24.3 Antiparticles, hadrons, and leptons

Specification reference: 6.4.2

Learning outcomes

Demonstrate knowledge, understanding, and application of:

- → particles and antiparticles: electron–positron, proton–antiproton, neutron–antineutron, and neutrino–antineutrino
- → relative masses and charges of particles and their corresponding antiparticles
- → classification, examples, and behaviour of hadrons
- → classification, examples, and behaviour of leptons.

Antimatter

Antimatter is not just a useful device for science-fiction writers – it actually exists in nature. Antimatter was first predicted by the theoretical physicist Paul Dirac in 1928. His theory predicted that every particle has a corresponding **antiparticle**, and that if the two meet they completely destroy each other in a process called annihilation, where the masses of both particle and antiparticle are converted into a high-energy pair of photons. An antiparticle has the opposite charge to the particle (if the particle has charge) and exactly the same rest mass as the particle.

The antiparticle of the electron is the **positron**. A positron has mass 9.11×10^{-31} kg – like an electron, and charge $+1.60 \times 10^{-19}$ C – the opposite of the charge on an electron. The antiproton, antineutron, and antineutrino are the antiparticles of the proton, neutron, and neutrino respectively. Most antiparticles are symbolised by a bar over the letter for the particle. For example, the symbol for a neutrino is the Greek letter ν and the symbol for an antineutrino is $\bar{\nu}$.

Fundamental forces

In order to study subatomic particles, you need to be aware of the four fundamental forces in nature that can explain all known interactions. Table 1 shows these four forces and some of their characteristics. You have already met all but one of these fundamental forces – the **weak nuclear force** is responsible for inducing beta-decay within unstable nuclei. You will study two types of beta decay in Topic 24.5, Beta decay.

▼ **Table 1** *The four fundamental forces or interactions*

Fundamental force	Effect	Relative strength	Range
strong nuclear	experienced by nucleons	1	$\sim 10^{-15}$ m
electromagnetic	experienced by static and moving charged particles	10^{-3}	infinite
weak nuclear	responsible for beta-decay	10^{-6}	$\sim 10^{-18}$ m
gravitational	experienced by all particles with mass	10^{-40}	infinite

Fundamental particles?

In some particle accelerators, protons are accelerated to enormous speeds and then smashed together. Some of the kinetic energy of the protons is transformed into mass in the form of an incredible array of particles like baryons, mesons, kaons, and pions. The important question is – are these particles fundamental?

When physicists talk about a **fundamental particle**, they mean a particle that has no internal structure and hence cannot be divided into smaller bits. The four types of particles mentioned above are not fundamental particles, and nor are protons and neutrons, because they are all composed of quarks, as you will see in Topic 24.4. Quarks *are* considered to be fundamental particles, as are electrons and neutrinos.

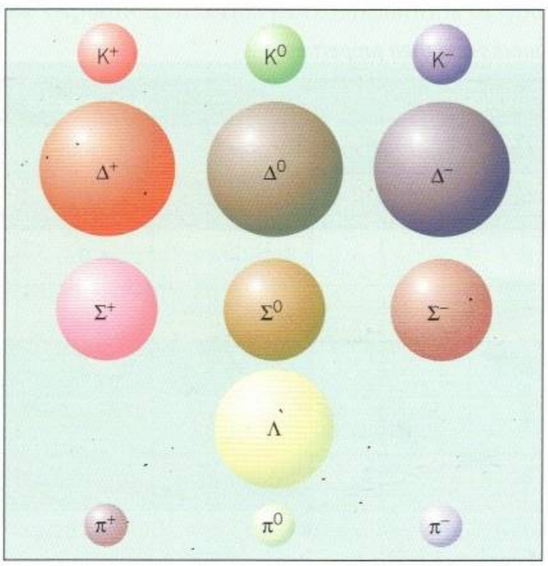
Hadrons and leptons

Subatomic particles are classified into two families – **hadrons** and **leptons**.

- Hadrons are particles and antiparticles that are affected by the strong nuclear force. Examples include protons, neutrons, and mesons. Hadrons, if charged, also experience the electromagnetic force. Hadrons decay by the weak nuclear force.
- Leptons are particles and antiparticles that are not affected by the strong nuclear force. Examples include electrons, neutrinos, and muons. Leptons, if charged, also experience the electromagnetic force.

At the Large Hadron Collider (LHC) at CERN in Geneva (Figure 1), hadrons are used to probe fundamental particles. In 2013, CERN announced the discovery of the Higgs boson, the existence of which had been predicted in order to explain why all particles have the property of mass.

Figure 2 shows a small fraction of the hundreds of hadrons discovered in the last fifty or so years. They are all composed of quarks, and as such, are not fundamental particles.



▲ **Figure 2** *Some of the many hadrons known to exist*

▲ **Figure 1** *The CMS detector in the LHC, shown here, was one of two experiments that gave physicists clear evidence for the existence of the Higgs boson*

Study tip

The names 'hadron' and 'lepton' come from Greek – they mean 'thick' and 'lightweight', respectively.

Summary questions

1. State two fundamental forces with an infinite range. (*1 mark*)
2. State the forces that will affect all protons. (*1 mark*)
3. What are hadrons? Give one example of a particle that is a hadron. (*2 marks*)
4. The mass of a proton p is 1.7×10^{-27} kg and it has a charge $+e$. Write a symbol for the antiproton and state its mass and charge. (*2 marks*)
5. The muon μ^- is a particle that is not affected by the strong nuclear force. It has a mass of 1.9×10^{-28} kg. Calculate the mass of the antimuon μ^+ as a multiple of electron masses and state whether this antiparticle is a hadron or a lepton. (*2 marks*)
6. Use the data sheet on page 565 to determine the properties of an antineutron. (*2 marks*)

24.4 Quarks

Specification reference: 6.4.2

Learning outcomes

Demonstrate knowledge, understanding, and application of:

- → the simple quark model of hadrons in terms of up, down, and strange quarks and their anti-quarks
- → the quark model of the proton and the neutron
- → the charges of the up, down, strange, anti-up, anti-down, and anti-strange quarks as fractions of the elementary charge *e*.

James Joyce and particle physics

In Topic 24.3, Antiparticles, hadrons, and leptons, it was mentioned that all hadrons are made of **quarks**. You will look in details at quarks in this topic. The unusual name 'quark' was coined by the American physicist Murray Gell-Mann, one of the people who first postulated their existence in the 1960s. The name comes from a single line in James Joyce's novel *Finnegans Wake*, 'three quarks for Muster Mark'.

Hadrons and quarks

Quarks, together with leptons, are the building blocks of all matter. They are considered to be fundamental particles. Any particle that contains quarks is called a hadron. Amazingly, it only takes a small number of quarks and anti-quarks to make up the hundreds of hadrons discovered in collisions in particle accelerators.

The **standard model** of elementary particles requires six quarks and their six anti-quarks. The six types of quarks are up, down, charm, strange, top, and bottom. They are denoted by the symbols u, d, c, s, t, and b. Their corresponding anti-quarks are anti-up, anti-down, anti-charm, anti-strange, anti-top, and anti-bottom ($\bar{u}$, $\bar{d}$, $\bar{c}$, $\bar{s}$, $\bar{t}$, and $\bar{b}$). All quarks have a charge Q that is a fraction of the elementary charge e. For example, the up quark has a charge $+\frac{2}{3}e$, often written as just $+\frac{2}{3}$ for simplicity.

All the quarks are listed in Table 1, but for this course you need to know only about the up, down, and strange quarks and their anti-quarks.

▼ **Table 1** *The quarks and their properties*

Quarks			Anti-quarks		
Name	Symbol	Charge Q/e	Name	Symbol	Charge Q/e
up	u	$+\frac{2}{3}$	anti-up	$\bar{u}$	$-\frac{2}{3}$
down	d	$-\frac{1}{3}$	anti-down	$\bar{d}$	$+\frac{1}{3}$
charm	c	$+\frac{2}{3}$	anti-charm	$\bar{c}$	$-\frac{2}{3}$
strange	s	$-\frac{1}{3}$	anti-strange	$\bar{s}$	$+\frac{1}{3}$
top	t	$+\frac{2}{3}$	anti-top	$\bar{t}$	$-\frac{2}{3}$
bottom	b	$-\frac{1}{3}$	anti-bottom	$\bar{b}$	$+\frac{1}{3}$

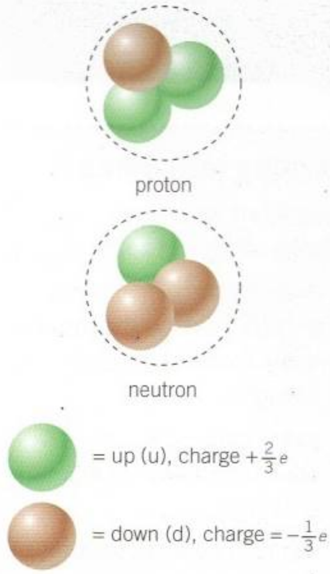
Protons and neutrons

All hadrons experience the strong nuclear force. In fact, it is the individual quarks that are bound together within the particle by the attractive strong nuclear force. The force is so strong that it may not be possible to separate the individual quarks.

A proton consists of three quarks – up, up, and down, or simply u u d. The total charge of the proton is the sum of the individual charges of the quarks. Even at this subatomic level, the principle of conservation of charge is upheld. Therefore

$$\text{proton charge } Q = (+\tfrac{2}{3})e + (+\tfrac{2}{3})e + (-\tfrac{1}{3})e = +1e$$

A neutron also consists of three quarks, but this time they are up, down, down, or u d d. You can show that the total charge of the neutron is zero. You can determine the charge of any hadron using Table 1, as illustrated in the worked example below.



▲ **Figure 1** *The quark combinations of the proton and the neutron*

Worked example: What is the charge?

One hadron formed in particle collisions is Λ, which has the composition u d s. What is the charge on the Λ particle?

Step 1: Look up the charges of each quark and add them together.
charge Q = charge of the up quark + charge of the down quark + charge of the strange quark

$$Q = (+\tfrac{2}{3})e + (-\tfrac{1}{3})e + (-\tfrac{1}{3})e = 0$$

The Λ particle has no charge.

Mesons and baryons

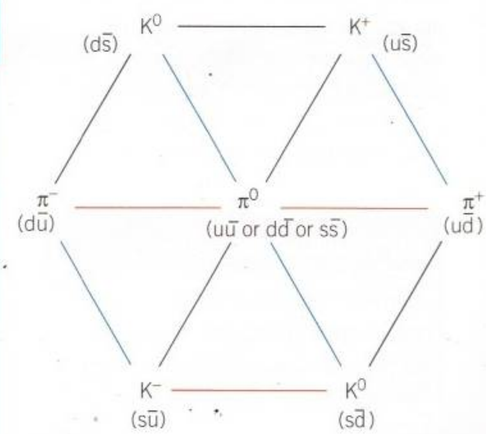
Baryons are any hadrons made with a combination of three quarks. Protons and neutrons are baryons, as are antiprotons because they have the combination $\bar{u}\,\bar{u}\,\bar{d}$. **Mesons** are the hadrons made with a combination of a quark and an anti-quark. Figure 2 lists all the quark combinations for the mesons. As you can see, the properties of all hadrons can be explained in terms of combinations of quarks.

Study tip

The names 'baryon' and 'meson' for the two types of hadron come from Greek. They mean 'heavy' and 'medium', respectively.

Summary questions

1. List all the positive quarks. *(1 mark)*
2. State the quark combinations for the proton and the neutron. *(2 marks)*
3. Compare baryons and mesons. *(2 marks)*
4. Write the anti-quark combination of the antineutron. *(1 mark)*
5. Determine the charge Q of these hadrons:
   a. K^+ meson $u\bar{s}$
   b. π^0 meson $u\bar{u}$. *(4 marks)*
6. A hadron named Z(4430) was discovered at the LHC in Geneva in 2014. It has the quark combination $c\,\bar{c}\,d\,\bar{u}$. Determine the charge of this particle. *(2 marks)*



▲ **Figure 2** *Quark combinations for the mesons using u, d, s, and their anti-quarks. The blue lines join particles with the same charge, the red lines join particles with the same strangeness (another property of quarks – you don't need to know about it right now)*