Section 1

Particles and radiation

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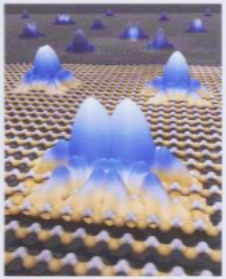
1 Matter and radiation
1.1 Inside the atom

Learning objectives:
- → Describe what is inside an atom.
- → Explain the term isotope.
- → Represent different atoms.

Specification reference: 3.2.1.1

Study tip

Don't mix up 'n' words – nucleus, neutron, nucleon, nuclide!



▲ **Figure 1** *Atoms seen using a scanning tunnelling microscope (STM)*

▲ **Figure 2** *Inside the atom (not to scale)*

The structure of the atom

Atoms are so small (less than a millionth of a millimetre in diameter) that we need to use an electron microscope to see images of them. Although we cannot see inside them, we know, from Rutherford's alpha-scattering investigations, that every atom contains

- a positively charged nucleus composed of protons and neutrons
- electrons that surround the nucleus.

We use the word **nucleon** for a proton or a neutron in the nucleus.

Each electron has a negative charge. Because the nucleus is positively charged, the electrons are held in the atom by the electrostatic force of attraction between them and the nucleus. Rutherford's investigations showed that the nucleus contains most of the mass of the atom and its diameter is of the order of 0.00001 times the diameter of a typical atom.

Table 1 shows the charge and the mass of the proton, the neutron, and the electron in SI units (coulomb for charge and kilogram for mass) and relative to the charge and mass of the proton. Notice that:

1. The electron has a much smaller mass than the proton or the neutron.
2. The proton and the neutron have almost equal mass.
3. The electron has equal and opposite charge to the proton. The neutron is uncharged.

▼ **Table 1** *Inside the atom*

	Charge / C	Charge relative to proton	Mass / kg	Mass relative to proton
proton	$+1.60 \times 10^{-19}$	1	1.67×10^{-27}	1
neutron	0	0	1.67×10^{-27}	1
electron	-1.60×10^{-19}	−1	9.11×10^{-31}	0.0005

This means that an uncharged atom has equal numbers of protons and electrons. An uncharged atom becomes an ion if it gains or loses electrons.

Isotopes

Every atom of a given element has the same number of protons as any other atom of the same element. The **proton number** is also called the **atomic number** (symbol Z) of the element. For example:

- $Z = 6$ for carbon because every carbon atom has six protons in its nucleus.
- $Z = 92$ for uranium because every uranium atom has 92 protons in its nucleus.

The atoms of an element can have different numbers of neutrons. Atoms of the same element with different numbers of neutrons are called **isotopes**.

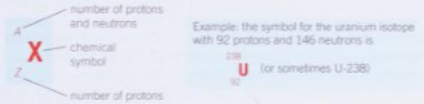
For example, the most abundant isotope of natural uranium contains 146 neutrons and the next most abundant contains 143 neutrons.

Isotopes are atoms with the same number of protons and different numbers of neutrons.

The total number of protons and neutrons in an atom is called the **nucleon number** (symbol A) or sometimes the **mass number** of the atom. This is because it is almost numerically equal to the mass of the atom in relative units (where the mass of a proton or neutron is approximately 1). A nucleon is a neutron or a proton in the nucleus.

We label the isotopes of an element according to their atomic number Z, their mass number A, and the chemical symbol of the element. Figure 3 shows how we do this. Notice that:

- Z is at the bottom left of the element symbol and gives the number of protons in the nucleus.
- A is at the top left of the element symbol and gives the number of protons and neutrons in the nucleus.
- The number of neutrons in the nucleus = $A - Z$.



▲ **Figure 3** *Isotope notation*

Each type of nucleus is called a **nuclide** and is labelled using the isotope notation. For example, a nuclide of the carbon isotope $^{12}_{6}C$ has two fewer neutrons and two fewer protons than a nuclide of the oxygen isotope $^{16}_{8}O$.

Specific charge

The **specific charge** of a charged particle is defined as its charge divided by its mass. We can calculate the specific charge of a charged particle if we know the charge and the mass of the particle. For example:

A nucleus of $^{1}_{1}H$ has a charge of 1.60×10^{-19} C and a mass of 1.67×10^{-27} kg. Its specific charge is therefore 9.58×10^{7} C kg^{-1}.

The electron has a charge of -1.60×10^{-19} C and a mass of 9.11×10^{-31} kg. Its specific charge is therefore 1.76×10^{11} C kg^{-1}. Note that the electron has the largest specific charge of any particle.

An ion of the magnesium isotope $^{24}_{12}Mg$ has a charge of $+3.2 \times 10^{-19}$ C and a mass of 3.98×10^{-26} kg (ignoring the mass of the electrons). Its specific charge is therefore 8.04×10^{6} C kg^{-1}.

Summary questions

You will need to use data from the data sheet on pages 262–265 to answer some of the questions below.

1 a State the number of protons and the number of neutrons in a nucleus of
   i $^{12}_{6}C$ ii $^{16}_{8}O$
   iii $^{235}_{92}U$ iv $^{24}_{11}Na$
   v $^{63}_{29}Cu$.
   b Which of the above nuclei has
   i the smallest specific charge?
   ii the largest specific charge?

2 Name the part of an atom which
   a has zero charge
   b has the largest specific charge
   c when removed, leaves a different isotope of the element.

3 (VR) A $^{63}_{29}Cu$ atom loses two electrons. For the ion formed,
   a calculate its charge in C
   b state the number of nucleons it contains
   c calculate its specific charge in C kg^{-1}.

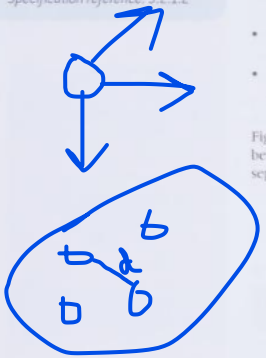
4 a Calculate the mass of an ion with a specific charge of 1.20×10^{7} C kg^{-1} and a negative charge of 3.2×10^{-19} C.
   b The ion has eight protons in its nucleus. Calculate its number of neutrons and electrons.

1.2 Stable and unstable nuclei

Learning objectives:

- State what keeps the protons and neutrons in a nucleus together.
- Explain why some nuclei are stable and others unstable.
- Describe what happens when an unstable nucleus emits an alpha particle or a beta minus particle.

Specification reference: 3.2.1.2



d > 15 * 10^-15 - attraction
d < 15 * 10^-15 - repulsion
15Fm

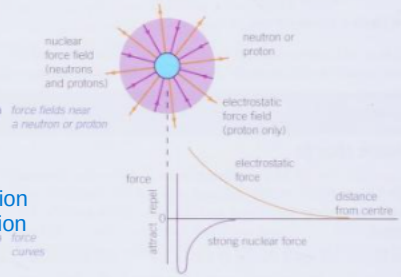
The strong nuclear force

A stable isotope has nuclei that do not disintegrate, so there must be a force holding them together. We call this force the **strong nuclear force** because it overcomes the electrostatic force of repulsion between the protons in the nucleus and keeps the protons and neutrons together.

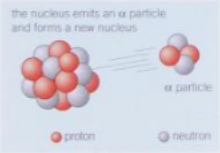
Some further important points about the strong nuclear force are:

- Its range is no more than about 3–4 femtometres (fm), where 1 fm = 10^{-15} m = 0.000 000 000 000 001 m. This range is about the same as the diameter of a small nucleus. In comparison, the electrostatic force between two charged particles has an infinite range (although it decreases as the range increases).
- It has the same effect between two protons as it does between two neutrons or a proton and a neutron.
- It is an attractive force from 3–4 fm down to about 0.5 fm. At separations smaller than this, it is a repulsive force that acts to prevent neutrons and protons being pushed into each other.

Figure 1 shows how the strong nuclear force varies with separation between two protons or neutrons. Notice that the equilibrium separation is where the force curve crosses the x-axis.



▲ **Figure 1** *The strong nuclear force*



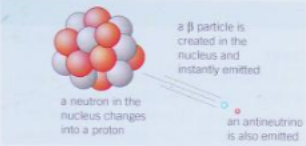
▲ **Figure 2** *Alpha particle emission [not to scale]*

Radioactive decay

Naturally occurring radioactive isotopes release three types of radiation.

1 **Alpha radiation** consists of alpha particles which each comprise two protons and two neutrons. The symbol for an alpha particle is ${}^{4}_{2}\alpha$ because its proton number is 2 and its mass number is 4.

Figure 2 shows what happens to an unstable nucleus of an element X when it emits an alpha particle. Its nucleon number A decreases by 4 and its atomic number Z decreases by 2. As a result of the change, the product nucleus belongs to a different element Y.



▲ **Figure 3** *Beta particle emission [not to scale]*

We can represent this change by means of the equation below:

$$ {}^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}\alpha $$

2 **Beta radiation** consists of fast-moving electrons. The symbol for an electron as a beta particle is ${}^{0}_{-1}\beta$ (or β^-) because its charge is equal and opposite to that of the proton and its mass is much smaller than the proton's mass.

Figure 3 shows what happens to an unstable nucleus of an element X when it emits a β^- particle. This happens as a result of a neutron in the nucleus changing into a proton. The beta particle is created when the change happens and is emitted instantly. In addition, an antiparticle with no charge, called an antineutrino (symbol $\bar{\nu}$), is emitted. You will learn more about antiparticles in Topic 1.4, and neutrinos in Topic 1.5. Because a neutron changes into a proton in the nucleus, the atomic number increases by 1 but the nucleon number stays the same. As a result of the change, the product nucleus belongs to a different element Y. This type of change happens to nuclei that have too many neutrons.

We can represent this change by means of the equation below:

$$ {}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + {}^{0}_{-1}\beta + \bar{\nu} $$

3 **Gamma radiation** (symbol γ) is electromagnetic radiation emitted by an unstable nucleus. It can pass through thick metal plates. It has no mass and no charge. It is emitted by a nucleus with too much energy, following an alpha or beta emission.

Journey into the atom (part 1): A very elusive particle!

When the energy spectrum of beta particles was first measured, it was found that beta particles were released with kinetic energies up to a maximum that depended on the isotope. The scientists at the time were puzzled why the energy of the beta particles varied up to a maximum, when each unstable nucleus lost a certain amount of energy in the process. Either energy was not conserved in the change or some of it was carried away by mystery particles, which they called **neutrinos** and **antineutrinos**. This hypothesis was unproven for over 20 years until antineutrinos were detected. Antineutrinos were detected as a result of their interaction with cadmium nuclei in a large tank of water. This was installed next to a nuclear reactor as a controllable source of these very elusive particles. Now we know that billions of these elusive particles from the Sun sweep through our bodies every second without interacting!

Summary questions

1 Which force, the strong nuclear force or the electrostatic force,
   a does not affect a neutron
   b has a limited range
   c holds the nucleons in a nucleus
   d tends to make a nucleus unstable?

2 Complete the following radioactive decay equations:
   a ${}^{229}_{90}Th \rightarrow Ra + \alpha$
   b ${}^{65}_{29}Ni \rightarrow Cu + \beta + \bar{\nu}$.

3 A bismuth ${}^{213}_{83}Bi$ nucleus emits a beta particle then an alpha particle then another beta particle before it becomes a nucleus X.
   a Show that X is a bismuth isotope.
   b i Determine the nucleon number of X.
   ii How many protons and how many neutrons are in the nucleus just after it emits the alpha particle?

4 The neutrino hypothesis was put forward to explain beta decay.
   a Explain the term *hypothesis*.
   b i State one property of the neutrino.
   ii Name two objects that produce neutrinos.

1.3 Photons

Learning objectives:

- Recall what is meant by a photon.
- Calculate the energy of a photon.
- Estimate how many photons a light source emits every second.

Specification reference: 3.2.1.3

Electromagnetic waves

Light is just a small part of the spectrum of **electromagnetic waves**. Our eyes cannot detect the other parts. The world would appear very different to us if they could. For example, all objects emit infrared radiation. Infrared cameras enable objects to be observed in darkness.

In a vacuum, all electromagnetic waves travel at the speed of light, c, which is $3.00 \times 10^8\ \mathrm{m\,s^{-1}}$. As you know from GCSE, the wavelength λ of **electromagnetic radiation** of frequency f in a vacuum is given by the equation

$$\lambda = \frac{c}{f}$$

Note that we often express light wavelengths in nanometres (nm), where $1\ \mathrm{nm} = 0.000000001\ \mathrm{m} = 10^{-9}\ \mathrm{m}$.

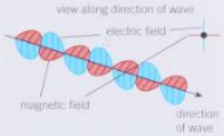
The main parts of the electromagnetic spectrum are listed in Table 1.

▼ **Table 1** *The main parts of the electromagnetic spectrum*

Type	radio	microwave	infrared	visible	ultraviolet	X-rays	gamma rays
Wavelength range	>0.1 m	0.1 m to 1 mm	1 mm to 700 nm	700 nm to 400 nm	400 nm to 1 nm	10 nm to 0.001 nm	<1 nm

As shown in Figure 1, an electromagnetic wave consists of an electric wave and a magnetic wave which travel together and vibrate

- at right angles to each other and to the direction in which they are travelling
- in phase with each other. As you can see the two waves reach a peak together so they are in step. When waves do this we say they are in phase.



▲ **Figure 1** *Electromagnetic waves*

Photons

Electromagnetic waves are emitted by a charged particle when it loses energy. This can happen when

- a fast-moving electron is stopped (for example, in an X-ray tube) or slows down or changes direction
- an electron in a shell of an atom moves to a different shell of lower energy.

Electromagnetic waves are emitted as short bursts of waves, each burst leaving the source in a different direction. Each burst is a packet of electromagnetic waves and is referred to as a **photon**. The photon theory was established by Einstein in 1905, when he used his ideas to explain the **photoelectric effect**. This is the emission of electrons from a metal surface when light is directed at the surface.

power = energy/time

Synoptic link

You will meet the photoelectric effect and the photon theory in more detail in Topic 3.1, The photoelectric effect.

Einstein imagined photons to be like *flying needles*, and he assumed that the energy E of a photon depends on its frequency f in accordance with the equation

$$\textbf{photon energy } E = hf$$

where h is a constant referred to as the Planck constant. The value of h is 6.63×10^{-34} J s.

Worked example

Calculate the frequency and the energy of a photon of wavelength 590 nm.

$h = 6.63 \times 10^{-34}$ J s, $c = 3.00 \times 10^8\ \mathrm{m\,s^{-1}}$

Solution

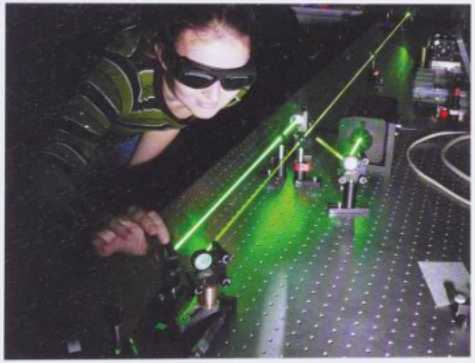
To calculate the frequency, use $f = \frac{c}{\lambda} = \frac{3.00 \times 10^8}{590 \times 10^{-9}} = 5.08 \times 10^{14}$ Hz.

To calculate the energy of a photon of this wavelength, we use $E = hf$.

$E = hf = 6.63 \times 10^{-34} \times 5.08 \times 10^{14} = 3.37 \times 10^{-19}$ J.

$\frac{v}{\lambda} = f$

Laser power



▲ **Figure 2** *A laser at work*

A laser beam consists of photons of the same frequency. The power of a laser beam is the energy per second transferred by the photons. For a beam consisting of photons of frequency f,

$$\textbf{the power of the beam} = nhf$$

where n is the number of photons in the beam passing a fixed point each second. This is because each photon has energy hf. Therefore, if n photons pass a fixed point each second, the energy per second (or power) is nhf.

Summary questions

$c = 3.00 \times 10^8\ \mathrm{m\,s^{-1}}$

$h = 6.63 \times 10^{-34}$ J s

1 a List the main parts of the electromagnetic spectrum in order of increasing wavelength.

b Calculate the frequency of

i light of wavelength 590 nm

ii radio waves of wavelength 200 m.

2 With the aid of a suitable diagram, explain what is meant by an electromagnetic wave.

3 Light from a certain light source has a wavelength of 430 nm. Calculate

a the frequency of light of this wavelength

b the energy of a photon of this wavelength.

4 a Calculate the frequency and energy of a photon of wavelength 635 nm.

b A laser emits light of wavelength 635 nm in a beam of power 1.5 mW. Calculate the number of photons emitted by the laser each second.

1.4 Particles and antiparticles

Learning objectives:

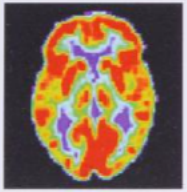
- Define antimatter.
- Describe what happens when a particle and its antiparticle meet.
- Discuss whether anti-atoms are possible.

Specification reference: 3.2.1.3

Brain imaging

PET scanners are used in hospitals for brain imaging of, for example, stroke patients. The T stands for tomography, which is the name for the electronic and mechanical system used to perform the scan.

Q: What type of radiation is detected in a PET scanner?



▲ Gamma radiation

Antimatter

When **antimatter** and matter particles (i.e., the particles that make up everything in our universe) meet, they destroy each other and radiation is released. We make use of this effect in a positron emitting tomography (PET) hospital scanner. The P in PET stands for the **positron**, which is the antiparticle of the electron. When a PET scanner is used for a brain scan, a positron-emitting isotope is administered to the patient and some of it reaches the brain via the blood system. Each positron emitted travels no further than a few millimetres before it meets an electron and they annihilate each other. Two gamma photons, produced as a result, are sensed by detectors linked to computers. Gradually, an image is built up from the detector signals of where the positron-emitting nuclei are inside the brain.

Positron emission takes place when a proton changes into a neutron in an unstable nucleus with too many protons. The positron (symbol $^{0}_{+1}\beta$ or β^+) is the antiparticle of the electron, so it carries a positive charge. In addition, a neutrino (symbol ν), which is uncharged, is emitted.

$$^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y + {}^{0}_{+1}\beta + \nu$$

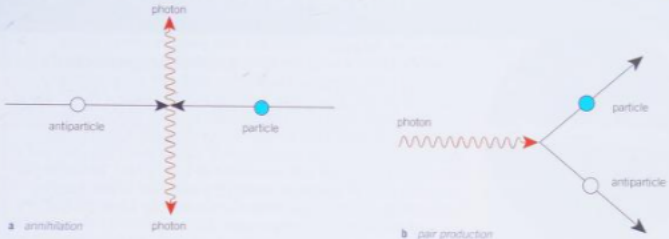
Positron-emitting isotopes do not occur naturally. They are manufactured by placing a stable isotope, in liquid or solid form, in the path of a beam of protons. Some of the nuclei in the substance absorb extra protons and become unstable positron-emitters.

Antimatter was predicted in 1928 by the English physicist Paul Dirac, before the first antiparticle, the positron, was discovered. More than 20 years earlier, Einstein had shown that the mass of a particle increases the faster it travels, and that his famous equation $E = mc^2$ related the energy supplied to the particle to its increase in mass. More significantly, Einstein said that the mass of a particle when it is stationary, its rest mass (m_0), corresponds to **rest energy** m_0c^2 locked up as mass. He showed that rest energy must be included in the conservation of energy. Dirac predicted the existence of antimatter particles (or **antiparticles**) that would unlock rest energy, whenever a particle and a corresponding antiparticle meet and annihilate each other.

Dirac's theory of antiparticles predicted that for every type of particle there is a corresponding antiparticle that:

- annihilates the particle and itself if they meet, converting their total mass into photons
- has exactly the same rest mass as the particle
- has exactly opposite charge to the particle if the particle has a charge.

In addition to the annihilation process described above, Dirac predicted the opposite process of **pair production**. In this process, Dirac predicted that a photon with sufficient energy passing near a nucleus or an electron can suddenly change into a particle–antiparticle pair, which would then separate from each other. Figure 1 shows both of these processes.



▲ **Figure 1** *Particles and antiparticles*

Particles, antiparticles, and $E = mc^2$

The energy of a particle or antiparticle is often expressed in millions of electron volts (MeV), where **1 MeV = 1.60 × 10^{-13} J**. One electron volt is defined as the energy transferred when an electron is moved through a potential difference of 1 volt. Given the rest mass of a particle or antiparticle, its rest energy in MeV can be calculated using $E = mc^2$. However, you won't need to do this type of calculation in this topic, as the rest energies of different particles are listed on pages 262–265 of this book.

Annihilation occurs when a particle and a corresponding antiparticle meet and their mass is converted into radiation energy. Two photons are produced in this process (as a single photon cannot ensure a total momentum of zero after the collision). Therefore, the minimum energy of each photon, hf_{min}, is given by equating the energy of the two photons, $2hf_{min}$, to the rest energy of the particle and of the antiparticle (i.e. $2hf_{min} = 2E_0$, where E_0 is the rest energy of the particle).

Minimum energy of each photon produced, $hf_{min} = E_0$

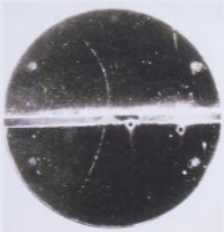
In **pair production**, a photon creates a particle and a corresponding antiparticle, and vanishes in the process. For a particle and antiparticle, each of rest energy E_0, we can calculate the minimum energy and minimum frequency f_{min} that the photon must have to produce this particle–antiparticle pair. Remember, c is the speed of light in a vacuum (3.00×10^8 m s^{-1}).

Minimum energy of photon needed = $hf_{min} = 2E_0$

For example, the electron has a rest energy of 0.511 MeV. Therefore, for pair production of an electron and a positron from a photon:

Minimum energy of a photon = 2 × 0.511 MeV = 1.022 MeV
= 1.64 × 10^{-13} J

A photon with less energy could not therefore create a positron and an electron.



▲ **Figure 2** *The discovery of the positron*

Journey into the atom (part 2): The discovery of the positron

We can see the path of alpha and beta particles using a cloud chamber. This is a small transparent container containing air saturated with vapour and made very cold. The same conditions exist high in the atmosphere. Ionising particles leave a visible trail of liquid droplets when they pass through the air – just like a jet plane does when it passes high overhead on a clear day. In 1932, the American physicist Carl Anderson was using a cloud chamber and a camera to photograph trails produced by cosmic rays. He decided to see if the particles could pass through a lead plate in the chamber. With a magnetic field applied to the chamber, he knew the trail of a charged particle would bend in the field.

- A positive particle would be deflected by the magnetic field in the opposite direction to a negative particle travelling in the same direction.
- The slower it went, the more it would bend.

If a particle went through the plate, he thought it would be slowed down so its trail would bend more afterwards. Imagine his surprise when he discovered a beta particle that slowed down but bent in the opposite direction to all the other beta trails he had photographed. He had made a momentous discovery – a positron, the first antiparticle to be detected (Figure 2).

Summary questions

1 MeV = 1.60 × 10^{-13} J

1 a The rest energy of a proton is 1.501 × 10^{-10} J. Calculate its rest energy in MeV.

b Show that a photon must have a minimum energy of 1876 MeV to create a proton–antiproton pair.

2 Explain why a photon of energy 2 MeV could produce an electron–positron pair but not a proton–antiproton pair.

3 The rest energy of an electron is 0.511 MeV.

a State the minimum energy in J of each photon created when a positron and an electron annihilate each other.

b A positron created in a cloud chamber in an experiment has 0.158 MeV of kinetic energy. It collides with an electron at rest, creating two photons of equal energies as a result of annihilation.

i Calculate the total energy of the positron and the electron.

ii Show that the energy of each photon is 0.590 MeV.

4 A positron can be produced by pair production or by positron emission from a proton-rich nucleus.

a Describe the changes that take place in a proton-rich nucleus when it emits a positron.

b State two ways in which pair production of a positron and an electron differs from positron emission.

1.5 Particle interactions

The electromagnetic force

What is a force? We can measure forces using newtonmeters and force sensors. We know that when a single force acts on an object, it changes the momentum of the object. The **momentum** of an object is its mass multiplied by its velocity.

When two objects interact, they exert equal and opposite forces on each other. Momentum is transferred between the objects by these forces, if no other forces act on them. For example, if two protons approach each other, they repel each other and move away from each other. The American physicist Richard Feynman worked out in detail how this happens. He said the electromagnetic force between two charged objects is due to the exchange of **virtual photons**. He described them as virtual because we can't detect them directly. If we intercepted them, for example, by using a detector, we would stop the force acting. The interaction is represented by the diagram shown in Figure 1. This is a simplified version of what is known as a **Feynman diagram**. Note that the lines do not represent the paths of the particles. The virtual photon exchanged between the two protons is represented by a wave.

An interaction model

Imagine two people on skateboards facing each other and one of them throws a ball to the other. The thrower recoils when the ball leaves his or her hands; the other person recoils when he or she catches the ball. Figure 2 shows the idea. The ball transfers momentum from the thrower to the catcher so they repel each other. The exchange of a virtual photon between two like-charged particles has the same effect – except we can't detect the virtual photon. But the ball analogy won't work for two oppositely charged particles – it would need to be changed to a boomerang, so the thrower and the catcher attract each other!

Learning objectives:

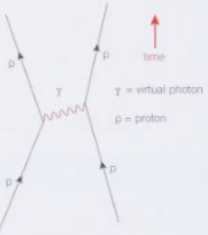
→ Describe what is meant by an interaction.

→ Name different types of interaction.

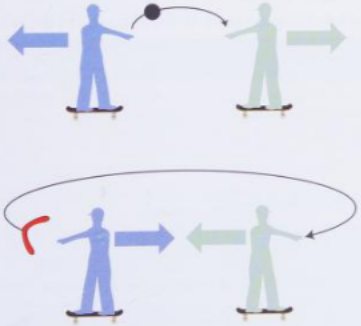
→ Explain what makes charged particles attract or repel each other.

→ Describe an exchange particle.

Specification reference: 3.2.1.4



▲ **Figure 1** *Diagram for the electromagnetic force between two protons*



▲ **Figure 2** *Exchange analogies*

The weak nuclear force

The strong nuclear force holds the neutrons and protons in a nucleus together. But it doesn't cause a neutron to change into a proton in β^- decay, or a proton to change into a neutron in β^+ decay. These changes can't be due to the electromagnetic force, as the neutron is uncharged. There must be a different force at work in the nucleus causing these changes. It must be weaker than the strong nuclear force, otherwise it would affect stable nuclei – we refer to it as the **weak nuclear force**.

In both β^- decay and β^+ decay, a new particle and a new antiparticle are created in each type of decay – but they're not a corresponding particle–antiparticle pair, as one is an electron or a positron and the other is a neutrino or an antineutrino.

Neutrinos and antineutrinos hardly interact with other particles, but such interactions do sometimes happen. For example:

- A neutrino can interact with a neutron and make it change into a proton. A β^- particle (an electron) is created and emitted as a result of the change.
- An antineutrino can interact with a proton and make it change into a neutron. A β^+ particle (a positron) is created and emitted as a result of the change.

These interactions are due to the exchange of particles referred to as **W bosons**. Unlike photons, these exchange particles:

- have a non-zero rest mass
- have a very short range of no more than about 0.001 fm
- are positively charged (the W^+ boson) or negatively charged (the W^- boson).

The diagram for each of these changes is shown in Figure 3. Notice that the total charge at the end is the same as at the start (i.e., charge is conserved).

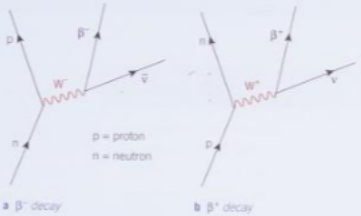
Journey into the atom (part 3): The discovery of the W boson

W bosons were first detected directly in 1983 by scientists using the 2 km diameter Super Proton Synchrotron at CERN in Geneva. Protons and antiprotons at very high energies were made to collide and annihilate each other. At sufficiently high energies, these annihilation events produce W bosons as well as photons. The β particles from the W boson decays were detected exactly as predicted.

Back to beta decay

So what role does a W boson play in beta decay? You can see from Figure 3 that the W boson in each case meets a neutrino or antineutrino, changing them into a β^- particle (an electron) or a β^+ particle (a positron), respectively. But if no neutrino or antineutrino is present:

- the W^- boson decays into a β^- particle and an antineutrino
- the W^+ boson decays into a β^+ particle and a neutrino.



▲ **Figure 4** *W bosons in beta decay*

Figure 4 shows the diagram for each of these decay processes. Notice that charge is conserved in both processes.

Electron capture

Sometimes a proton in a proton-rich nucleus turns into a neutron as a result of interacting through the weak interaction with an inner-shell electron from outside the nucleus (**electron capture**). Figure 5 shows the diagram for this process. Notice that the W^+ boson changes the electron into a neutrino.

The same change can happen when a proton and an electron collide at very high speed. In addition, for an electron with sufficient energy, the overall change could also occur as a W^- exchange from the electron to the proton.

Force carriers

The photon and the W boson are known as force carriers because they are exchanged when the electromagnetic force and the weak nuclear force act respectively. You will soon meet the pion, which is known to be the exchange particle of the strong nuclear force. But what about gravity? Scientists think the carrier of the force of gravity is the graviton – but it has yet to be observed.

Summary questions

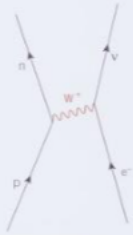
$c = 3.00 \times 10^8\ \mathrm{m\,s^{-1}}$

1 Sketch the diagram for the electromagnetic interaction between
   a two protons b a proton and an electron c two electrons.

2 Sketch the diagram for a β^+ decay b β^- decay.

3 a Sketch the diagram for the interaction between i a neutron and a neutrino, ii a proton and an antineutrino.
   b State the approximate range of the W boson and estimate its lifetime, given it cannot travel faster than the speed of light.

4 a State three differences between a W boson and a virtual photon.
   b In both Figure 4b and Figure 5, a proton changes into a neutron. Describe how these two processes differ.



▲ **Figure 5** *Electron capture*

Study tip

Scientists think there are four fundamental interactions in nature:

1 the force of gravitational attraction between any two objects due to their mass

2 the electromagnetic force which acts between objects due to their electric charge, and explains all electrical and magnetic effects

3 the strong nuclear force which holds the protons and neutrons together in stable nuclei

4 the weak nuclear force which causes β-decay.

Only the gravitational and electromagnetic forces are observed in everyday life but you will learn more about all four of these forces as you progress through your physics course.

1 (a) Copy and complete the table below: *(3 marks)*

	Particle or antiparticle	Charge / proton charge
antiproton	antiparticle	
neutrino		
neutron		0
positron		

(b) The tracks of a positron and an electron created by pair production in a magnetic field curve in opposite directions as shown above.
(i) Why do they curve in opposite directions?
(ii) Both particles spiral inwards. What can you deduce from this observation about their kinetic energy?
(iii) In **Figure 4** of Topic 1.4, the track is a typical beta track. Explain how Carl Anderson deduced from the photograph that the track was created by a positron rather than an electron travelling in the opposite direction. *(5 marks)*

2 (a) $^{229}_{90}Th$ is a neutral atom of thorium. How many protons, neutrons, and electrons does it contain? *(2 marks)*

(b) $^{Y}_{X}Th$ is a neutral atom of a different isotope of thorium which contains Z electrons. Give possible values for X, Y, and Z. *(3 marks)*
AQA, 2001

3 An atom of argon $^{37}_{18}Ar$ is ionised by the removal of two orbiting electrons.
(a) How many protons and neutrons are there in this ion? *(2 marks)*
(b) What is the charge, in C, of this ion? *(2 marks)*
(c) Which constituent particle of this ion has
(i) a zero charge per unit mass ratio?
(ii) the largest charge per unit mass ratio? *(2 marks)*
(d) Calculate the percentage of the total mass of this ion that is accounted for by the mass of its electrons. *(3 marks)*
AQA, 2002

4 (a) A neutral atom contains 28 nucleons.
Write down a possible number of protons, neutrons, and electrons contained in the atom. *(2 marks)*
(b) A certain isotope of uranium may split into a caesium nucleus, a rubidium nucleus, and four neutrons in the following process:

$$^{236}_{92}U \rightarrow {}^{137}_{55}Cs + {}^{X}_{37}Rb + 4\,^{1}_{0}n$$

(i) Explain what is meant by isotopes.
(ii) How many neutrons are there in the $^{137}_{55}Cs$ nucleus?
(iii) Calculate the ratio $\frac{\text{charge}}{\text{mass}}$, in C kg^{-1}, for the $^{236}_{92}U$ nucleus.
(iv) Determine the value of X for the rubidium nucleus. *(4 marks)*
AQA, 2003

6 (a) (i) Describe an α particle and state its properties.
(ii) $^{218}_{85}At$ is an isotope of the element astatine (At) which decays into an isotope of bismuth (Bi) by emitting an α particle. Write down the equation to represent this reaction. *(5 marks)*

(b) (i) State what happens when an unstable nucleus decays by emitting a β^- particle.
(ii) Write down and complete the following equation, showing how an isotope of molybdenum decays into an isotope of technetium:

$$^{\ldots}_{42}Mo \rightarrow {}^{99}_{\ldots}Tc + \beta^- + \ldots$$

(5 marks)

7 In a radioactive decay of a nucleus, a β^+ particle is emitted followed by a γ photon of wavelength 8.30 10^{-13} m.
(a) (i) State the rest mass, in kg, of the β^+ particle.
(ii) Calculate the energy of the γ photon.
(iii) Determine the energy of the γ photon in MeV. *(6 marks)*

(b) Name the fundamental interaction or force responsible for β^+ decay. *(1 mark)*
AQA, 2004

8 (a) (i) State the name of the antiparticle of a positron.
(ii) Describe what happens when a positron and its antiparticle meet. *(3 marks)*

(b) Calculate the minimum amount of energy, in J, released as radiation energy when a particle of rest energy 0.51 MeV meets its corresponding antiparticle. *(2 marks)*
AQA, 2005

9 In a particle accelerator a proton and an antiproton, travelling at the same speed, undergo a head-on collision and produce subatomic particles.
(a) The total kinetic energy of the two particles just before the collision is 3.2×10^{-10} J.
(i) What happens to the proton and antiproton during the collision?
(ii) State why the total energy after the collision is more than 3.2×10^{-10} J. *(2 marks)*

(b) In a second experiment the total kinetic energy of the colliding proton and antiproton is greater than 3.2×10^{-10} J.
State *two* possible differences this could make to the subatomic particles produced. *(2 marks)*
AQA, 2001

10 An electron may interact with a proton in the following way:

$$e^- + p \rightarrow n + \nu_e$$

Name the fundamental force responsible for this interaction. *(1 mark)*
AQA, 2003

11 (a) Give an example of an exchange particle other than a W^+ or W^- particle, and state the fundamental force involved when it is produced. *(2 marks)*
(b) State what roles exchange particles can play in an interaction. *(2 marks)*
AQA, 2006

12 Describe what happens in pair production and give *one* example of this process. *(3 marks)*
AQA, 2005

2 Quarks and leptons
2.1 The particle zoo

Learning objectives:

- → Explain how we can find new particles.
- → State whether we can predict new particles.
- → Describe strange particles.

Specification reference: 3.2.1.5

Practical link

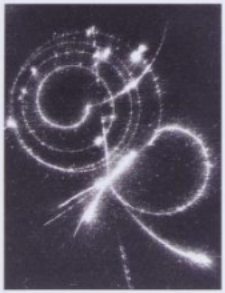
Two Geiger counters can be used to detect the presence of cosmic radiation. Cosmic rays are probably present if the two counters click simultaneously.

Space invaders

Cosmic rays are high-energy particles that travel through space from the stars, including the Sun. When cosmic rays enter the Earth's atmosphere, they create new short-lived particles and antiparticles, as well as photons. Most physicists thought, when cosmic rays were first discovered, that they were from terrestrial radioactive substances. This theory was disproved when the physicist and amateur balloonist, Victor Hess, found the ionising effect of the rays was significantly greater at 5000 m than at ground level.

Further investigations showed that most cosmic rays were fast-moving protons or small nuclei. They collide with gas atoms in the atmosphere, creating showers of particles and antiparticles that can be detected at ground level. By using cloud chambers and other detectors, new types of short-lived particles and antiparticles were discovered, including:

- the **muon** or heavy electron (symbol μ), a negatively charged particle with a rest mass over 200 times the rest mass of the electron
- the **pion** or π meson, a particle which can be positively charged (π^+), negatively charged (π^-), or neutral (π^0), and has a rest mass greater than a muon but less than a proton
- the **kaon** or K meson, which also can be positively charged (K^+), negatively charged (K^-), or neutral (K^0), and has a rest mass greater than a pion but still less than a proton.



▲ **Figure 1** *Creation and decay of a pion. The short spiral track is a π^+ meson created when an antiproton from the bottom edge annihilates a proton. The π^+ meson decays into an antimuon that spirals and decays into a positron.*

Journey into the atom (part 4): An unusual prediction

Before the above particles were first detected, the Japanese physicist Hideki Yukawa predicted the existence of exchange particles for the strong nuclear force between nucleons. He thought they would have a range of no more than about 10^{-15} m and he calculated that their mass would be between the electron and the proton mass. He called them **mesons**, because the predicted mass was somewhere in the middle between the electron mass and the proton mass.

A year later, a cloud chamber photograph obtained by Carl Anderson showed an unusual track that could have been produced by such a particle. However, the track length of 40 mm indicated that it lasted much longer than a strongly interacting particle should. Further investigations showed this unexpected particle to be a heavy electron, now referred to as a **muon** but not classed as a meson. It decays through the weak interaction.

Yukawa's meson was discovered some years later by the British physicist Cecil Powell from tiny microscopic tracks found in photographic emulsion exposed to cosmic rays at high altitude. Powell called these particles π **mesons** or **pions** – Yukawa's prediction was correct!

A strange puzzle

Less than a year after Powell's discovery, further cloud chamber photographs revealed the existence of short-lived particles we now refer to as kaons. Like pions, kaons are produced in twos through the strong interaction, when protons moving at high speed crash into nuclei and they each travel far beyond the nucleus in which they originate before they decay. However, the decay of kaons took longer than expected and included pions as the product. This means that kaons must decay via the weak interaction. These and other properties of kaons led to them being called **strange particles** (see Topic 2.4).

All the new particles listed above can also be created using accelerators in which protons collide head-on with other protons at high speed. The kinetic energy of the protons is converted into mass in the creation of these new particles. So these new particles could be studied under controlled conditions by teams of physicists using accelerators to create them.

The rest masses, charge (if they were charged), and lifetimes of the new particles were measured. Their antiparticles, including the **antimuon**, were detected. Their decay modes were worked out:

- A kaon can decay into pions, or a muon and an antineutrino, or an antimuon and a neutrino.
- A charged pion can decay into a muon and an antineutrino, or an antimuon and a neutrino. A π^0 meson decays into high-energy photons.
- A muon decays into an electron and an antineutrino. An antimuon decays into a positron and a neutrino.
- Decays always obey the conservation rules for energy, momentum, and charge (see Topic 2.5).

About accelerators

A TV tube in a traditional TV is an accelerator because it accelerates electrons inside the tube through a potential difference of about 5000 V. The electrons form a beam that hits the inside of the TV screen. Magnetic fields produced by electromagnets deflect the beam so it scans the screen to create an image. LCD (liquid crystal display) TVs work on a different principle.

- The longest accelerator in the world is the Stanford linear accelerator in California. It accelerates electrons over a distance of 3 km through a potential difference of 50 000 million volts. The energy of an electron accelerated through this pd is 50 000 MeV (= 50 GeV). When the electrons collide with a target, they can create lots of particle–antiparticle pairs.
- The biggest accelerator in the world, the Large Hadron Collider at CERN near Geneva, is designed to accelerate charged particles to energies of more than 7000 GeV. Unlike a linear accelerator, this accelerator is a 27 km circumference ring constructed in a circular tunnel below the ground. It is used by physicists from many countries to find out more about the fundamental nature of matter and radiation. In 2012, an uncharged particle called the Higgs boson was discovered at CERN. It had been predicted in 1964 as the cause of the rest mass of W bosons.

▲ **Figure 2** *A particle accelerator*

Summary questions

1 a List the following particles in order of increasing rest mass: the electron, the K^0 meson, the muon, the neutron, the π^+ meson, the proton.

b Which of the above particles are uncharged?

2 State whether the strong or the weak interaction acts when

a a muon decays

b a kaon decays

c pions are produced.

3 a Which creates the longer trail in a cloud chamber, a muon or a π^+ meson?

b In terms of their properties, state one similarity and one difference between a muon and a pion.

4 A high-energy collision between two protons creates pions and kaons which then decay.

a What happens to

i the kaons

ii the pions?

b What particles are ultimately formed by the above decays?

2.2 Particle sorting

Learning objectives:

- → Identify different classifications of particles.
- → Recognise hadrons.
- → Recognise leptons.

Specification reference: 3.2.1.5

Classifying particles and antiparticles

The new particle discoveries raised the important question – how do all these new particles and antiparticles fit in with each other and with protons, neutrons, and electrons? They are created through high-energy interactions and, apart from the neutrino, they decay into other particles and antiparticles. Also, charged pions were often produced in pairs – leading to the conclusion that the π^+ meson and the π^- meson are a particle–antiparticle pair. The same conclusion was reached for charged kaons. So is there an underlying pattern?

All the particles we have discussed so far are listed in Table 1 together with some of their properties. Can you see any links between the different particles?

▼ **Table 1** *Particles and their properties*

Particle and symbol	Charge / proton charge	Antiparticle and symbol	Charge / proton charge	Rest energy / MeV	Interaction
proton p	+1	antiproton $\bar{p}$	−1	938	strong, weak, electromagnetic
neutron n	0	antineutron $\bar{n}$	0	939	strong, weak
electron e^-	−1	positron e^+	+1	0.511	weak, electromagnetic
neutrino ν	0	antineutrino $\bar{\nu}$	0	0	weak
muon μ^-	−1	antimuon μ^+	+1	106	weak, electromagnetic
pions π^+, π^0, π^-	+1, 0, −1	π^+ for a π^- π^- for a π^+ π^0 for a π^0	−1, 0, +1	140, 135, 140	strong, electromagnetic (π^+, π^-)
kaons K^+, K^0, K^-	+1, 0, −1	see Topic 2.4, Quarks and antiquarks	−1, 0, +1	494, 498, 494	strong, electromagnetic (K^+, K^-)

Notice the symbol for an antiproton, an antineutron, or an antineutrino is the particle symbol with a bar above it, except for the positron and the antimuon which have their own symbols. The charged pions are antiparticles of each other.

How would you classify these particles? In fact, we can divide them into two groups, called **hadrons** and **leptons**, according to whether or not they interact through the strong interaction.

- Hadrons are particles and antiparticles that can interact through the strong interaction (e.g., protons, neutrons, π mesons, K mesons).
- Leptons are particles and antiparticles that do not interact through the strong interaction (e.g., electrons, muons, neutrinos).

1 **Leptons interact through the weak interaction, the gravitational interaction, and through the electromagnetic interaction (if charged).**

2 **Hadrons can interact through all four fundamental interactions. They interact through the strong interaction and through the electromagnetic interaction if charged.**

Apart from the proton, which is stable, hadrons tend to decay through the weak interaction.

Study tip

lepton – light and weak
hadron – strong and heavy

Synoptic link

You will meet baryons, mesons, and the smaller particles that make them up in more detail in Topic 2.4, Quarks and antiquarks.

Energy matters

The Large Hadron Collider is a ring-shaped accelerator that boosts the kinetic energy of the charged particles in the ring at several places round it. Fixed magnets all the way round the ring bend the path of the particles to keep them in the ring. When they collide with other particles:

- The total energy of the particles and antiparticles before the collision = their rest energy + their kinetic energy.
- The total energy of the new particles and antiparticles after the collision = their rest energy + their kinetic energy.

Using conservation of energy,

$$\text{the rest energy of the products} = \text{total energy before} - \text{the kinetic energy of the products}$$

For example, if a proton and an antiproton each with kinetic energy of 2 GeV collide, their total energy before the collision is 6 GeV (as each particle has 2 GeV of kinetic energy and approximately 1 GeV of rest energy – see Table 1). The result could be a range of products, as long as their total energy does not exceed 6 GeV, provided the conservation rules (e.g., charge) are obeyed.

Note:
1 GeV = 1000 MeV

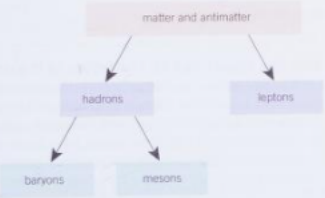
Baryons and mesons

When kaons are created, short-lived particles with greater rest masses than protons may also be produced. These particles are created through the strong interaction, so they are hadrons. However, in comparison with kaons, they decay into protons as well as into pions (whereas protons are never among the decay products of kaons). Consequently, we can divide hadrons into two groups:

1 **Baryons** are protons and all other hadrons (including neutrons) that decay into protons, either directly or indirectly.

2 **Mesons** are hadrons that do *not* include protons in their decay products. In other words, kaons and pions are not baryons.

Baryons and mesons are composed of smaller particles called **quarks** and **antiquarks**.



▲ **Figure 2** *Particle sorts*

▲ **Figure 1** *The Large Hadron Collider*

Summary questions

1 a What is
   i a hadron
   ii a lepton?

   b State whether each of the following particles or antiparticles is a baryon, a meson, or a lepton:
   i an electron
   ii a neutron
   iii a kaon.

2 State one similarity and one difference between
   a a muon and a π^- meson
   b a π^+ meson and a K^+ meson
   c a K^0 meson and a neutron.

3 Complete the following sentences:
   a A particle that is not a hadron is a _____.
   b Hadrons are divided into _____ and _____.
   c _____ do not include protons in their decay products.

4 A K^+ meson can decay into three charged mesons.
   a Complete the following equation for this decay:
   $K^+ \rightarrow \quad + \pi^+ +$
   b (V2) Use the rest energy values in Table 1 to calculate the maximum kinetic energy of the pions, assuming the kaon is at rest before it decays.

2.3 Leptons at work

Learning objectives:

- Consider whether leptons are elementary.
- Distinguish between different types of neutrinos.
- Evaluate the importance of lepton numbers.

Specification reference: 3.2.1.5

▲ **Figure 1** *A two-jet event after an electron–positron collision*

Synoptic link

You have met neutrinos in Topic 1.2, Stable and unstable nuclei.

Synoptic link

You met neutrino–neutron and antineutrino–proton interactions in Topic 1.5, Particle interactions.

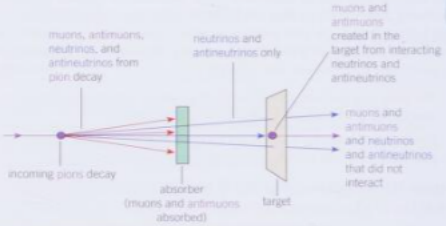
Lepton collisions

The universe would be very dull if all its particles were leptons. Neutrinos interact very little, muons are very short-lived, and the electrons would repel each other. However, leptons and antileptons can interact to produce hadrons. Figure 1 shows two jets of hadrons produced from a single electron–positron annihilation event. This event produces a **quark** and a corresponding **antiquark**, which move away in opposite directions, producing a shower of hadrons in each direction.

Neutrino types

Neutrinos travel almost as fast as light, billions of them sweeping through the Earth from space every second with almost no interaction. They are produced in much smaller numbers when particles in accelerators collide.

Further research on neutrinos showed that the neutrinos and antineutrinos produced in beta decays were different from those produced by muon decays. In effect, neutrinos and antineutrinos from muon and antimuon decays create only muons and no electrons when they interact with protons and neutrons. If there were only one type of neutrino and antineutrino, equal numbers of electrons and muons would be produced. We use the symbol ν_μ for the **muon neutrino** and ν_e for the **electron neutrino** (and similarly for the two types of antineutrinos).



▲ **Figure 2** *Muon and electron neutrinos*

Journey into the atom (part 5): The future of the universe?

Neutrinos and antineutrinos are the subject of on-going research. The rest mass of the neutrino is about a millionth of the electron's rest mass. If this rest mass can be measured accurately, physicists will be able to work out how much neutrinos contribute to the mass of the universe and whether the universe will continue to expand forever (Big Yawn) or stop expanding and contract (Big Crunch).

Lepton rules

Leptons can change into other leptons through the weak interaction and can be produced or annihilated in particle–antiparticle interactions. But all the experiments on them indicate that they don't break down into non-leptons. They appear to be fundamental.

1 **In an interaction between a lepton and a hadron, a neutrino or antineutrino** can change into or from a corresponding charged lepton. An electron neutrino can interact with a neutron to produce a proton and an electron:

$$\nu_e + n \rightarrow p + e^-$$

However, even though charge is conserved, an electron neutrino and a neutron could not change into an antiproton and a positron:

$$\nu_e + n \not\rightarrow \bar{p} + e^+$$

By assigning +1 to a lepton, −1 to an antilepton, and 0 for any non-lepton, we can see that the first equation has a lepton number of +1 before the change and a lepton number of +1 after the change. This equation is permitted. The second equation has a lepton number of +1 before the change and a lepton number of −1 after the change. This change is not permitted.

2 **In muon decay**, the muon changes into a muon neutrino. In addition, an electron is created to conserve charge and a corresponding antineutrino is created to conserve lepton number. For example:

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

However, a muon cannot decay into a muon antineutrino, an electron, and an electron antineutrino even though charge is conserved.

$$\mu^- \not\rightarrow e^- + \bar{\nu}_e + \bar{\nu}_\mu$$

The first equation has a lepton number of +1 before the change and a lepton number of +1 (= +1 − 1 + 1) after the change. This equation is permitted.

The second equation has a lepton number of +1 before the change and a lepton number of − 1 (= +1 − 1 − 1) after the change. This change is not permitted.

The lepton number is conserved in any change.

A weak puzzle

Consider the following possible change for a muon decay:

$$\mu^- \overset{?}{\rightarrow} e^- + \nu_e + \bar{\nu}_\mu$$

It obeys the lepton conservation law and conservation of charge but it is never seen. The reason is that the muon can only change into a muon neutrino. A muon can't change into a muon antineutrino, and an electron can only be created with an electron antineutrino. So we always need to apply the rule below separately to electrons and muons.

The lepton number is +1 for any lepton, −1 for any antilepton, and 0 for any non-lepton.

Summary questions

1 State one similarity and one difference between
   - a a positron and a muon
   - b an electron neutrino and a muon neutrino.

2 a What type of interaction occurs when
   - i two protons collide and create pions
   - ii a beta particle is emitted from an unstable nucleus
   - iii a muon decays?

   b The muon decays into an electron, a neutrino, and an antineutrino.
   - i Complete the equation below representing this decay:

     $\mu^- \rightarrow e^- \quad + \quad +$
   - ii Use the rest energy values in Table 1 on page 20 to calculate how much energy, in MeV, is removed by the neutrino and the antineutrino, if the muon and the electron have no kinetic energy.

3 a What is the charge of
   - i a muon neutrino
   - ii an antimuon
   - iii a positron
   - iv an electron antineutrino?

   b What is the lepton number of each of the above leptons?

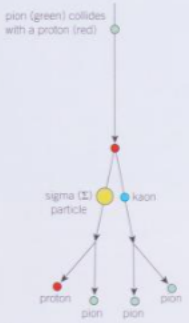
4 State whether or not each of the following reactions is permitted, giving a reason if it is not permitted:
   - a $\nu_e + p \rightarrow n + e^-$
   - b $\bar{\nu}_e + p \rightarrow n + e^+$
   - c $\nu_e + p \rightarrow n + e^+$
   - d $\bar{\nu}_e + p \rightarrow n + \mu^+$.

2.4 Quarks and antiquarks

Learning objectives:

- Define strange particles.
- Define quarks and explain how we know they exist.
- Explain the quark changes that happen in beta decay.
- Explain why it could be said that there are no antimesons.

Specification reference: 3.2.1.6; 3.2.1.7



▲ **Figure 1** *Strange particles*

▼ **Table 1** *Some reactions that were predicted*

1	$\pi^- + p \rightarrow K^+ + \Sigma^-$	observed
2	$\pi^+ + n \rightarrow K^+ + \Sigma^0$	observed
3	$\pi^- + n \rightarrow K^0 + \Sigma^-$	observed
4	$\pi^- + n \rightarrow K^- + \Sigma^0$	*not observed*

Study tip

You may be asked to work out the charge or strangeness of any baryon or antibaryon from its quark composition.

Strangeness

When kaons were first discovered they were called V particles because the cloud chamber photographs often showed V-shaped tracks. They were called strange particles after investigations showed that the V tracks decay into pions only, or into pions and protons. Although these strange particles all decay through the weak interaction:

1 those that decay into pions only were referred to as kaons
2 the others, such as the sigma (Σ) particle in Figure 1, were found to:
   - have different rest masses which were always greater than the proton's rest mass
   - decay either in sequence or directly into protons and pions.
3 strange particles are created in twos.

Journey into the atom (part 6): Predictions and observations

Accelerators were used to create these other particles and to study their properties. The results showed that some reactions that were predicted were never observed (Table 1).

All the observed reactions conserve charge. To explain why certain reactions were not observed, a **strangeness number** S was introduced for each particle and antiparticle (starting with +1 for the K^+ meson) so that strangeness is always conserved in strong interactions. Non-strange particles (i.e., the proton, the neutron, pions, leptons) were assigned zero strangeness. The strangeness numbers for the other strange particles and antiparticles can then be deduced from the observed reactions.

In reaction 1, S = −1 for Σ^- so that the total strangeness is zero before and after the reaction.

In reaction 2, S = −1 for Σ^0 so that the total strangeness is zero before and after the reaction.

In reaction 3, S = +1 for K^0 so that the total strangeness is zero before and after the reaction.

But reaction 4 is not observed so the K^- meson does not have S = +1.

The above interactions are all strong interactions. Observations that strangeness is not conserved when strange particles decay leads to the conclusion that strangeness is not conserved in a weak interaction.

Strangeness is always conserved in a strong interaction, whereas strangeness can change by 0, +1, or −1 in weak interactions.

The quark model

The properties of the hadrons, such as charge, strangeness, and rest mass can be explained by assuming they are composed of smaller particles known as quarks and antiquarks. For the hadrons studied in this course, three different types of quarks and their corresponding antiquarks are necessary. These three types are referred to as up, down, and strange quarks, and are denoted by the symbols u, d, and s, respectively. The properties of these three quarks are shown in Table 1.

▼ **Table 2** *Quark properties*

	Quarks			Antiquarks		
	up u	down d	strange s	up $\bar{u}$	down $\bar{d}$	strange $\bar{s}$
charge Q	$+\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{2}{3}$	$+\frac{1}{3}$	$+\frac{1}{3}$
strangeness S	0	0	−1	0	0	+1
baryon number B	$+\frac{1}{3}$	$+\frac{1}{3}$	$+\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$

Quark combinations

The rules for combining quarks to form baryons and mesons are astonishingly simple.

Mesons are hadrons, each consisting of a quark and an antiquark. Figure 2 shows all nine different quark–antiquark combinations and the meson in each case. Notice that:

- a π^0 meson can be any quark–corresponding antiquark combination
- each pair of charged mesons is a particle–antiparticle pair
- there are two uncharged kaons, the K^0 meson and the $\bar{K}^0$ meson
- the antiparticle of any meson is a quark–antiquark pair and therefore another meson.

Baryons and **antibaryons** are hadrons that consist of three quarks for a baryon or three antiquarks for an antibaryon.

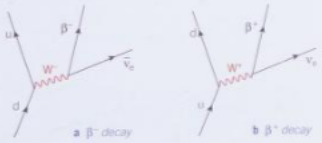
- A proton is the uud combination.
- A neutron is the udd combination.
- An antiproton is the $\bar{u}\bar{u}\bar{d}$ combination.
- The Σ particle is a baryon containing a strange quark.

The proton is the only stable baryon. A free neutron decays into a proton, releasing an electron and an electron antineutrino, as in β^- decay.

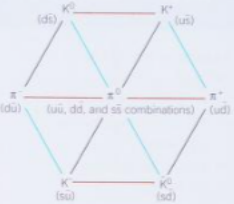
Quarks and beta decay

In β^- decay, a neutron in a neutron-rich nucleus changes into a proton, releasing an electron and an electron antineutrino. In quark terms, a down quark changes to an up quark. The diagram for this change is shown in Figure 3a.

In β^+ decay, a proton in a proton-rich nucleus changes into a neutron, releasing a positron and an electron neutrino. In quark terms, an up quark changes to a down quark. The diagram for this change is shown in Figure 3b.



▲ **Figure 3** *Quark changes in beta decay*



▲ **Figure 2** *Quark combinations for the mesons*

Summary questions

1 Determine the quark composition of each of the following hadrons, given its strangeness:
   a a π^0 meson (S = 0)
   b an antiproton (S = 0)
   c a K^- meson (S = −1)
   d a Σ^0 baryon (S = −1).
2 In β^+ decay, a positron and an electron neutrino are emitted when a proton in the nucleus changes into a neutron.
   a In terms of quarks, draw a diagram to represent this change.
   b Describe the changes that are represented in the diagram.
3 a A Σ^- particle has a strangeness of −1. Show that it is composed of a strange quark and two down quarks.
   b A K^+ meson is composed of a strange antiquark and an up quark. A Σ^- baryon is composed of a strange quark and two down quarks. They can be created in the reaction: $\pi^- + p \rightarrow K^+ + \Sigma^-$
   Describe this reaction in terms of quarks and antiquarks.

2.5 Conservation rules

Learning objectives:

- → State the conservation rules for particle interactions.
- → Explain what is sometimes conserved.
- → Explain what is never conserved.

Specification reference: 3.2.1.6; 3.2.1.7

▼ **Table 1** *The decay of the antimuon (interaction is weak)*

	μ^+	e^+	ν_e	$\bar{\nu}_\mu$
charge	+1	+1	0	0
muon lepton number	−1	0	0	−1
electron lepton number	0	−1	+1	0

▼ **Table 2** *A proton–π^- meson collision (interaction is strong)*

	π^-	p	K^0	Λ^0
charge	−1	+1	0	0
strangeness	0	0	+1	−1

Study tip

Strangeness is not necessarily conserved when the weak interaction is involved. In weak interactions, strangeness can be unchanged or changed by ±1.

▼ **Table 3** *Some reactions conserve baryons and mesons*

$p + \bar{p} \rightarrow \pi^+ + \pi^-$	observed
$p + \bar{p} \rightarrow p + \pi^-$	not observed
$p + p \rightarrow p + p + p + \bar{p}$	observed
$p + \bar{p} \rightarrow p + \pi^+$	not observed

Particles and properties

Particles and antiparticles possess energy – they may be charged or uncharged, they may have non-zero strangeness, and they may not be stable. They obey certain **conservation rules** when they interact. Some rules apply to all interactions and decays and some do not.

1. **Conservation of energy and conservation of charge** apply to all changes in science, not just to all particle and antiparticle interactions and decays. Remember conservation of energy includes the rest energy of the particles (see Topic 2.2, Particle sorting).
2. **Conservation rules used only for particle and antiparticle interactions and decays** are essentially particle-counting rules, based on what reactions are observed and what reactions are not observed. So far, we have used the following conservation rules (in addition to energy and charge):
   a. **Conservation of lepton numbers**. In any change, the total lepton number for each lepton branch before the change is equal to the total lepton number for that branch after the change.

      For example, when an antimuon decays, it changes into a positron, an electron neutrino, and a muon antineutrino, as shown below:

      $$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

      The properties of each particle or antiparticle in this change are shown in Table 1. We can see from this table that the lepton numbers for each type of lepton are conserved, as in all changes involving leptons.
   b. **Conservation of strangeness**. In any strong interaction, strangeness is always conserved.

      For example, a K^0 meson and a strange baryon called the neutral lambda particle (symbol Λ^0) are produced when a π^- meson collides with a proton, as shown below:

      $$\pi^- + p \rightarrow K^0 + \Lambda^0$$

      The properties of each particle involved in this change are shown in Table 2. We can see from this table that strangeness is conserved, just as in all changes involving the strong interaction.

Are baryons and mesons conserved?

Table 3 shows some reactions that are observed and some that are not observed. They all obey the above conservation laws so why are some not observed?

Let's consider the first reaction in terms of quarks (Figure 1):

$$uud + \overline{uud} \rightarrow u\bar{d} + \bar{u}d$$

We can see that an up quark and an up antiquark annihilate each other and the other quarks and antiquarks rearrange to form mesons.

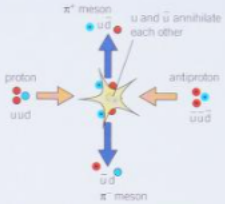
This reaction shows that we can keep track of the baryons and antibaryons, if we assign a **baryon number** of:

- +1 to any baryon and −1 to any antibaryon
- 0 to any meson or lepton.

In effect, the above rules amount to assigning a baryon number of $+\frac{1}{3}$ to any quark, $-\frac{1}{3}$ to any antiquark, and 0 to any lepton.

So in the first reaction, the baryon number is 0 (= +1 − 1) for the left-hand side and 0 for the right-hand side. In other words, the baryon number is conserved. Prove for yourself that this rule applies to the third reaction but not to the second or fourth reactions.

In any reaction, the total baryon number is conserved.



▲ **Figure 1** *Using the quark model*

Journey into the atom (part 7): Big questions

Is there a deeper structure of matter that is still to be discovered? Radiation released in the Big Bang produced quarks and leptons in equal numbers to their antiparticles. So why haven't they all annihilated to turn back into radiation and why is the universe made of matter, not antimatter?

The study of particle physics raises lots of interesting questions! Scientists now know there are six different quarks and six different leptons. The properties and behaviour of matter on the smallest possible scale affects what happens on the largest scale (i.e., the universe). Perhaps the Large Hadron Collider and the discovery of the Higgs boson (see Topic 2.1) at CERN will provide some of the answers.

▲ **Figure 2** *Hubble Ultra Deep Field*

Summary questions

1. The following reaction was observed when two protons collided head-on at high speed:

   $p + p \rightarrow p + n + \pi^+$

   a. i. Show that charge is conserved in this reaction.

      ii. What other quantity is conserved in this reaction?

   b. Use the rest energy values in Table 1 on page 20 to show that the two protons must have at least 141 MeV of kinetic energy to create the π^+ meson.

   c. i. State the quark compositions of a proton and of a neutron.

      ii. The π^+ meson has a quark compositions of $u\bar{d}$. Describe the above reaction in terms of quarks.

2. a. State the baryon number of

   i. an up quark ii. an antiproton iii. a muon.

   b. State the lepton number of

   i. a neutrino ii. an antimuon iii. a neutron.

3. The omega minus particle (Ω^-) is a baryon with a strangeness of −3 and a charge of −1.

   a. Determine its quark composition.

   b. It decays into a π^- meson and a baryon X composed of two strange quarks and an up quark.

      i. Determine the charge and the strangeness of X from its quark composition.

      ii. What type of interaction occurs in this change?

      iii. Describe the quark changes that take place.

1 (a) Kaons were originally called strange because they are produced in *one* type of interaction and they decay through a different type of interaction.
(i) In which type of interaction are they produced?
(ii) Which type of interaction causes them to decay?
(iii) In which type of interaction is strangeness always conserved? *(3 marks)*

(b) (i) Describe the three-quark model of hadrons.
(ii) The three-quark model originated from a theory that explained the properties of baryons and mesons. Show that the three-quark model explains why there are just four charged mesons. *(6 marks)*

2 From the following list of particles

p $\quad \bar{n} \quad \nu_e \quad e^+ \quad \mu^- \quad \pi^0$

identify all the examples of
(i) hadrons (ii) leptons
(iii) antiparticles (iv) charged particles. *(4 marks)*
AQA, 2006

3 (a) (i) Write down the particles in the following list that may be affected by the weak interaction:
positron neutron photon neutrino positive pion
(ii) Write down the particles in the following list that may be affected by the electromagnetic force:
electron antineutrino proton neutral pion negative muon *(4 marks)*

(b) A positive muon may decay in the following way:

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

(i) Exchange each particle for its corresponding antiparticle and complete the equation to show how a negative muon may decay:

$$\mu^- \rightarrow$$

(ii) Give *one* difference and *one* similarity between a negative muon and an electron. *(3 marks)*
AQA, 2003

4 (a) State the quark composition of a neutron. *(2 marks)*
(b) Which of the following terms can be used to describe a neutron?
antiparticle baryon fundamental particle hadron lepton meson *(2 marks)*
AQA, 2004

5 (a) A particle is made up of an up antiquark and a down quark.
(i) Name the classification of particles that has this type of structure.
(ii) Find the charge on the particle.
(iii) State the baryon number of the particle. *(3 marks)*

(b) A suggested decay for the positive muon (μ^+) is

$$\mu^+ \rightarrow e^+ + \nu_e$$

Showing your reasoning clearly, deduce whether this decay satisfies the conservation rules that relate to baryon number, lepton number, and charge. *(3 marks)*
AQA, 2003

6 A sigma plus particle, Σ^+, is a baryon.
(i) How many quarks does the Σ^+ contain?
(ii) If *one* of these quarks is an s quark, by what interaction will it decay?
(iii) Which baryon will the Σ^+ eventually decay into? *(3 marks)*
AQA, 2005

7 Some subatomic particles are classified as *hadrons*.
(a) What distinguishes a hadron from other subatomic particles? *(1 mark)*
(b) Hadrons fall into two subgroups.
Name each subgroup and describe the general structure of each. *(3 marks)*
(c) The following equation represents an event in which a positive muon collides with a neutron to produce a proton and an antineutrino:

$$n + \mu^+ \rightarrow p + \bar{\nu}_\mu$$

Show that this equation obeys the conservation laws of charge, lepton number, and baryon number. *(3 marks)*
AQA, 2004

8 A negative pion (π^-) is a meson with a charge of –1e.
State and explain the structure of the π^- in terms of the up and down quarks. *(3 marks)*
AQA, 2002

9 The following is an incomplete equation for the decay of a free neutron:

$${}^{1}_{0}n \rightarrow {}^{1}_{1}p + {}^{0}_{-1}e + \ldots$$

(a) Complete the equation by writing down the symbol for the missing particle. *(2 marks)*
(b) Use the principles of conservation of charge, baryon number, and lepton number to demonstrate that decay is possible. *(3 marks)*
(c) The following reaction can take place when two protons meet head-on, provided the two colliding protons have sufficient kinetic energy:

$$p + p \rightarrow p + p + \bar{p} + p$$

If the two colliding protons each have the same amount of energy, calculate the minimum kinetic energy, in MeV, each must have for the reaction to proceed. *(2 marks)*
AQA, 2005

10 (a) (i) What class of particle is represented by the combination of three antiquarks, $\bar{q}\bar{q}\bar{q}$?
(ii) Name a hadron that has an antiparticle identical to itself. *(3 marks)*

(b) The kaon K^+ has a strangeness of +1.
(i) Give its quark composition
(ii) The K^+ may decay via the process

$$K^+ \rightarrow \pi^+ + \pi^0$$

State the interaction responsible for this decay.
(iii) The K^+ may also decay via the process

$$K^+ \rightarrow \mu^+ + \nu_\mu$$

Change each particle of this equation to its corresponding antiparticle in order to complete an allowed decay process for the negative kaon K^-:

$$K^- \rightarrow$$

(iv) Into what class of particle can both the μ^+ and the ν_μ be placed?
(v) State *one* difference between a positive muon and a positron, e^+. *(6 marks)*
AQA, 2002

11 The following equation represents the collision of a neutral kaon with a proton, resulting in the production of a neutron and a positive pion:

$$K^0 + p \rightarrow n + \pi^+$$

(a) Show that this collision obeys *three* conservation laws in addition to energy and momentum. *(3 marks)*
(b) The neutral kaon has a strangeness of +1.
Write down the quark structure of the following particles:

$K^0 \quad \pi^+ \quad p$ *(4 marks)*