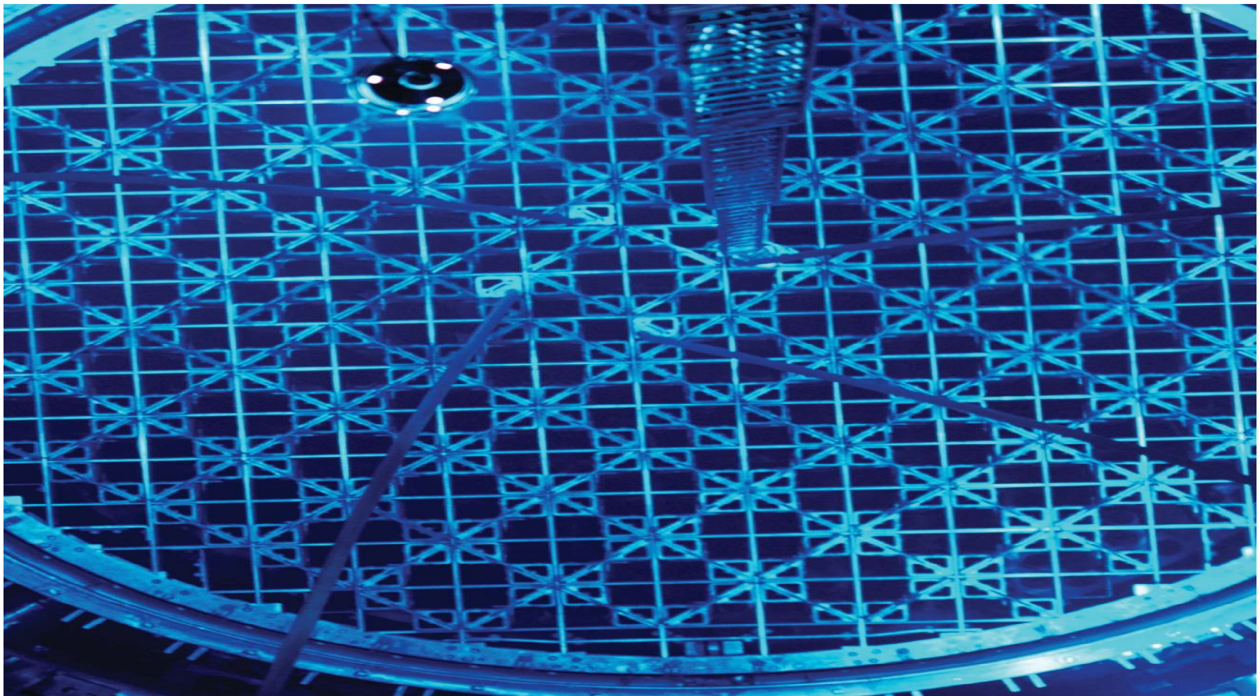

Chapter 15

Atomic structure and particle physics

LEARNING INTENTIONS

In this chapter you will learn how to:

- describe the nuclear model of the atom and the evidence for it
- show an understanding of the nature and properties of α-, β- and γ-radiations
- understand that in α and β decay a nuclide changes into a different nuclide
- recognise that there are two classes of sub-atomic particles – leptons and hadrons
- recognise that leptons are fundamental particles
- appreciate that electrons and neutrinos are leptons
- recognise that hadrons are not fundamental particles
- understand that hadrons are made up of particles called quarks.

BEFORE YOU START

- Try drawing the structure of the atom.
- Suggest why, in the late 19th century, physicists felt that atoms were not the basic building blocks of matter and that the atoms themselves had an internal structure. Discuss your ideas with your fellow students.

RADIOACTIVITY AT WORK

Radioactive substances have many uses, for example, in engineering and medicine.

In the 1950s, many shoe shops had an X-ray machine where you put your feet into an opening and you could view the bones in your feet on a fluorescent screen – quite exciting for a young child! These have long since disappeared. Why do you think they are not used anymore?

Radioactive substances must be handled with great care to ensure that no-one becomes contaminated and so exposed to the radiation that comes from these substances (Figure 15.1).

Do you know how modern-day workers who are likely to be exposed to radiation (such as radiographers in a hospital) are protected from radiation? Are the short-term and long-term protections different?

In this chapter, we will look at the structure of the atom, and then the nature of radioactive substances and the different types of radiation they produce.

Figure 15.1: A worker at a nuclear power station is checked for any radioactive material on his body.

15.1 Looking inside the atom

The idea that matter is composed of very small particles called atoms was first suggested by the Ancient Greeks about 2000 years ago. However, it was not until the middle of the 19th century that any ideas about the **inside** of the atom were proposed.

It was the English scientist J.J. Thomson who suggested that the atom is a neutral particle made of a positive charge with lumps of negative charge (electrons) in it. He could not determine the charge and the mass of the negative particles separately, but it was clear that a new particle, probably much smaller than the hydrogen atom, had been discovered. Since atoms are neutral and physicists had discovered a negatively charged part of an atom, it meant that there were both positive and negative charges in an atom. We now call this the **plum pudding model of the atom** (positive pudding with negative plums!).

Other experiments show that the electron has a mass of approximately 9.11×10^{-31} kg (m_e) and a charge of -1.60×10^{-19} C ($-e$). Today, we use the idea of the electron to explain all sorts of phenomena, including electrostatics, current electricity and electronics.

15.2 Alpha-particle scattering and the nucleus

Early in the 20th century, many physicists were investigating the recently discovered phenomenon of radioactivity, the process whereby unstable nuclei emit radiation. One kind of radiation they found consisted of what they called α-particles (alpha-particles).

These α-particles were known to have a similar mass to the smaller atoms (such as hydrogen, helium and lithium) and had relatively high kinetic energies. Hence, they were useful in experiments designed to discover the composition of atoms.

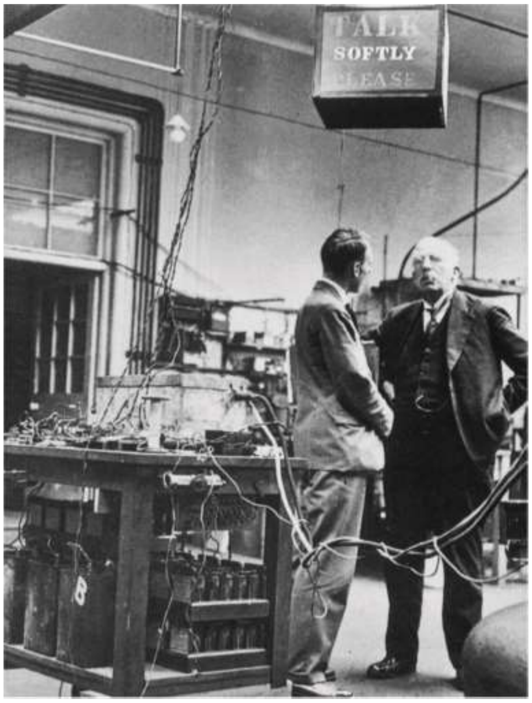

Figure 15.2: Ernest Rutherford (on the right) in the Cavendish Laboratory, Cambridge, England. He had a loud voice that could disturb sensitive apparatus and so the notice was a joke aimed at him.

In 1906, while experimenting with the passage of α-particles through a thin mica sheet, Ernest Rutherford (Figure 15.2) noticed that most of the α-particles passed straight through. (Mica is a natural mineral that can be split into very thin sheets.) This suggested to him that there might be a large amount of empty space in the atom, and by 1909 he had developed what we now call the **nuclear model of the atom**.

In 1911, Rutherford carried out a further series of experiments with Hans Geiger and Ernest Marsden at the University of Manchester using gold foil in place of the mica. They directed parallel beams of α-particles at a piece of gold foil only 10^{-6} m thick. Most of the α-particles went straight through. Some were deflected slightly, but about 1 in 20 000 were deflected through an angle of more than 90°, so that they appeared to bounce back off the foil. This helped to confirm Rutherford in his thinking about the atom – that it was mostly empty space, with most of the mass and all of the positive charge concentrated in a tiny region at the centre. This central **nucleus** only affected the α-particles when they came close to it.

Later, Rutherford wrote: 'It was quite the most incredible event that has happened to me in my life. It was almost as incredible as if you fired a 15-inch shell at a piece of tissue paper and it came back and hit you.' In fact, he was not quite as surprised as this suggests, because the results confirmed ideas he had used in designing the experiment.

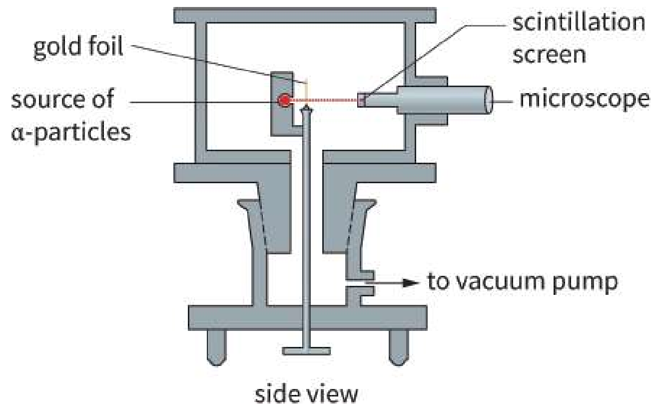

Figure 15.3: The apparatus used for the α-scattering experiment. The microscope can be moved round to detect scattered radiation at different angles.

Figure 15.3 shows the apparatus used in the α-scattering experiment. Notice the following points:

- The α-particle source was encased in metal with a small aperture, allowing a fine beam of α-particles to emerge.
- Air in the apparatus was pumped out to leave a vacuum; α-radiation is absorbed by a few centimetres of air.
- One reason for choosing gold was that it can be made into a very thin sheet or foil. Rutherford's foil was only a few hundreds of atoms thick.
- The α-particles were detected when they struck a solid 'scintillating' material. Each α-particle gave a tiny flash of light and these were counted by the experimenters (Geiger and Marsden).
- The detector could be moved round to detect α-particles scattered through different angles.

Geiger and Marsden had the difficult task of observing and counting the tiny flashes of light produced by individual α-particles striking the scintillation screen. They had to spend several minutes in the darkened laboratory to allow the pupils of their eyes to become dilated so that they could see the faint flashes. Each experimenter could only stare into the detector for about a minute before the strain was too much and they had to change places.

Explaining α-scattering

How can we explain the back-scattering of α-particles by the gold atoms?

If the atom was as Thomson pictured it, with negatively charged electrons scattered through a 'pudding' of positive charge, an individual α-particle would pass through it like a bullet, hardly being deflected at all. This is because the α-particles are more massive than electrons–they might push an electron out of the atom, but their own path would be scarcely affected.

However, if the mass and positive charge of the atom were concentrated at one point in the atom, as Rutherford suggested, an α-particle striking this part would be striking something more massive than itself and with a greater charge. A head-on collision would send the α-particle backwards.

The paths of an α-particle near a nucleus are shown in Figure 15.4.

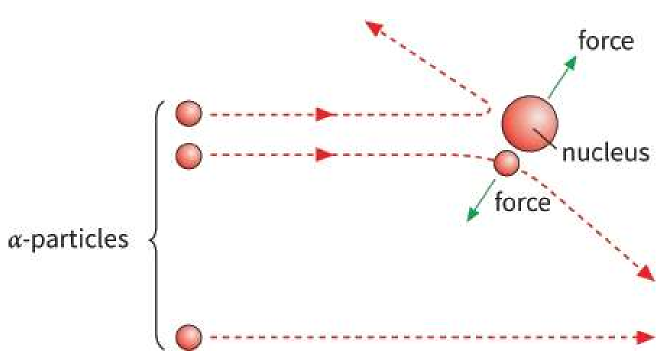

Figure 15.4: Possible paths of an α-particle near a nucleus. The nucleus and the α-particle both experience electrostatic repulsion.

Rutherford reasoned that the large deflection of the α-particle must be due to a very small charged nucleus. From his experiments he calculated that the diameter of the gold nucleus was about 10^{-14} m. It has since been shown that the very large deflection of the α-particle is due to the electrostatic repulsion between the positive charge of the α-particle and the positive charge of the nucleus of the atom. The closer the path of the α-particle gets to the nucleus, the greater will be this repulsion. An α-particle making a 'head-on' collision with a nucleus is back-scattered through 360°. The α-particle and nucleus both experience an equal but opposite repulsive electrostatic force *F*. This force has a much greater effect on the motion of the α-particle than on the massive nucleus of gold.

PRACTICAL ACTIVITY 15.1

An analogy for Rutherford scattering

Roll a ball-bearing down a slope towards a cymbal. It may be deflected but, even if you roll it directly at the cymbal's centre, it will not come back – it will roll over the centre and carry on to the other side. However, if you roll the ball-bearing towards a 'tin hat' shape (with a much narrower but higher central bulge) any ball-bearings that you roll close to the centre will deflect a lot, and any ball-bearings that you roll directly towards the centre will roll straight back. This is a very simple analogy (or model) of Rutherford's experiment.

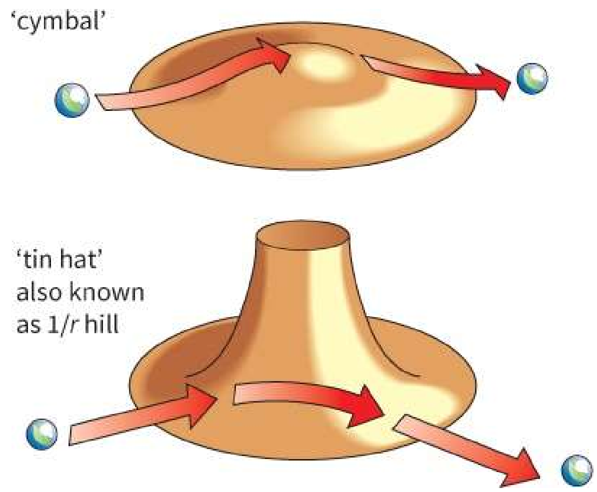

Figure 15.5: An analogy for Rutherford's experiment.

The shape of the cymbal represents the shape of the electric field of an atom in the 'plum pudding' model: low central intensity and spread out. The 'tin hat' represents the shape of the electric field for the nuclear model: high central intensity and concentrated.

From the α-particle scattering experiment, Rutherford deduced the following.

- An α-particle is deviated due to the repulsive force between the α-particle and the positive charge in the atom.
- Most α-particles have little or no deviation–so most of an atom is empty space.
- A very few α-particles are deviated more than 90° – so most of the mass of an atom is concentrated in a small space (the nucleus) and most of the atom is empty space.

Questions

1 Rutherford's scattering experiments were done in an evacuated container. Explain why this is necessary.

2 In Rutherford's experiment, α-particles were directed at a thin gold foil. A small fraction of the α-particles were back-scattered through 180°.

Describe and explain how the fraction back-scattered changes if each of the following changes are (separately) made.

a A thicker foil is used.

b Faster α-particles are used.

c A silver foil is used – a silver nucleus has less positive charge than a gold nucleus.

15.3 A simple model of the atom

After Rutherford had presented his findings, the nuclear model of the atom gained rapid acceptance. This was partly because it helped chemists to explain the phenomenon of chemical bonding (the way in which atoms bond together to form molecules). Subsequently, the proton was discovered. It had a positive charge, equal and opposite to that of the electron. However, its mass was too small to account for the entire mass of the atom and it was not until the early 1930s that this puzzle was solved by the discovery of the neutron, an uncharged particle with a similar mass to that of the proton. This suggests a model for the atom like the one shown in Figure 15.6:

- Protons and neutrons make up the nucleus of the atom.
- The electrons move around the nucleus in a cloud, some closer to and some further from the centre of the nucleus.

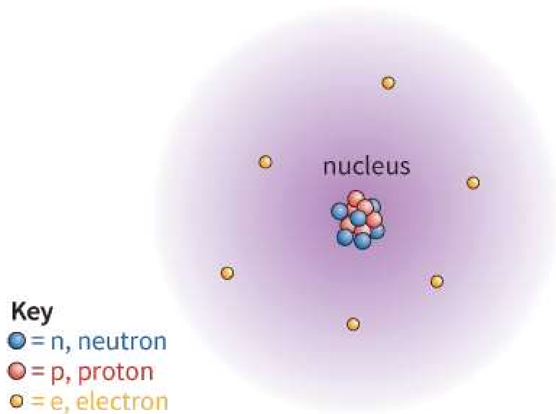

Figure 15.6: A simple model of the atom. If the nucleus were drawn to scale, it would be invisible (and the electrons are even smaller!).

From this model it looks as though all matter, including ourselves, is mostly empty space. For example, if we scaled up the hydrogen atom so that the nucleus was the size of a 1 cm diameter marble, the orbiting electron would be a grain of sand about 800 m away!

The scale of things

It is useful to have an idea of the approximate sizes of typical particles:

- radius of proton ~ radius of neutron ~ 10^{-15} m
- radius of nucleus ~ 10^{-15} m to 10^{-14} m
- radius of atom ~ 10^{-10} m
- size of molecule ~ 10^{-10} m to 10^{-6} m.

(Some molecules, such as large protein molecules, are very large indeed – compared to an atom!)

The radii of nuclear particles are often quoted in femtometres (fm), where 1 fm = 10^{-15} m.

Nuclear density

We can picture a proton as a small, positively charged sphere. Knowing its mass and radius, we can calculate its density:

$$\text{mass of proton } m_{\mathrm{p}} = 1.67 \times 10^{-27}\ \text{kg}$$

$$\text{radius of proton } r = 0.80\ \text{fm} = 0.80 \times 10^{-15}\ \text{m}$$

(In fact, the radius of the proton is not very accurately known; it is probably between 0.80×10^{-15} m and 0.86×10^{-15} m.)

$$
\begin{aligned}
\text{volume of proton} &= \tfrac{4}{3}\pi r^3 \\
&= \tfrac{4}{3}\pi \times \left(0.80 \times 10^{-15}\right)^3 \\
&= 2.14 \times 10^{-45}\,\text{m}^3 \\
\text{density} &= \tfrac{\text{mass}}{\text{volume}} \\
&= \tfrac{1.67\times10^{-27}}{2.14\times10^{-45}} \\
&\approx 7.8 \times 10^{17}\,\text{kg m}^{-3}
\end{aligned}
$$

So the proton has a density of roughly 10^{18} kg m^{-3}. This is also the density of a neutron, and of an atomic nucleus, because nuclei are made of protons and neutrons held closely together.

Compare the density of nuclear material with that of water whose density is 1000 kg m^{-3} – the nucleus is 10^{15} times as dense. Nuclear matter the size of a tiny grain of sand would have a mass of about a million tonnes! This is a consequence of the fact that the nucleus occupies only a tiny fraction of the volume of an atom. The remainder is occupied by the cloud of orbiting electrons whose mass makes up less than one-thousandth of the atomic mass.

Question

3 Gold has a density of 19 700 kg m^{-3}. A mass of 193 g of gold contains 6.02×10^{23} atoms. Use this information to estimate the volume of a gold atom, and hence its radius. State any assumptions you make.

15.4 Nucleons and electrons

We will start this topic with a summary of the particles mentioned so far (Table 15.1).

Particle	**Relative mass (proton = 1)[a]**	**Charge[b]**
proton (p)	1	$+e$
neutron (n)	1	0
electron (e)	0.0005	$-e$
alpha-particle (α)	4	$+2e$

(a) The numbers given for the masses are approximate.

(b) $e = 1.60 \times 10^{-19}$ C.

Table 15.1: Summary of the particles that we have met so far in this chapter. The α-particle is in fact a helium nucleus (with two protons and two neutrons).

All nuclei, except the lightest form of hydrogen, contain protons and neutrons, and each nucleus is described by the number of protons and neutrons that it contains.

- Protons and neutrons in a nucleus are collectively called **nucleons**. For example, in a nucleus of gold, there are 79 protons and 118 neutrons, giving a total of 197 nucleons altogether.
- The total number of nucleons in a nucleus is called the **nucleon number** (or mass number) A.
- The nucleon number is the sum of the number of neutrons and protons in the nucleus, or A = N +Z (where A = nucleon number, N = **neutron number** and Z = **proton number**).

The unit used to measure masses at this level is the **unified atomic mass unit** (u).

1 u is defined as being one-twelfth of the mass of a carbon-12 atom.

An isolated proton has a mass of 1.007 276 466 77 u and an isolated neutron has a mass 1.008 665 u. You can see that there is a discrepancy between the sum of the masses of the protons and neutrons in a carbon-12 atom and the sum of the masses of six isolated protons and six isolated neutrons

The reasons for these discrepancies are explored in detail in Chapter 29.

A specific combination of protons and neutrons in a nucleus is called a **nuclide**.

The nucleus of any atom can be represented by the symbol for the element (shown here as X) along with the nucleon number A and proton number Z:

$$\begin{matrix}\text{nucleon number}\rightarrow \\ \text{proton number}\rightarrow\end{matrix} {}^{A}_{Z}X$$

For example:

Element	**Symbol**	**Nucleon number *A***	**Proton number *Z***	**Represented as:**
oxygen	O	18	8	${}^{16}_{8}\text{O}$
gold	Au	197	79	${}^{197}_{79}\text{Au}$
uranium	U	238	92	${}^{238}_{92}\text{U}$

The proton and nucleon numbers of some common nuclides are shown in Table 15.2.

Element	**Nucleon number *A***	**Proton number *Z***	**Element**	**Nucleon number *A***	**Proton number *Z***
hydrogen	1	1	bromine	79	35
helium	4	2	silver	107	47
lithium	7	3	tin	120	50
beryllium	9	4	iodine	130	53
boron	11	5	caesium	133	55
	12	6		138	56

carbon			barium		
nitrogen	14	7	tungsten	184	74
oxygen	16	8	platinum	195	78
neon	20	10	gold	197	79
sodium	23	11	mercury	202	80
magnesium	24	12	lead	206	82
aluminium	27	13	bismuth	209	83
chlorine	35	17	radium	226	88
calcium	40	20	uranium	238	92
iron	56	26	plutonium	239	94
nickel	58	28	americium	241	95

Table 15.2: Proton and nucleon numbers of some nuclides.

Questions

4 Table 15.2 shows the proton and nucleon numbers of several nuclei. Determine the number of neutrons in the nuclei of the following elements shown in the table:

- **a** nitrogen
- **b** bromine
- **c** silver
- **d** gold
- **e** mercury.

5 State the charge of each of the following in terms of the elementary charge *e*:

- **a** proton
- **b** neutron
- **c** nucleus
- **d** molecule
- **e** α-particle.

Isotopes

Although atoms of the same element may be identical chemically, their nuclei may be slightly different. The number of protons in the nucleus of an atom determines what element it is: helium always has two protons, carbon six protons, oxygen eight protons, neon 10 protons, radium 88 protons, uranium 92 protons and so on.

However, the number of neutrons in the nuclei for a given element can vary. Take neon as an example. Three different naturally occurring forms of neon are:

$$^{20}_{10}\text{Ne} \quad ^{21}_{10}\text{Ne} \quad ^{22}_{10}\text{Ne}$$

The first has 10 neutrons in the nucleus, the second 11 neutrons and the third 12 neutrons. These three types of neon nuclei are called **isotopes** of neon. Each isotope has the same number of protons (for neon this is 10) but a different number of neutrons. The word ‘isotope’ comes from the Greek *isotopos* (same place), because all isotopes of the same element have the same place in the Periodic Table of elements.

Isotopes are nuclei of the same element with different numbers of neutrons but the same number of protons.

Any atom is electrically neutral (it has no net positive or negative charge), so the number of electrons surrounding the nucleus must equal the number of protons in the nucleus of the atom. If an atom gains or loses an electron, it is no longer electrically neutral and is called an **ion**.

For an atom, the number of protons (and hence the number of electrons) determines the chemical properties of the atom. The number of protons and the number of neutrons determine the nuclear properties. It is important to realise that, since the number of protons, and therefore the number of electrons, in isotopes of the same element are identical, they will all have the same chemical properties but very different nuclear properties.

Hydrogen has three important isotopes, ${}^{1}_{1}\mathrm{H}$ (sometimes called protium), ${}^{2}_{1}\mathrm{H}$ (deuterium) and ${}^{3}_{1}\mathrm{H}$ (tritium) (Figure 15.7).

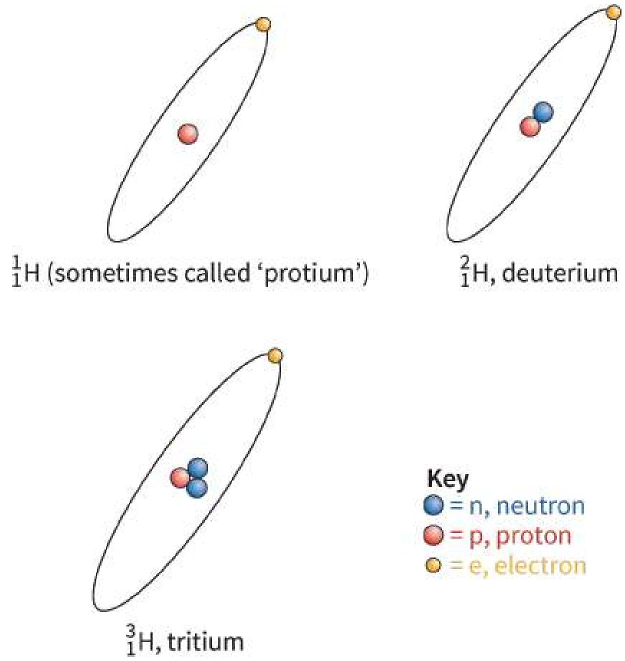

Figure 15.7: The isotopes of hydrogen.

Protium and deuterium occur naturally, but tritium has to be made. Deuterium and tritium form the fuel of many fusion research reactors. Hydrogen is the most abundant element in the Universe (Figure 15.8), because it consists of just one proton and one electron, which is the simplest structure possible for an atom.

Figure 15.8: The Horsehead Nebula in Orion. The large coloured regions are expanses of dust and gas, mostly hydrogen, that are ionised by nearby stars so that they emit light. The dark 'horse head' is where the areas of gas and dust remain in atomic form and block out the light from behind.

The different numbers of neutrons in the isotopes of an element means that the isotopes will have different relative atomic masses. There are differences too in some of their physical properties, such as density and boiling point. For example, heavy water, which is water containing deuterium, has a boiling point of 104 °C under normal atmospheric pressure.

Table 15.3 gives details of some other commonly occurring isotopes.

Element	**Nucleon number *A***	**Proton number *Z***	**Neutron number *N***

hydrogen	1	1	0
	2	1	1
carbon	12	6	6
	14	6	8
oxygen	16	8	8
	18	8	10
neon	20	10	10
	21	10	11
potassium	39	19	20
	40	19	21
strontium	88	38	50
	90	38	52
caesium	135	55	80
	137	55	82
lead	206	82	124
	208	82	126
radium	226	88	138
	228	88	140
uranium	235	92	143
	238	92	146

Table 15.3: Some commonly occurring isotopes.

Questions

6 Uranium has atomic number 92. Two of its common isotopes have nucleon numbers 235 and 238. Determine the number of neutrons for these isotopes.

7 There are seven naturally occurring isotopes of mercury, with nucleon numbers (and relative abundances) of 196 (0.2%), 198 (10%), 199 (16.8%), 200 (23.1%), 201 (13.2%), 202 (29.8%) and 204 (6.9%).

a Determine the proton and neutron numbers for each isotope.

b Determine the average relative atomic mass (equivalent to the 'average nucleon number') of naturally occurring mercury.

8 Eight different atoms are labelled A to H. Group the elements A–H into isotopes and name them using the Periodic Table in Appendix 3.

	A	B	C	D	E	F	G	H
Proton number	20	23	21	22	20	22	22	23
Nucleon number	44	50	46	46	46	48	50	51

15.5 Forces in the nucleus

As you know from earlier in this chapter, there are two kinds of particle in the nucleus of an atom: protons, which carry positive charge $+e$; and neutrons, which are uncharged. It is therefore quite surprising that the nucleus holds together at all. You would expect the electrostatic repulsions from all those positively charged protons to blow it apart. The fact that this does not happen is very good evidence for the existence of an attractive force between the nucleons. This is called the **strong nuclear force**. It only acts over very short distances (10^{-14} m), and it is what holds the nucleus together.

Why are some atoms are unstable?

In small nuclei, the strong nuclear force from all the nucleons reaches most of the others in the nucleus, but as we go on adding protons and neutrons the balance becomes much finer. The longer-range electrostatic force affects the whole nucleus, but the short-range strong nuclear force of any particular nucleon only affects those nucleons around it – the rest of the nucleus is unaffected. In a large nucleus, the nucleons are not held together so tightly and this can make the nucleus unstable. The more protons there are in a nucleus, the greater the electric forces between them and we need a few extra neutrons to help 'keep the protons apart'. This is why heavy nuclei have more neutrons than protons. The strong interaction can explain α-decay, but not β-decay; we will look at this later in the chapter.

The proton and neutron numbers for some common nuclides are shown in Table 15.3. You can see that for light elements these two numbers are the same, but they become very different for heavy elements. Adding more neutrons helps to keep the nucleus stable, but when the number of protons is greater than 83, adding more neutrons is not enough. Elements with a proton number greater than 83 are all unstable – they undergo radioactive decay.

Most atoms that make up our world have stable nuclei; that is, they do not change as time goes by, which is quite fortunate really! However, some are less stable and give out radiation. Whether or not an atom is unstable depends on the numbers of protons and neutrons in its nucleus. Hydrogen-1 (1p), helium-4 (2p, 2n), carbon-12 (6p, 6n) and oxygen-16 (8p, 8n) are all stable – but add or subtract neutrons and the situation changes.

For example, add a neutron to helium-4 and you get helium-5, a very unstable nucleus – it undergoes radioactive emission. (There is much more about radioactive decay later in this chapter.)

Question

9 State which of the following forces act between protons and neutrons in a nucleus.

- **a** gravitational
- **b** electrostatic
- **c** strong nuclear.

15.6 Discovering radioactivity

The French physicist Henri Becquerel (Figure 15.9) is credited with the discovery of radioactivity in 1896. He had been looking at the properties of uranium compounds when he noticed that they affected photographic film–he realised that they were giving out radiation all the time and he performed several ingenious experiments to shed light on the phenomenon.

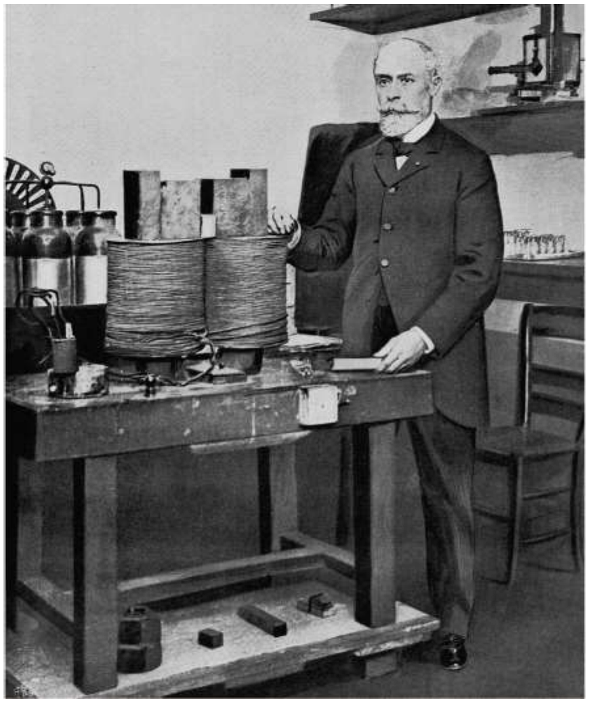

Figure 15.9: Henri Becquerel, the discoverer of radioactivity, in his laboratory. His father and grandfather had been professors of physics in Paris.

15.7 Radiation from radioactive substances

The three types of radiation commonly emitted by radioactive substances – alpha (α), beta (β) and gamma (γ)–come from the unstable nuclei of atoms. Nuclei consist of protons and neutrons, and if the balance between these two types of particles is too far to one side, or the nucleus is just too big to hold together, the nucleus may emit α- or β-radiation as a way of achieving greater stability. Gamma-radiation is usually emitted after α or β decay, to release excess energy from the nuclei.

Table 15.4 shows the basic characteristics of the different types of radiation. The masses are given relative to the mass of a proton; charge is measured in units of e, the elementary charge. Figure 15.10 summarises the penetrating powers of the different types of radiation.

Radiation	Symbol	Mass (relative to proton)	Charge	Typical speed
α-particle	$\alpha, {}^{4}_{2}\mathrm{He}$	4	$+2e$	'slow' (10^6 m s^{-1})
β^--particle	$\beta, \beta^-, e, {}^{0}_{-1}e$	$\frac{1}{1840}$	$-e$	'fast' (10^8 m s^{-1})
β^+-particle	$\beta, \beta^+, e^+, {}^{0}_{+1}e$	$\frac{1}{1840}$	$+e$	'fast' (10^8 m s^{-1})
γ-ray	γ	0	0	speed of light (3×10^8 m s^{-1})

Table 15.4: The basic characteristics of ionising radiations.

Note the following points:

- α- and β-radiation are particles of matter. A γ-ray is a photon of electromagnetic radiation, similar to an X-ray. (X-rays are produced when electrons are decelerated; γ-rays are produced in nuclear reactions.)
- An α-particle consists of two protons and two neutrons; it is a nucleus of helium-4. A β^--particle is simply an electron and a β^+-particle is a positron.
- The mass of an α-particle is nearly 10 000 times that of an electron and it travels at roughly one-hundredth of the speed of a β-particle.

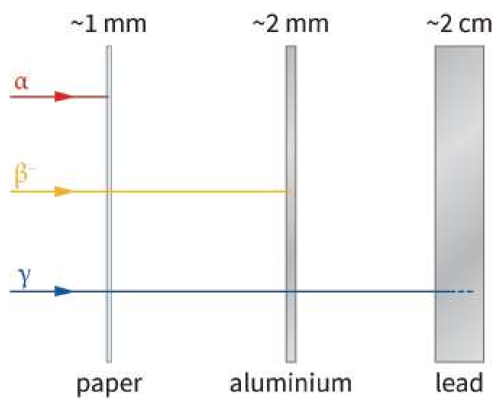

Figure 15.10: A summary of the penetrating powers of α-, β- and γ-radiations. The approximate thickness of the absorbing material is also shown.

Identification and properties of α-radiation

α-particles are relatively slow moving and large particles. They were identified as helium nuclei (He^{2+} ions) by their deflection in electric and magnetic fields (see Chapter 25). The helium nucleus, which consists of two protons and two neutrons, is extremely stable. Scientists believe that, within larger nuclei, α groups are continually forming, breaking apart and reforming. Occasionally, such a group will have enough energy to break away from the strong nuclear forces holding the mother nucleus together and will escape as an α-particle. The α-particles (which are relatively large and carry a charge) interact with atoms in the medium through which they are travelling, causing ionisation within the medium. They lose energy rapidly. This means they are not very penetrative (they are absorbed by a thin sheet of paper) and have a very short range (only a few centimetres in air).

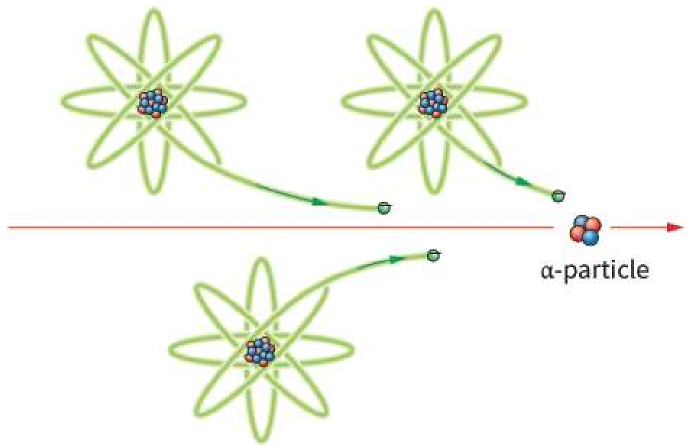

Figure 15.11: As an α-particle passes through a material, it causes ionisation of atoms.

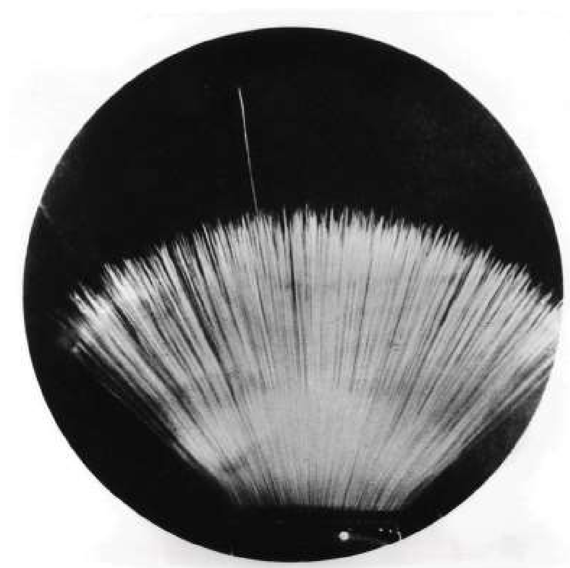

Figure 15.12: Alpha-particle tracks show up in this photograph of a cloud chamber. Notice that the particles all travel approximately the same distance. What does this suggest?

Identification and properties of β-radiation

β-particles were identified as very fast electrons. Like α-particles, β-particles carry a charge. But, because β-particles are much smaller, they cause less ionisation and penetrate further into matter. They are absorbed by approximately one centimetre of aluminium or one millimeter of lead.

β-decay occurs when there is an imbalance of protons and neutrons in the nucleus, usually too many neutrons. A neutron will then decay into a proton (positive) and an electron (negative). The proton remains in the new nucleus and the electron is expelled at a very high velocity. However, some isotopes (such as V-48) have excess protons; because of this, a proton decays into a neutron and emits a positively charged electron or **positron**. This is known as **β^+ (beta plus) decay**. The decay of a neutron into a proton and an electron is known as **β^- (beta minus) decay**.

The positron was the first example of antimatter to be identified. It is now known that all particles have an antiparticle, which has the same mass as the particle but the opposite charge. The general term for antiparticles is **antimatter**.

What happens when matter meets antimatter?

When an antiparticle meets its particle, such as a positron meets an electron, they annihilate each other and two gamma ray photons are produced and the two masses become pure energy!

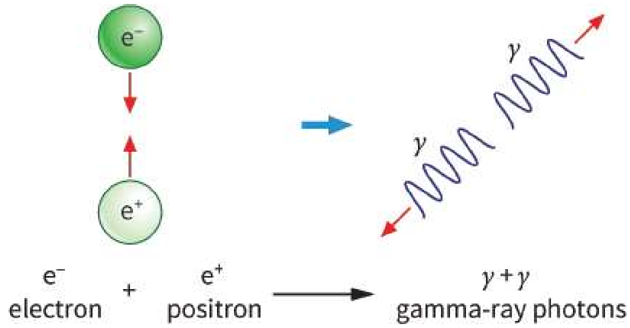

Figure 15.13: Energy is released in the annihilation of matter and antimatter.

Identification and properties of γ-radiation

γ- radiation was identified from its speed in a vacuum, 3×10^8 m s^{-1}, the speed of all electromagnetic radiation. It is very high frequency electromagnetic radiation; as such, it has no rest mass and no charge. Consequently, it does not interact with matter to the same degree as alpha or beta radiation. It produces only a small amount of ionisation and is highly penetrative – it will penetrate through several centimetres of lead.

It is generally emitted following alpha or beta decay. After the initial decay, the nucleus is left in an unstable high energy state – it will drop into a lower energy, more stable state with the emission of a gamma ray.

Question

10 **a** Explain why you would expect β^--particles to travel further through air than α-particles.

b Explain why you would expect β^--particles to travel further through air than through metal.

15.8 Energies in α and β decay

Look back at Figure 15.12. You were asked what conclusion could be drawn from the observation that all the α-particle tracks were the same length. The answer is quite simple: it suggests that they all have the same initial kinetic energy. This should not surprise you, as they are all the result of the similar reactions in identical nuclei. However, when we look at the energies of β-particles (both β^- and β^+) the results are quite different, as shown by the graph in Figure 15.14.

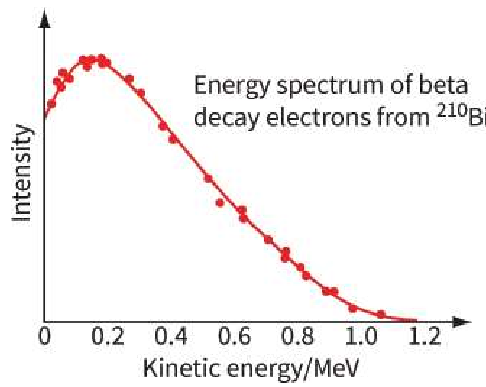

Figure 15.14: The energy spectrum for β^--decay of bismuth-210.

You will notice that the energy of the β-particles is measured in MeV (mega electronvolts). Alpha and beta particles move quickly; gamma photons travel at the speed of light. These types of radiation all have energy, but the energy of a single particle or photon is very small and far less than a joule. So we use another, much smaller unit of energy, the electronvolt, when considering the energy of individual particles or photons.

When an electron (with a charge of magnitude 1.60×10^{-19} C) travels through a potential difference, energy is transferred. The energy change W is given by:

$$W = QV = 1.60 \times 10^{-19} \times 1 = 1.60 \times 10^{-19}\ \text{J}$$

One electronvolt (1 eV) is the energy transferred when an electron travels through a potential difference of one volt.

Therefore:

$$1\ \text{eV} = 1.60 \times 10^{-19}\ \text{J}$$

There is more about the electronvolt and its use in energy calculations in Chapter 28.

The graph shows that the β-particles have a wide range of energies. One of the great physicists of the early 20th century, Wolfgang Pauli, suggested that another particle carries off some of the kinetic energy. This particle was not easy to detect–Pauli hypothesised its existence in 1930, but it was not detected until 1956. The particle has no charge and virtually no rest mass (much less than an electron) and barely interacts with matter at all. We now know that there is a steady stream of them given off by the Sun, some of which travel straight through the Earth without any interaction with it at all (which is why it’s difficult to detect them!) The particle was named the antineutrino, and is now known as the **electron antineutrino**. The particle given off when a positron is emitted is called the **electron neutrino**. The symbol used for the electron neutrino is the Greek letter (nu), and the electron antineutrino is (nu bar).

15.9 Equations of radioactive decay

In radioactive decay, the nucleus changes. It is important to realise that both the nucleon number and the proton number are conserved in the reaction.

We have already established that an α-particle is a helium nucleus and can be represented as:

$$^{4}_{2}\alpha$$

The isotope radon-222 decays by α-emission, we can describe this by the equation:

$$^{222}_{86}\mathrm{Rn} \rightarrow {}^{218}_{84}\mathrm{Po} + {}^{4}_{2}\alpha$$

A quick glance tells us there are 222 nucleons before the decay and 218 + 4 = 222 after the decay. Similarly, there are 86 protons before and 84 + 2 = 86 after the decay.

The isotope Mn-56 decays by β^- emission:

$$^{56}_{25}\mathrm{Mn} \rightarrow {}^{56}_{26}\mathrm{Fe} + {}^{0}_{-1}\beta + {}^{0}_{0}\bar{\nu}$$

Again, it is easy to see the nucleons are conserved; however, we need to recognise that the electron is regarded as −1 proton.

Note also that an antineutrino is also emitted; interestingly, this suggests the number of particles/antiparticles are the same before and after the decay.

For the β^+ decay we look at the isotope V-48:

$$^{48}_{23}\mathrm{V} \rightarrow {}^{48}_{22}\mathrm{Ti} + {}^{0}_{1}\beta + {}^{0}_{0}v$$

Once again there is a balance of proton numbers, nucleon numbers and particles/antiparticles (remember that the positron is an antiparticle).

There is another quantity that is conserved. You might expect mass to be conserved, but this is not so. For example, in the α decay equation given previously, the combined mass of the polonium nucleus and the alpha particle is slightly less than that of the original radon nucleus. The 'lost' mass has become energy – this is where the fast-moving alpha particle gets its kinetic energy. The relationship between mass m and energy E is given by Einstein's equation $E = mc^2$, where c is the speed of light in free space. So, instead of saying that mass is conserved in nuclear processes, we have to say that mass–energy is conserved. There is much more about this in Chapter 29.

Questions

In these questions, use the Periodic Table in Appendix 3 to determine the identity, or the proton number, of the relevant elements.

11 The isotope thorium-227 decays by α-emission.

Write down an equation to describe this decay and identify the element that is produced.

12 Copper-64 can decay by either β^+ or β^- emission.

Give equations for both processes and identify the resulting elements.

13 Uranium 238 decays through a series of α and β^- decays to eventually form the stable isotope lead-206 in what is known as a decay chain.

Determine the number of each type of decay in the decay chain.

15.10 Fundamental particles

Chemistry is complicated because there are billions of different molecules that can exist. The discovery of the Periodic Table simplified things because it suggested that there were roughly 92 different elements whose atoms could be arranged to make the billions of molecules. The idea that atoms are made up of just three types of particle (protons, neutrons and electrons) seemed to simplify things still more, and scientists were happy because it provided a simple explanation of a complex world.

Protons, neutrons and electrons were thought of as fundamental particles, which could not be subdivided further. However, in the middle decades of the 20th century, physicists discovered many other particles that did not fit this pattern. They gave them names such as pions, kaons, muons and so on, using up most of the letters of the Greek alphabet.

These new particles were found in two ways:

- by looking at cosmic rays, which are particles that arrive at the Earth from outer space
- by looking at the particles produced by high-energy collisions in particle accelerators (Figure 15.15).

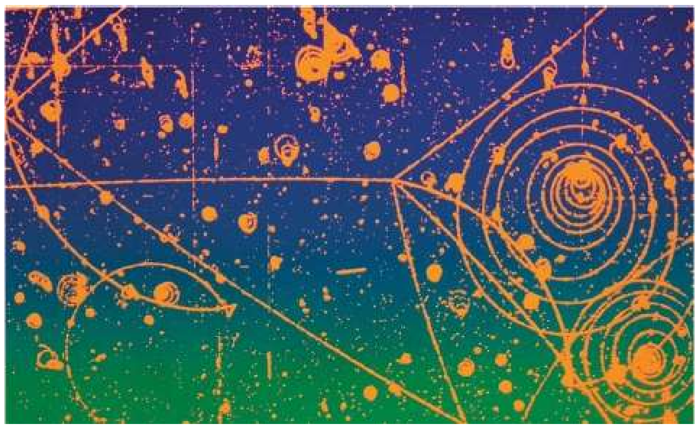

Figure 15.15: Particle tracks in a bubble chamber detector. A particle has entered from the left and then struck another particle just to the right of the centre. Four new particles fly out from the point of impact.

The discovery of dozens of new particles with masses different from those of protons, neutrons and electrons suggested that these were not fundamental particles. Various attempts were made to tidy up this very confusing picture.

15.11 Families of particles

Today, sub-atomic particles are divided into two families:

- **Leptons** such as electrons and neutrinos. These are particles that are unaffected by the strong nuclear force.
- **Hadrons** such as protons and neutrons. These are all particles that are affected by the strong nuclear force.

The word 'lepton' comes from a Greek word that means 'light' (in mass) while 'hadron' means 'bulky'. It is certainly true that protons and neutrons are bulky compared to electrons.

Leptons

Leptons are (currently) considered to be fundamental particles, although, in principle, we can never know for certain whether a particle, such as the electron, is truly fundamental; the possibility will always remain that a physicist will discover some deeper underlying structure.

Hadrons

Figure 15.16 shows the Large Hadron Collider at the CERN laboratory in Geneva. Physicists are experimenting with hadrons in the hope of finding answers to some fundamental questions about this family of particles. In 2013, they announced the discovery of the Higgs boson, a particle that was predicted 50 years earlier and which is required to explain why matter has mass.

Figure 15.16: Particle accelerators have become bigger and bigger, accelerating particles to higher and higher energies as scientists have sought to look further and further into the fundamental nature of matter. This is one of the particle detectors of the Large Hadron Collider (LHC), as it was about to be installed. The entire collider is 27 km in circumference.

Type of quark	**up**	**down**	**charm**	**strange**	**top**	**bottom**
Symbol	u	d	c	s	t	b
Charge	$+\frac{2}{3}e$	$-\frac{1}{3}e$	$+\frac{2}{3}e$	$-\frac{1}{3}e$	$+\frac{2}{3}e$	$-\frac{1}{3}e$
Type of antiquark	antiup	antidown	anticharm	antistrange	antitop	antibottom
Symbol	$\bar{u}$	$\bar{d}$	$\bar{c}$	$\bar{s}$	$\bar{t}$	$\bar{u}$
Charge	$-\frac{2}{3}e$	$+\frac{1}{3}e$	$-\frac{2}{3}e$	$+\frac{1}{3}e$	$-\frac{2}{3}e$	$+\frac{1}{3}e$

Table 15.5: The charges on the different types of quark and antiquark.

Quarks

To sort out the complicated picture of the hadron family of particles, Murray Gell-Mann in 1964 proposed a new model. He suggested that they were made up of just a few different particles, which he called **quarks**.

There are many surprising things about quarks. First, quarks have charges of less than the fundamental charge, *e*. However, quarks are never found outside a hadron. The quarks combine so that the resulting hadron will have a charge of *e* or a multiple of *e*.

There are six types (or 'flavours') of quark, each with an associated antiquark. Table 15.5 lists these quarks together with their charges.

In addition to the property of charge, quarks have other properties such as strangeness, charm, upness and downness. We do not need to concern ourselves about these properties; however, recognising that they exist should help you to understand how a large number of different hadrons can be made up from these half-dozen flavours of quark.

There are two ways in which quarks can combine to produce hadrons:

- three quarks make up a class of hadrons called **baryons**
- a quark and an antiquark make up a class of hadron called **mesons**.

Baryons

Examples of baryon are the proton and the neutron.

- A proton is made up of two up quarks and a down quark; proton = (uud).
- A neutron is made up of one up quark and two down quarks; neutron = (udd).

Mesons

There are many examples of mesons; here are two described:

- A π^+ meson is made up of an up quark and a down antiquark; $\pi^+\text{meson} = \left(\text{u}\bar{\text{d}}\right)$.
- A ϕ meson is made up of a strange quark and an antistrange quark; ϕ meson $= (\text{s}\bar{\text{s}})$.

Questions

14 **a** Show that the charges on the quarks making up a proton give it a charge of +1*e*.

b Show that the charges on the quarks making up a neutron give it a charge of 0.

15 A ρ-meson is made up of an up quark and an antidown quark. Calculate its charge.

16 Suggest which quarks or antiquarks make up a π^- meson.

17 Show that the ϕ-meson is neutral.

15.12 Another look at β decay

This is interesting as a hadron decays into another hadron emitting a lepton and an antilepton.

So, what happens in β decay?

The neutron is made up of an up quark and two down quarks (udd), the proton is made up of two up quarks and a down quark (uud)

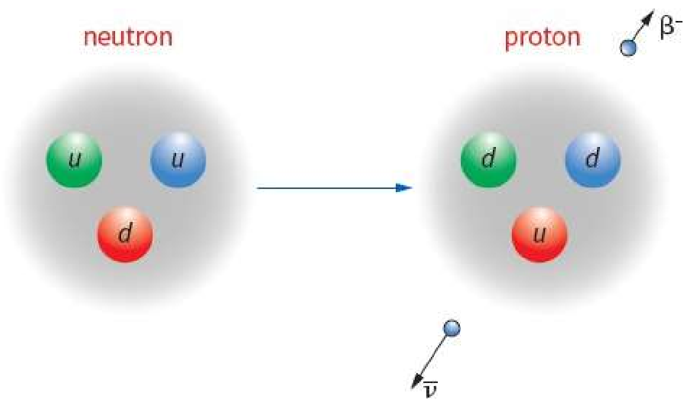

Figure 15.17: A visual representation of the change within the neutron as it decays into a proton.

The equation representing this at a quark level is:

$$\mathrm{d} \rightarrow \mathrm{u} + {}^{0}_{-1}\mathrm{e} + \bar{v}$$

KEY EQUATION

$$\mathrm{d} \rightarrow \mathrm{u} + {}^{0}_{-1}\mathrm{e} + \bar{v}$$

The decay of a down quark into an up quark in β^{-} decay.

Question

18 **a** Draw a diagram similar to Figure 15.17 to show β^{+} decay.

b Write an equation to describe the changes in β^{+} decay.

15.13 Another nuclear force

We have met and described the strong nuclear force in some detail, as a short range force that holds the nucleons in a nucleus together. It is a force that is felt only by hadrons, not leptons.

There is a second nuclear force, known as the weak nuclear force or weak interaction. It is felt by both hadrons and leptons and, more importantly, it is the interaction that causes β-decay, in which a hadron changes to a different hadron with the emission of a lepton and an antilepton.

Questions

19 The equation ${}^{1}_{1}\mathrm{p} \rightarrow {}^{1}_{0}\,\mathrm{n} + {}^{0}_{+1}\beta + v$ represents β^{+} decay.

Use the equation to explain why the neutrino v can have no charge and very little mass.

20 What are the differences between a proton, a positron and a photon? You can describe how their masses differ, how their charges differ or whether they are particles or antiparticles.

21 State **two** differences between hadrons and leptons.

REFLECTION

We have mentioned that quarks have different properties known as strangeness, charm, upness and downness. What is charm? What is strangeness? And what is electric charge?

Discuss your ideas in a group.

What were some of the most interesting discoveries you made while working through this chapter?

SUMMARY

The α-particle scattering experiment provides evidence for the existence of a small, massive and positively charged nucleus at the centre of the atom.

Most of the mass of an atom is concentrated in its nucleus.

The nucleus consists of protons and neutrons, and is surrounded by a cloud of electrons.

The number of protons and neutrons in the nucleus of an atom is called its nucleon number A.

The number of protons in the nucleus of an atom is called its proton number (or atomic number) Z.

Isotopes are nuclei of the same element with a different number of neutrons but the same number of protons.

Different isotopes (or nuclides, if referring to the nucleus only) can be represented by the notation $^{A}_{Z}\mathrm{X}$, where X is the chemical symbol for the element.

There are three types of ionising radiation produced by radioactive substances: α-particles, β-particles and γ-rays.

In radioactive decay, the following quantities are conserved: proton number, nucleon number and mass–energy.

The most strongly ionising, and hence the least penetrating, is α-radiation. The least strongly ionising is γ-radiation.

Because of their different charges, masses and speeds, the different types of radiation can be identified by the effect of an electric or magnetic field.

Antimatter is material made up of antiparticles of the corresponding particles of ordinary matter. All particles have an antiparticle, which has the same mass as the particle but the opposite charge.

Quarks are particles that make up hadrons. There are six flavours of quark: up, down, strange, charm, top and bottom. Quarks have charges of $+\frac{2}{3}e\ or\ -\frac{1}{3}e$.

The strong nuclear force is the force that acts between quarks and holds the nucleus together.

Leptons (such as the electron) are particles that are unaffected by the strong nuclear force.

Hadrons (such as the neutron) are particles that consist of quarks and hence are affected by the strong nuclear force.

EXAM-STYLE QUESTIONS

1 Which of the interactions is **not** possible? **[1]**

A ${}^{4}_{2}\text{He} + {}^{1}_{0}\text{n} \rightarrow {}^{5}_{2}\text{He}$

B ${}^{209}_{84}\text{Po} \rightarrow {}^{205}_{82}\text{Pb} + {}^{4}_{2}\alpha$

C ${}^{14}_{8}\text{O} \rightarrow {}^{14}_{7}\text{N} + {}^{0}_{1}\beta + {}^{0}_{0}\text{v}$

D ${}^{31}_{14}\text{Si} \rightarrow {}^{31}_{15}\text{N} + {}^{0}_{-1}\beta + {}^{0}_{0}\text{v}$

2 Hadrons are made up from quarks.

Which combination of quarks could make up a meson? **[1]**

A $\text{dd}\bar{\text{s}}$

B ssc

C $\text{s}\bar{\text{b}}$

D sc

3 Explain why the most strongly ionising radiation (α-particles) is the least penetrating, while the least ionising (γ-rays) is the most penetrating. **[1]**

4 Before Rutherford's model, scientists believed that the atom was made up of negatively charged electrons embedded in a 'plum pudding' of positive charge that was spread throughout the atom. Explain how the α-particle scattering experiment proved that this old model of the atom was incorrect. **[3]**

5 A nucleus of strontium has a nucleon number of 90 and a proton number of 38. Describe the structure of this strontium nucleus. **[1]**

6 State the changes that take place in a nucleus when it emits an α-particle and then two β^--particles. **[5]**

7 The nuclide of iodine with a nucleon number of 131 and a proton number 53 emits a β^--particle. Write a nuclear equation for this decay. **[3]**

8 An isotope of carbon ${}^{14}_{6}\text{C}$ emits a β^--particle and changes into an isotope of nitrogen (N).

a What are β^--particles? **[1]**

b Write a nuclear decay equation for the decay. **[2]**

c Draw a graph with the *y*-axis representing nucleon numbers between 10 and 16 and the *x*-axis representing proton numbers between 4 and 10. On your graph, mark:

i the isotope ${}^{14}_{6}\text{C}$ **[2]**

ii the daughter nucleus produced in the decay. **[1]**

[Total: 6]

9 The uranium isotopes U-236 and U-237 both emit radioactive particles. A nucleus of uranium-237 may be written as ${}^{237}_{92}\text{U}$ and emits a β^--particle. A nucleus of uranium-236 emits an α-particle. The number of protons in a nucleus of uranium is 92.

a Describe the differences between an α-particle and a β^--particle. **[4]**

b Explain how uranium can exist in a number of different isotopes. **[2]**

c Write down the nuclear equation for the decay of U-236. **[2]**

[Total: 8]

10 Approximate values for the radius of a gold atom and the radius of a gold nucleus are 10^{-10} m and 10^{-15} m, respectively.

a Estimate the ratio of the volume of a gold atom to the volume of a gold nucleus. **[2]**

b The density of gold is 19 000 kg m^{-3}. Estimate the density of a gold nucleus, stating any assumptions that you make in your answer. **[3]**

[Total: 5]

11 The nuclide of lead ${}^{210}_{82}\mathrm{Pb}$ decays in three separate stages by α and β^- emission to another lead nuclide, ${}^{206}_{82}\mathrm{Pb}$.

a Describe the structure of a nucleus of ${}^{206}_{82}\mathrm{Pb}$. **[2]**

b α- and β^--particles are known as **ionising radiations**. State and explain why such radiations can be described as **ionising**. **[2]**

c The two lead nuclides are shown in the graph, which plots nucleon number A against proton number Z.

Copy the graph and, on your copy, draw **three** arrows to represent one possible route for the three decays between the two isotopes of lead. Label each arrow to show whether an α-particle or a β^--particle is emitted. **[3]**

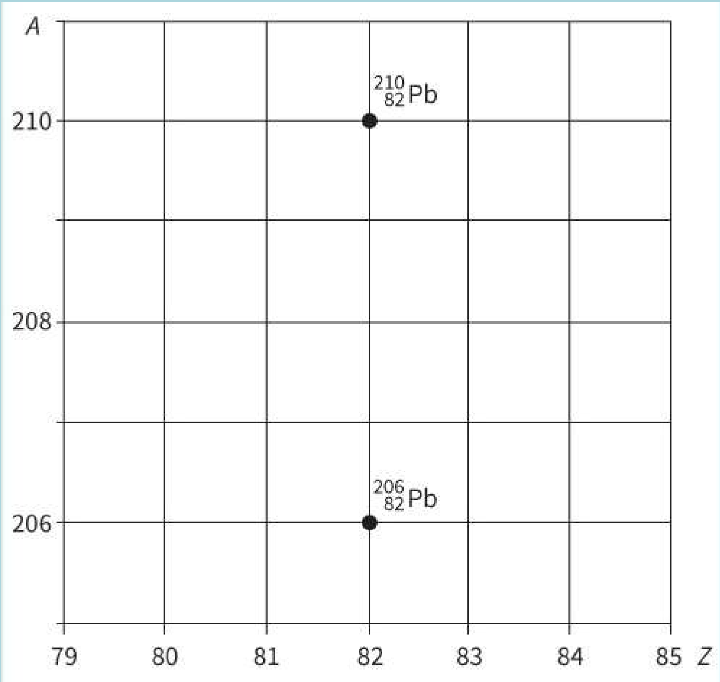

Figure 15.18

[Total: 7]

12 Geiger and Marsden carried out an experiment to investigate the structure of the atom. In this experiment, α-particles were scattered by a thin film of gold.

a When Rutherford analysed their results, what conclusions did he draw about the distribution of mass and charge in the atom? **[2]**

b Describe and explain the experimental observations that led to these conclusions. **[3]**

[Total: 5]

13 Beta decay occurs as either β^+ decay or β^- decay. An isotope of calcium Ca decays by β^+ emission into the isotope ${}^{46}_{21}\mathrm{Sc}$, and an isotope of magnesium ${}^{23}_{12}\mathrm{Mg}$ decays by β emission into the isotope ${}^{23}_{11}\mathrm{Na}$.

a Copy and complete the following decay equations for the calcium and magnesium isotopes.

i decay of calcium: ${}^{46}_{20}\mathrm{Ca} \rightarrow \mathrm{Sc} + \beta^+ + \ldots$ **[1]**

ii decay of magnesium: ${}^{23}_{12}\mathrm{Mg} \rightarrow \mathrm{Na} + \beta^+ + \ldots$ **[1]**

b State what happens in each type of β decay in terms of the quark model of nucleons.

i β^- decay **[1]**

ii β^+ decay. **[1]**

c Name the force responsible for β decay. **[1]**

[Total: 5]

14 a A quark is a fundamental particle but a neutron is not. Explain what this statement means. **[1]**

b A proton and a neutron each contain three quarks, either up or down quarks.

i Copy and complete the table to show the charge on a proton and a neutron and the quarks that they contain. **[2]**

	Charge	**Quarks**
proton		
neutron		

Table 15.6

ii Using information from your table, suggest why some quarks must have a positive charge and some quarks a negative charge. **[2]**

c State what interaction is responsible for holding the nucleus together. **[1]**

d When a neutron decays it produces an electron and two other particles. Copy and complete the decay equation for a neutron.

$^{0}_{1}\text{n} \rightarrow$ . . . . **[2]**

e The electron and the neutron belong to different groups of particles.

Copy and complete the table to show the group of particles to which the electron and neutron belong and state the name of another member of each group. **[2]**

	Group to which it belongs	**Another particle in the same group**
electron		
neutron		

Table 15.7

[Total: 10]