Chapter 8

Mesons, Baryons and Quarks

In the late 1950s, the physics of elementary particles resembled a zoo that was crowded with dozens of new particles that had been discovered in particle collisions. But then, at some point, physicists managed to change that chaos into order. They found out that there was a relatively simple scheme that permitted a description of the makeup of nuclear particles including the newly discovered ones: just imagine they are built up of three quarks. We have already seen that we need just two kinds of quarks, the u-quark and the d-quark: $p = (uud)$. This composite is color singlet, so its full description is $p'(u_\mathrm{r}u_\mathrm{g}d_\mathrm{b} + \cdots)$. Chameleon-like, the proton jumps from one color combination to the next, but on the average, the colors cancel each other; as a result, the proton is a color-neutral state from outside.

As far as its spin is concerned, it has spin 1/2, just like each of its quarks. But we know that spin is a directional quality; so, the proton spin is built up of two quark spins that have opposite direction so as to cancel each other, whereas the third quark spin determines the proton spin.

In the neutron, the parts played by the u-quark and d-quarks is interchanged. This is due to a higher symmetry which was discovered by Werner Heisenberg in the 1930s, shortly after the discovery of the neutron; he called this new degree of freedom "isospin", mathematically analogous to spin. This is the first instance of an internal symmetry: it is marked by the fact that, for a symmetry operation, external, i.e., geometric — properties do not run the show; only internal properties are important, the substructure of the nucleons. In the framework of QCD, isospin symmetry emerges quite naturally: any two quarks include their color degree of freedom in their strong interaction — their interaction does not differ. The only difference of u-quark and d-quarks is due to their electromagnetic interaction and to their masses. They form what we call an isospin symmetry in Nature.

Also in the phenomenology of the π mesons we mentioned preciously, isospin symmetry adds its mark: the electrically charged pions have a very simple substructure. They consist either of $\bar{u}d$ (which make up an electric charge of -1) or $u\bar{d}$, for a positive charge. Quite simply, the positive and the negative pions are each other's antiparticles. Isospin, however, postulates the existence of our electrically neutral pion with roughly the same mass, such that, altogether, there exists a triplet consisting of π^+, π^0, π^-. And indeed, the neutral pions were discovered soon after the charged ones. And their mass is very close to that of their charged partners, about 140 MeV.

It turns out that the substructure of the π^0 has some added complexity. We might think we should be able to build up two neutral mesons, based on $\bar{u}u$ and $\bar{d}d$. Now, which is the one that has long been seen? The obvious answer is: some linear combination of these two. Quantum theory comes to the rescue. The π^0 is one-half $\bar{u}u$, one-half $\bar{d}d$. And by implication the neutral π meson is its own antiparticle, just like the photon. Consisting in equal measure of matter and antimatter; it is very unstable. It is seen to decay right after having been created in some particle reaction, almost always into two photons. The decay is an electromagnetic one — the quarks and their antiquarks radiate off all their energy into photons.

The charged pions have a much longer lifetime, about one hundred-millionth of a second — which is relatively long in the particle physics context. It may be instructive to compare the distance they traverse in their lifetime with the distance light travels in the same amount of time. For a charged π meson, that distance is just 7.8 meters. But a charged pion may also travel across about 100 meter before decaying (assuming it is a high-energy one). At the bottom of this mystery is Einstein's relativity of time. The "light path" of the neutral pion is orders of magnitude smaller, and measures just about 100 atomic diameters.

If the charged meson has a lifetime much longer than that of its neutral cousin, that is due to the fact that its decay occurs by means of the so-called "weak interaction" — similar to the process which mediates the radioactive decay of many unstable atomic nuclei. We will notice later on that the electromagnetic and the weak interaction are closely related. The charged π mesons decay into two particles — a charged muon (the "heavy" brother of the electron) and a neutrino, a very light, electrically neutral partner.

It is not as though nucleons and π mesons were the only particles we can build up from quarks in the framework of QCD. We already mentioned the doubly charged Δ^{++} particle, often called the delta resonance, as an example. It is built up of three (uuu) quarks. Its spin of 3/2 units is a simple addition of three aligned quark spins. By systematically replacing up quarks by down quarks, we see that there must be four charge states with the substructures (uuu), (uud), (udd) and (ddd). The electric charges must then must be (+2, +1, 0, −1). They form an isospin quartet.

The Δ particles are, we might say, excited states of the proton, and we can produce them by running a pion beam into a nucleon target. They have short lifetimes, similar to the time in which light traverses a nucleus; their decay products are mesons and nucleons. Their lifetimes are so short, we might say, that calling them particles is a misnomer, since a "particle" is defined largely by its mass. But we know that quantum theory establishes the uncertainty relation between mass and lifetime. The shorter the time between creation and decay of a particle, the poorer the definition of its mass. To be more precise, we cannot measure a mass properly, but just a median mass value — averaging over many production instances of particles with the same composition and quantum numbers. This median mass for the Δ baryon is 1232 MeV, almost 4/3 of the proton mass. The decay width of the Δ, as we call its mass uncertainty, is almost 120 MeV, about 10% of its mass.

Now, we know that the Δ and the proton have the same quark substructure (uud), so we might ask: what's the most important difference? It turns out this is a matter of their spins only. In the Δ case, the three spins are aligned, but not so in the proton case. To convert a proton into a Δ, we would have to turn around one spin orientation. But that operation needs energy input — exactly as much as what corresponds to the mass difference of almost 300 MeV.

In addition to the Δ particles, we have quite a few unstable particles consisting of three quarks: they are objects the quarks of which have orbital angular momentum in addition to their spin, or that are in excited quantum states in analogy to what we see in atomic physics. The same is true for mesons: π mesons do not have angular momentum, because the spin of quark and antiquark compensate each other. If we turn around one quark spin, we obtain a particle of spin 1 with a considerably higher mass: it is the so-called ϱ (Greek letter rho) meson with mass 770 MeV. Just like the Δ baryons, the ϱ are very unstable and decay immediately after their production in a particle collision, into two π mesons. The width of the p meson is enormous: about 150 MeV, or some 20% of its mass.

Mesons also have many "resonances", where the individual quarks are in excited states, e.g., where they have relative angular momenta. Hundreds of such short-lived particles are mentioned in the "Particle Data Book" that is issued annually, including all new data. There is no space here for a more detailed description.

Just for the buildup of nuclear matter, we need only u-quark and d-quarks. To understand the mass values of various particles we deal with, we have to assign each quark type a mass of its own, be it quite small: It is of order 5 MeV, with the d-quark slightly heavier than the u-quark. This latter difference is at the basis of the observation that the neutron is heavier than the proton.

In the last four decades of the twentieth century, particle physicists discovered many new particles that show evidence of four additional quarks. They are called s (for "strange", with charge $-1/3$), c (for "charmed", with charge $2/3$), b (for "bottom", with charge $-1/3$) and t (for "top", again with charge $2/3$). These former "flavors" of quarks, which we categorize as pair, analogously to

(u, d), as (c, s) and (t, b), can be building blocks of heavier matter. All of their masses are much larger than the small masses of u and d; they reach from 150 MeV for the s quark to 175,000 MeV for the t-quark. This means the single t-quark has a mass as heavy as an entire atom of gold which consists of 197 nucleons in most cases.

The new theoretical ideas about quarks took hold shortly after the memorable date of November 11, 1974, which is often called the "November Revolution" among particle physicists. There was an experimental breakthrough at the Stanford Linear Accelerator Center (SLAC) and at the Brookhaven National Laboratory (BNL) on Long Island: it was the discovery of a very unusual particle with a lifetime about 10,000 times longer than expected under the circumstances. This particle is a meson consisting of a c-quark and its antiquark.

Particles containing an s-quark (or "strange" quark) had been discovered as early as the 1950s, and they were called "strange particles", a long time before the quark model existed. If we take a neutron and replace one d-quark of this (udd) composite by an s-quark, we come up with the Λ (Greek capital "Lambda") particle, which is about 150 MeV heavier and remarkably, its lifetime is relatively long when measured by its "light path" of almost 8 cm. It decays into a nucleon and a π meson, in the process changing the s-quark into a u-quark. This exchange is a "weak interaction" process the likes of which we will describe in the next chapter.

In addition to the Λ particle, there are quite a few particles containing s quarks, they may contain two s-quarks (like uss) with no electric charge, or even sss, with charge -1. This particle, the Ω (capital Greek Omega), has a mass of about 1670 MeV and is somewhat analogous to the Ω resonance we discussed above. But its lifetime is much longer; its "light path" measures some 2.5 cm. This is due to the fact that the Ω can decay only if its s-quarks change into u-quark or d-quarks in the process. That, however, is possible only as a "weak interaction" process and not a strong nuclear interaction as in the decay of Ω particles. This fact explains the long lifetime of the Ω. Its 1964 discovery at Brookhaven National Lab set a milestone in the twentieth century particle physics, because its existence had been predicted, including its mass, in the framework of symmetry models for elementary particle properties.

We have also known mesons that contain s-quarks, for a long time, in particular the lightest one of them, the K meson, with a mass of 496 MeV. There are four different versions of it, according to the quark contents: $(\bar{u}s)$ are the K^+, $(\bar{s}u)$ the K^-, (ds) the K^0, $(\bar{s}d)$ the K^0. Just like the π mesons, the kaons are unstable: they decay in a weak interaction, changing the s-quark to a u-quark.

Isospin symmetry can be seen as a symmetry which results if we take two quarks — say, the u-quarks and d-quarks — as coordinates of a two-dimensional coordinate system. The QCD interaction does not depend on the specific quark type, and the masses of the two quarks we are dealing with do not make much of a difference; as a result, we can perform a rotation in this coordinate system without affecting the strong interaction physics of the system. This is synonymous with isospin symmetry. If the s-quarks were massless or nearly massless, we could even deal with rotations in a three-dimensional quark space spanned by u, d and s. True, the mass of the s-quark exceeds the u and d masses by about 150 MeV, so this symmetry is broken; still, this broken symmetry, called SU(3), which was first studied by Murray Gell-Mann and Yuval Neeman, serves well for the description of the hadrons built up out of u-quarks, d-quarks and s-quarks. It predicts, for instance, that the two nucleons proton and neutron have six more partners with which they form an "octet". These added states contain the Δ particle we mentioned before. Similarly, the Δ resonances we discussed join the Ω states and others to form an "irreducible representation" containing 10 members, which we call a decuplet.

While, in the early 1970s, it was believed that there is some deep significance to the observed symmetries, we are now convinced that these symmetries are simply a consequence of the quark substructure of the hadron spectrum. The resulting SU(3) symmetry functions fairly well simply because the s-quarks are only about 150 MeV heavier than the u-quarks and the d-quarks. If the mass difference were ten times that, we could essentially abandon the symmetry. This is easily illustrated if we substitute a c-quark for the s-quark in the Λ particle. The resulting particle with the substructure (*udc*) has a much higher mass value than the Λ because of the relatively heavy mass of the *c*-quark; it "weighs in" at 2285 MeV. When we consider a symmetry which contains, in addition to light quarks *u*-quarks, *d*-quarks and *s*-quarks, also the *c*-quark (which is our SU(3) symmetry), this heavy particle will appear, together with the nucleons *n* and *p*, in a particle family containing a total of eight particles, which we called an octet above. The mass differences inside this octet are of order 100% — which illustrates the fact that we are dealing with a strongly broken symmetry.

If we extend these concepts to particles that also contain bottom or *b*-quarks, we encounter even more strongly broken symmetries. Actually, the mass differences within one grouping or family are now so large that the concept of a symmetry does not make sense any more. The mass of a baryon built up of the quarks *u*, *d* and *b*, winds up at about 5,600 MeV, i.e., at more than five proton masses.

A special role among the quarks is reserved to the top quark, for short *t*. Its gigantic mass of about 175 GeV (or 175,000 MeV) presented a real riddle to physicists. It is so heavy that it decays immediately after being "created" in an interaction; and with this vast mass, it has a huge amount of possible decay channels. That makes it decay even more rapidly. A bound hadron of quark content (*u*, *d*, *t*) cannot even form by the time of the decay. This is true although the time needed for the formation of such a hadron could be happening within the minuscule time that it takes a Δ particle to decay; its decay is still faster. As a result, that quark is only one of the six quark flavors that cannot act as a building block of hadronic matter. It remains just a phantom in high-energy particle collisions, just decaying immediately after creation — leaving a *b*-quark and many other particles in its wake.

Today, as we have seen the veils coming off the secrets of atomic nuclei and nuclear constituents, we observe a picture of nuclear forces and building blocks that, on one hand, is comprehensible in the framework of quantum field theory, but that is of an obfuscating complexity. True enough, our Nature needs only two quarks, *u* and *d*, to build up stable atomic nuclei; but the prevailing symmetry structure implies evidence for six quarks. Perceived from the outside, a stable atomic nucleus looks like a solid citizen of Nature; but way inside there is a boiling microcosm — a world of complex, unstable hadron interactions becomes visible if not fully intelligible, manifesting its existence in every high-energy particle collision.