-10}
Ξ^-	1321	1.6×10^{-10}
Ξ^0	1315	2.9×10^{-10}
Λ	1115.7	2.63×10^{-10}

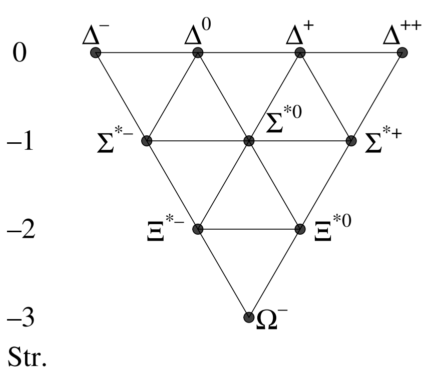


Spin $\frac{1}{2}$ Baryon Octet

neutrons, are stable. The other particles, with the exception of the Σ^0, live long enough to traverse a measurable distance in the usual detection instruments. The Λ is neutral, and in a bubble chamber it can be observed when it decays into a proton and a negative pion. That gives a 'V', some distance away from the point where the Λ was produced. In the early days (fifties) the Λ was called a V-particle. It contains one strange quark.

Now the spin $\frac{3}{2}$ baryon decuplet. The very short lifetimes are not indicated. Going down amounts to replacing a down quark by

particle	mass (MeV)
Δ	1232
Σ^*	1383
Ξ^*	1532
Ω^-	1672.5
Mass differences:	
$\Sigma^* - \Delta$	151
$\Xi^* - \Sigma^*$	149
$\Omega^- - \Xi^*$	140



Spin $\frac{3}{2}$ Baryon Decuplet

a strange quark. Thus the Σ contains one strange quark, the Ξ two and the Ω three. Correspondingly, going down, one would assume the mass to increase by something close to the strange quark mass. From the table that mass appears to be around 150 MeV. On the other hand, the mass difference between a pion and a kaon is 350 MeV, and it is clearly not easy to pinpoint the strange quark mass. It is probably somewhere between 60 and 170 MeV. Not knowing any better is a testimony to our poor understanding of the quark bound states.

Historically the Δ was discovered by Fermi, in 1952. It is the earliest highly unstable particle discovered. It took some time before physicists realized that such a highly unstable system must still be considered a particle. It is just very unstable.

8.7 Exotics

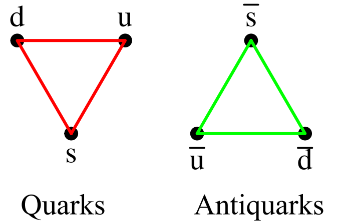
Here we will discuss a few quark bound states involving the charm, bottom and top quarks. The earliest detected is the J/ψ, a charm-$\overline{\text{charm}}$ bound state also called charmonium, with a mass of 3097 MeV. It was the first discovery of a state containing a charmed quark. Important are the B-particles, containing one bottom or $\overline{\text{bottom quark}}$: B^+, B^- B^0 and $\overline{B}^0$, all with a mass of about 5279 MeV. These B-particles are the subject of intensive study, because their decay modes may give information on the fourth parameter of the CKM rotation (see Chapter 3). That is the parameter related to CP violation, not discussed in this book.

The first sign of a bottom quark was the discovery of the Υ (or bottonium), mass 9460 MeV. From this the mass of the bottom quark was guessed to be in the region of 4.1 to 4.5 GeV. The top showed itself in certain events observed at Fermilab around 1995. From these events a mass of about 175 GeV was deduced. The wildly varying masses of the various quarks are really baffling: 5, 10, 200, 1300, 4500, 175 000 MeV!

8.8 Discovering Quarks

The state of affairs in 1964 was as described above: particles could be grouped into multiplets as shown, and very convincingly, open spots were filled in by experiment. One of the last particles discovered was the Ω^- in the baryon decuplet; it was finally seen in a bubble chamber experiment at Brookhaven. The mass was predicted rather precisely, simply by assuming that the Ω^- mass would be another 150 MeV up from the (known) Ξ^* mass. And indeed, there it was.

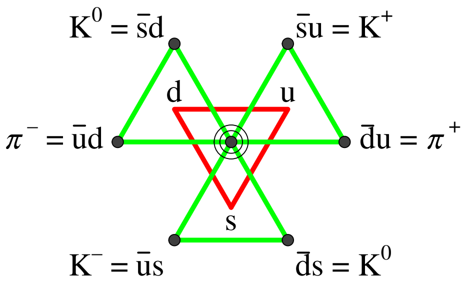
At this point it was completely natural[f] to assume that all these particles are bound states of more elementary objects, and this was how quarks were invented (by Gell-Mann, and Zweig). The idea is truly simple: it is quite obvious that the multiplets shown have basic building blocks, namely triangles. The convention is as described before: strangeness decreases when going down, charge increases when going to the right. Then for antiquarks an upside down triangle must be used, as shown in the figure.



The particles in these triangles were called quarks and antiquarks, and it is quite easy to see how the nine spin zero mesons can be obtained by combining a quark and an antiquark. Start with a quark triangle (the left triangle in the figure above), and then put an antiquark triangle (an upside down triangle) onto each of the vertices such that the centers of the antiquark

[f]That does not mean it was easy. Intellectual courage was needed to introduce never-seen particles with a non-integer charge.

triangles are precisely on the vertices. Presto, an octet and a singlet appear as shown in the next figure.



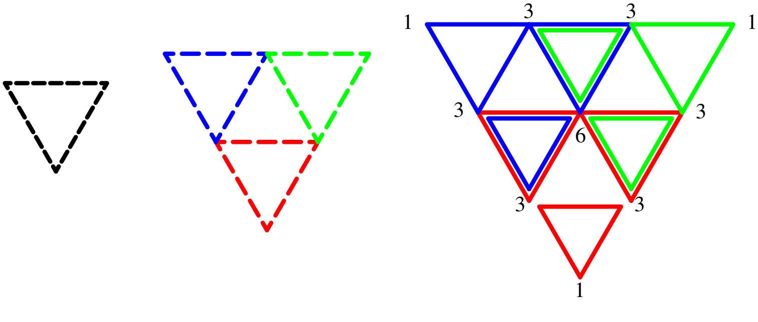
The triple circled point in the middle has the multiplicity three, as each of the three antiquark triangles has a point there. Of these three two are part of the octet and one of them is a singlet all by itself.

This procedure shows which quarks are contained in a given state. Just check which quarks have been used to generate the point. For example, the leftmost point contains the leftmost antiquark of the green triangle, which is the $\bar{u}$ quark, and the leftmost quark of the red triangle, the d-quark. If the multiplicity at some point is larger than 1 then the resulting states will usually be mixtures. The center of the figure has the multiplicity three, and the resulting particles will be mixtures of $\bar{u}u$, $\bar{d}d$ and $\bar{s}s$. The particles observed are the π^0, the η and the η', and they are thus mixtures. In the previous figure of the meson nonet we have drawn the η' on the side, but its quark content is that corresponding to the center of the picture shown here.

As shown above the spin 0 meson octet and singlet can thus be interpreted as quark–antiquark bound states, with the quark spin opposite to the antiquark spin resulting in a total spin of 0. The spin 1 meson octet and singlet must be understood as a similar construction, except that now the spins of the quark and antiquark contained in a given state point in the same direction.

The situation with the baryons is somewhat more complicated, but the figures show quite clearly how the triangle remains the basic building block. Combining the baryons as done for the mesons would give $3 \times 3 \times 3 = 27$ states, and it is not directly clear how this reduces to an octet and a decuplet (18 particles in total). The reason is that one must make groups of particles that transform into themselves when exchanging the quarks, such as for example a nonet splitting up in an octet and a singlet. It would carry us too far to dish this out, and it is not that urgent anyway.

The following figures nonetheless give an idea. The first quark triangle is dashed black. Drawing triangles around the corner points of the black triangle one obtains the second figure with the dashed red, blue and green triangles. Now add the third quark. Take the dashed blue triangle and draw a blue triangle around each of the corners. Similarly with the dashed red and green triangles. The result is shown in the third figure. Some of the triangles have been made a little smaller, for better visibility.



Note that the colors in these figures have nothing to do with the quark color charge, discussed in Chapter 2. Colors have been used here to make it easier to recognize the construction.

Several points in this plot are produced several times. The numbers show the multiplicity for the various points. For example, the second point in the top row (multiplicity 3) is touched by two blue and one green triangle and the point in the center (multiplicity 6) is touched by 2 red, 2 blue and 2 green triangles. The result is one decuplet, two octets (the points marked with 3 or 6) and one singlet. Indeed,

$$10 + 8 + 8 + 1 = 27\,.$$

One of the octets is the baryon octet. The remaining octet and singlet will not be discussed.

Consider the above as a simplified discussion, as there are complications relating to the spin structure. Note that the particles of the decuplet have spin $\frac{3}{2}$, while the particles of the baryon octet have spin $\frac{1}{2}$.

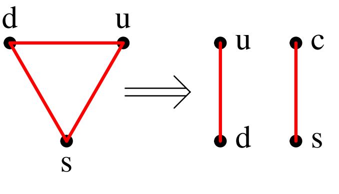
In Nature one does not observe states corresponding to bound states of two quarks as would correspond to the second figure (the dashed colored triangles) in the drawing above. At the time this was not understood. It was not known then that each quark comes in three varieties coded red, blue and green. With a quark and an antiquark one can make a neutral quark color state, for example the π^- can be understood as the bound state of an anti(red-up quark) with a red-down quark. With two quarks you cannot make a state that is neutral with respect to quark colors. You can do it with three quarks: make them red, blue and green (which is white) in every bound state. Why only neutral quark color states appear in Nature is not completely understood, but we have a good idea about it. It is due to the interactions of the gluons with quarks and with themselves.

I may perhaps terminate this section with a little anecdote. When quarks were not immediately discovered after the introduction by Gell-Mann he took to calling them symbolic, saying they were indices. In the early seventies I met him at CERN and he again said something in that spirit. I then jumped up, coming down with some impact that made the floor tremble, and I asked him: “Do I look like a heap of indices?” This visibly rattled him, and indeed after that he no more advocated this vision, at least not as far as I know.

8.9 Triplets versus Doublets and Lepton-Quark Symmetry

Here is an occasion to illustrate what is easy and what is hard in physics. To extend a theory, an idea, that is in general easy. When an idea is launched for the first time you will often see it followed up by many articles, one grander than the other, and most of them, seemingly, much clearer and brilliant than the one containing the original idea. In other words, it is not always directly visible which paper was the important one. It is this odd idea, the thing orthogonal to everything else that is so hard to produce. Usually after it is introduced everyone will say: "of course". The following example is perhaps not the very best possible one, but it may illustrate the point. Around 1970 most particle physicists were thinking in terms of Regge trajectories and SU3. Now SU3 is the scheme of octets and decuplets shown above, and we now understand this multitude of 'new' particles as bound states of only three basic particles, the quarks. Regge trajectories have been alluded to above, and their relevance has dwindled to a point where, in my opinion, it is not necessary to discuss them. Consider them as an idea that at one time was appealing, but which did not work out.

Then the direction of thought changed radically. Instead of three quarks as building blocks, instead of thinking in terms of triangles one had to change to the family type structure described in Chapter 2. The drawing illustrates the point. What was a triangle became two straight lines, with the addition of a fourth quark.[g]



[g]The third line, with top and bottom quark, came later.

Now that kind of change of vision is hard to accept, in particular because the three-quark model worked so nicely. We now realize that this was because the quarks are all equivalent if one restricts oneself to gluon interactions. Thus apart from a relatively small difference in the masses of the quarks, resulting in small mass differences between the various bound states, there was not that much difference between those bound states. However, in a larger picture where also weak interactions play a role the view changes. The three quark picture became an accident, a part of a larger scheme, while before it was often viewed as a basic concept of Nature. The three-quark picture would have been a four-quark picture if the charmed quark had been much lighter, and it would have been a six-quark picture if also the top and bottom quark masses had been of the order of a few hundred MeV. One shudders to think what kind of particle zoo that would have given!

The change of view from triangle to two lines is historically not precisely what happened, the evolution was much more involved. It is impossible to say when this new vision took hold. But there were things of that nature, and this example is perhaps useful to illustrate the point.

It is interesting to note here another fact. Gell-Mann, when introducing the three quarks conforming to the triangle picture sketched above, made remarks that seemed at odds with this view. He mentioned lepton-quark symmetry, and as the leptons appeared in doublets (electron plus electron-neutrino and muon plus muon-neutrino) while the quarks seemed to form a triplet it was not clear what he meant. The Japanese physicist Hara, working at Caltech near Gell-Mann, introduced a fourth quark, and to a large extent produced the two quark doublet picture just discussed. Up to a point he produced the new picture. Despite his fabulous memory Gell-Mann does not really remember Hara, and I do not think that they had much interaction. Nonetheless, surely Hara found his inspiration in Gell-Mann's quark paper. Glashow noted Hara's work, and the fourth quark, named charmed quark by him and Bjorken, became part of Glashow's later work on the Standard Model (with Iliopoulos and Maiani). Then the picture became clear.