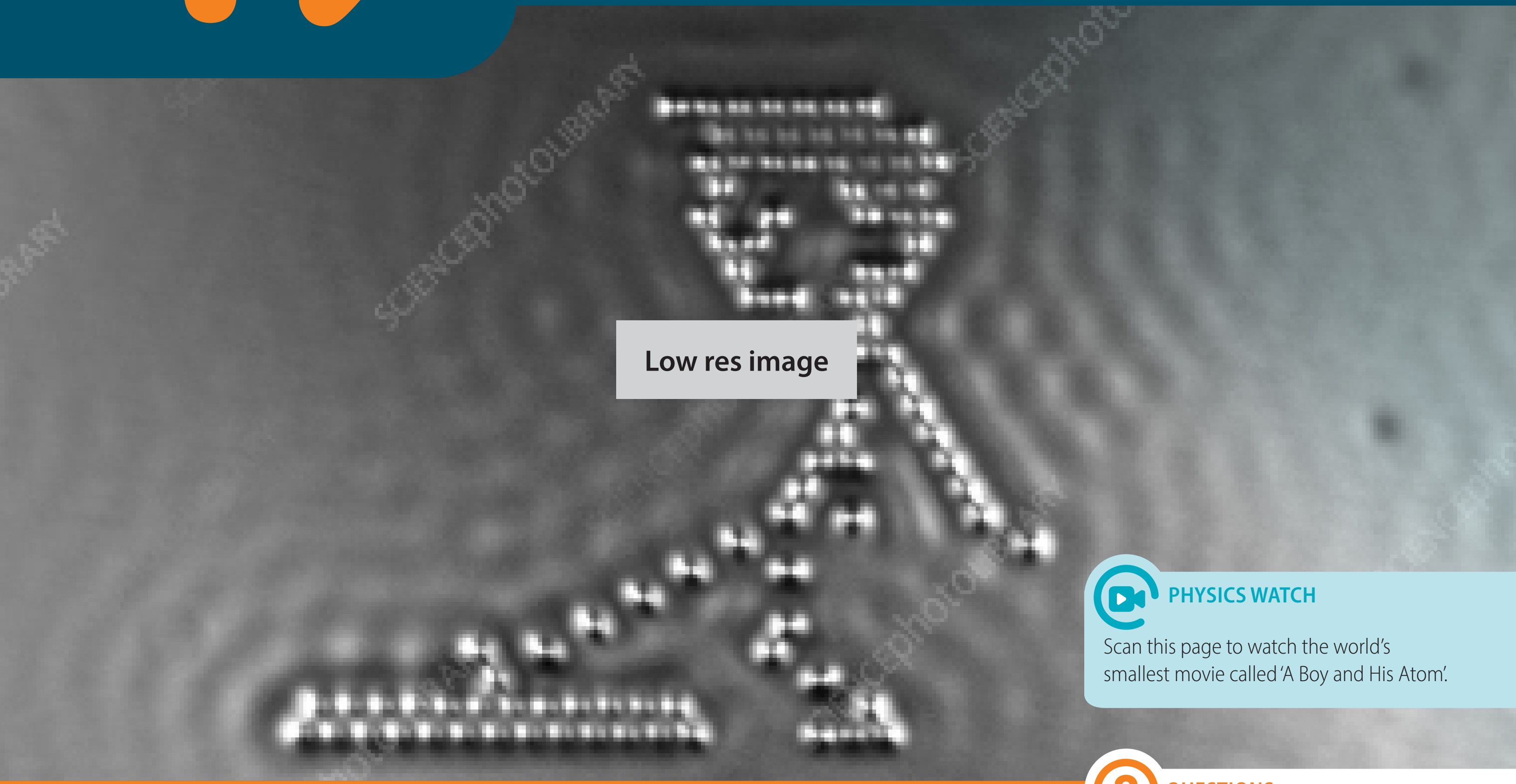
CHAPTER

19 Nuclear Model of the Atom



PHYSICS WATCH

Scan this page to watch the world's smallest movie called 'A Boy and His Atom'.

QUESTIONS

- What do you think atoms look like?
- The photo shows raised dots that make up the image of the boy. What are these raised dots caused by?
- How can atoms help to solve our data storage needs?

We are creating more and more data every day. How do we solve the problem of where to store this huge amount of data? Scientists have explored right down to the atomic level to find a solution for data storage.

The photo shows an image of a boy taken from a 1-minute movie called *A Boy and His Atom*, made by researchers at IBM. The movie was made by moving carbon monoxide molecules using a scanning tunneling microscope. The microscope can magnify atoms 100 million times. It is the oxygen atom of each molecule that showed up when photographed using the microscope. With this method, it is said that one bit of data can be stored in just 12 atoms, compared to about one million atoms that was used before.

***A Boy and His Atom* is the world's smallest movie. You would probably be interested to know how it is possible to make such a movie. But first, let's find out more about atoms!**

19.1 The atom

In this section, you will learn the following:
- Describe the structure of an atom.
- Know how atoms form positive or negative ions.
- S Describe how the scattering of alpha (α-) particles by a sheet of thin metal provide evidence to support the nuclear model of the atom.

What is an atom?

In the kinetic particle model of matter, matter is modelled as being made up of particles. What are these particles? They are atoms, molecules, ions and electrons. In this chapter, you will learn about other particles and how they are related to atoms, ions and electrons.

LINK

Recall what you have learnt in Chapter 8 about the particles that make up matter.

An atom is the smallest unit of a chemical element. However, each atom is made up of even smaller particles. You have learnt about electrons, which carry negative charges. Electrons are many million times smaller than an atom. They are part of an atom.

An **atom** consists of a *positively charged nucleus and negatively charged electrons in orbit around the nucleus* (Figure 19.1). Strong attractive forces between the positively charged nucleus and negatively charged electrons hold the electrons to the atom. The electrons furthest from the nucleus could become detached by friction or by other means.

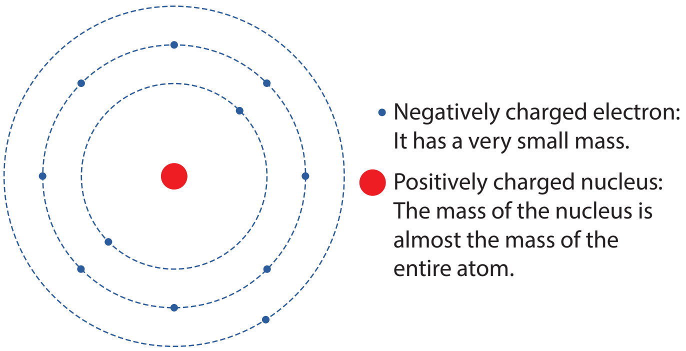


Figure 19.1 *Simplified structure of an atom*

How do atoms form ions?

An electrically neutral atom has equal negative charges and positive charges. How many electrons are there in the atom in Figure 19.1? Each electron carries the same quantity of negative charge. How many positive electronic charges should be in the nucleus for it to be a neutral atom?

An atom which loses or gains electrons has unbalanced positive and negative charges.

An atom which *loses electrons* has more positive charges — it becomes a **positive ion**.

An atom which *gains electrons* has more negative charges — it becomes a **negative ion**.

Figure 19.2 shows how a positive ion is formed.

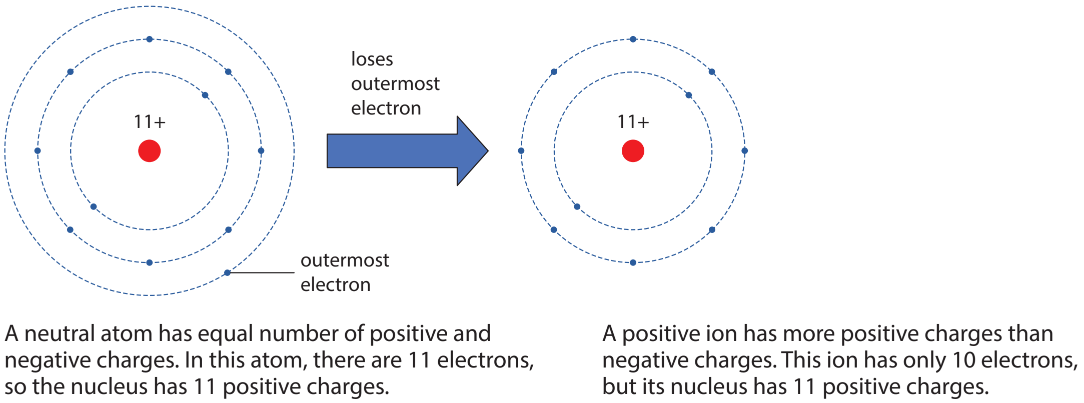
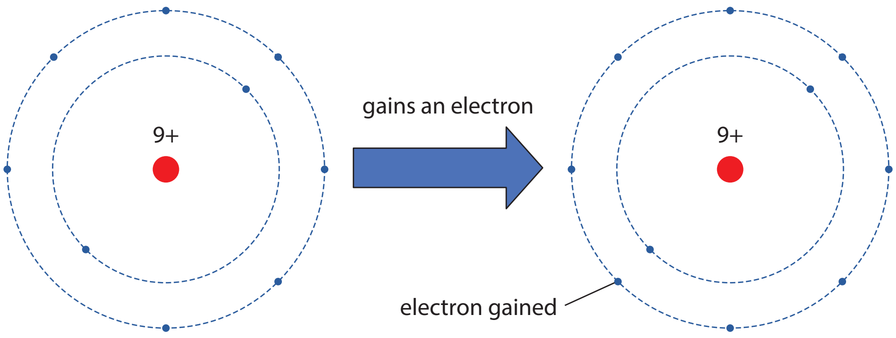


Figure 19.2 *When an atom loses electrons, it becomes a positive ion.*

Figure 19.3 shows how a negative ion is formed.



An electrically neutral atom has the same number of positive and negative charges. In this atom, there are 9 electrons, so the nucleus has 9 positive charges.

A negative ion has more negative charges than positive charges. This ion has 10 electrons, but its nucleus has only 9 positive charges.

Figure 19.3 *When a neutral atom gains electrons, it becomes a negative ion.*

QUICK CHECK

Atom *A* is a neutral atom. It has 24 electrons. Its nucleus has the same number of positives charges.

True or false?

What evidence do we have to support the nuclear model of the atom?

In 1911, scientists Geiger and Marsden carried out an experiment to study the internal structure of atoms. They directed alpha (α-) particles from a radioactive source at a thin metal foil (Figure 19.4). This is like shooting bullets at a locked box to find out what sort of material is hidden inside — if the bullets are deflected instead of passing right through, the box must contain some very dense material.

LINK

A radioactive source emits radioactive particles such as find out more in Chapter 20.

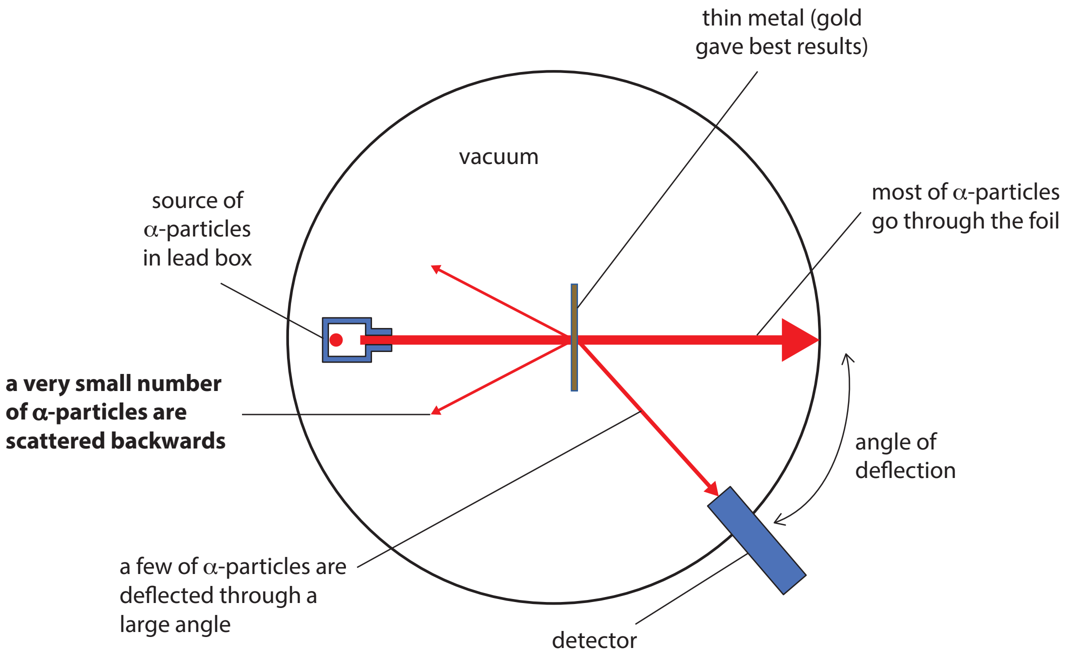


Figure 19.4 *Scattering of a-particles by thin metal foil*

ENRICHMENT *INFO*

Other Models of the Atom

The nuclear or planetary model of the atom (1911) by Ernest Rutherford was not the only model proposed to explain the atomic structure. Before this, there were the solid sphere model (1803) and the plum pudding model (1904).

Scientists continued to study atoms and later proposed the Bohr's model (1913) and the quantum model (1926) (Figure 19.6).

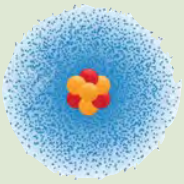


***Figure 19.6** The quantum atomic model suggests that electrons move in clouds around the nucleus instead of in fixed orbits.*

WORD ALERT

massive: has large mass

ENRICHMENT *INFO*

Work in groups. Search the Internet to find out more about the different models of the atom. Create a slide presentation and present your findings to the class.

LINK

Exercises 19A, pp. XX-XX

Geiger and Marsden's supervisor, Ernest Rutherford, was very puzzled by the fact that a few α-particles could be scattered backwards while almost all the particles passed right through. He knew that α-particles are positively charged particles. Also, the mass of an α-particle is much smaller than the mass of a gold atom.

Based on some mathematical calculations, Rutherford showed that the experimental results provided evidence for an atom that has

- a very small nucleus surrounded by mostly empty space (almost all the α-particles go right through);
- a nucleus containing most of the mass of the atom (an electron has a very small mass);
- a nucleus that is positively charged (positively charged α-particles are repelled).

The few α-particles that scattered backwards were going so close to the nucleus that they were strongly repelled as shown in Figure 19.5.

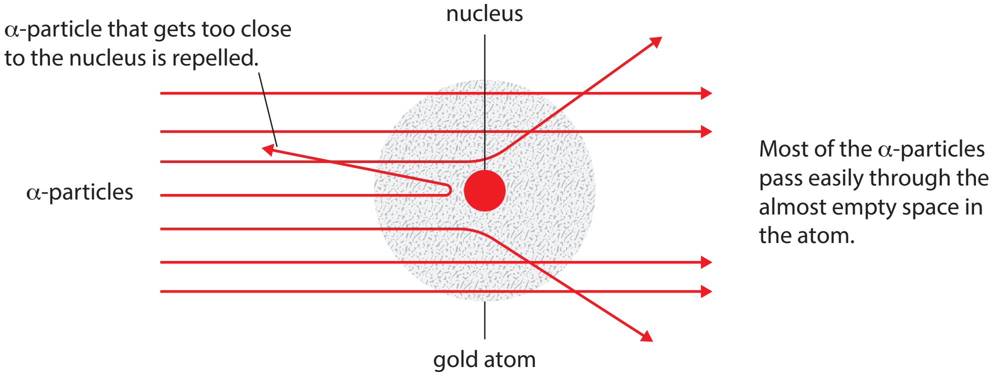


***Figure 19.5** Experimental evidence for a small, **massive** and positively charged nucleus surrounded by mostly empty space*

Let's Practise 19.1

1 Complete the sentences.

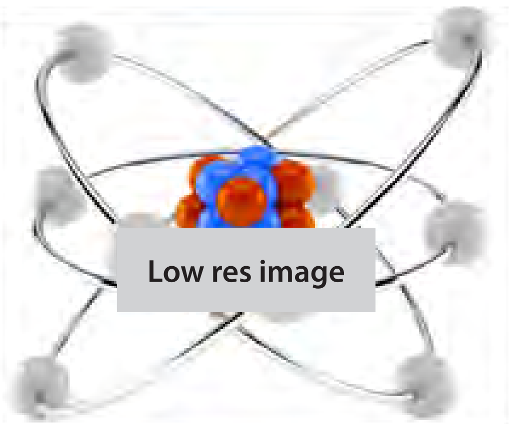
   (a) An atom consists of a ____________ (positively/negatively) charged nucleus and ____________ (positively/negatively) charged electrons in orbit round the nucleus.

   (b) When an atom ____________ (gains/loses) electrons, it becomes a positive ion.

   (c) A negative ion is formed when an atom ____________.

2 The scattering of α-particles by a sheet of thin metal supports the nuclear model of the atom. What evidence about the nucleus does the experiment provide?

3 **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.



19.2 The Nucleus

In this section, you will learn the following:

- Describe the composition of the nucleus in terms of protons and neutrons.
- State the relative charges of protons, neutrons and electrons.
- Define *proton number* (atomic number) Z and *nucleon number* (mass number) A.
- Calculate the number of neutrons in a nucleus.
- Use the nuclide notation $^{A}_{Z}X$.
- Explain the meaning of *isotope* and state that an element may have more than one isotope.

What makes up the nucleus of an atom?

Experiments show that the **nucleus** of an atom consists of two types of particles — **protons** (positively charged) and **neutrons** (no charge). Figure 19.7 shows the structure of a helium atom. The two protons are responsible for the nucleus being positively charged.

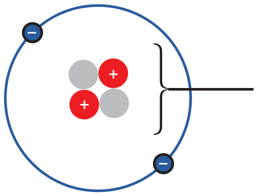


Figure 19.7 *The nucleus of a helium atom is made up of two protons and two neutrons.*

The amount of charge carried by each proton is the same as that carried by an electron. Can you recall the SI unit for charge? It is the coulomb. The charge of an electron is very much smaller than 1 coulomb. Instead of using the specific small number for the charge of an electron, scientists prefer to express the charge of small particles like electrons and protons in terms of the charge of an electron. Thus, the **relative charge of an electron is –1** (because it is negative) and the **relative charge of a proton is +1**. As the neutron does not carry any charge, the **relative charge of a neutron is 0**.

Proton number Z

The number of protons in an atom is called the **proton number** or atomic number. The symbol Z is used to represent the proton number of an element. It is unique to each element.

In a neutral atom, the total positive charge must equal the total negative charge. Therefore, in a neutral atom, the number of electrons is the same as the number of protons.

QUICK CHECK

A neutral atom with proton number Z has Z number of electrons.

True or false?

Nucleon number A

Protons and neutrons are also called *nucleons*. A nucleon can be a proton or a neutron. The total number of neutrons and protons in a nucleus is called the **nucleon number**. The symbol A is used to represent the nucleon number of the nucleus. (*Nucleon number* is also known as *mass number*.). Recall that the number of protons in a nucleus is the proton number Z. Therefore, we have:

The number of neutrons in a nucleus = nucleon number A – proton number Z

The nucleus of an atom is represented by the nuclide notation shown in Figure 19.8.

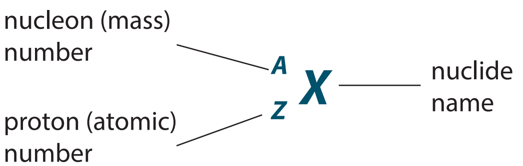


Figure 19.8 *Nuclide notation*

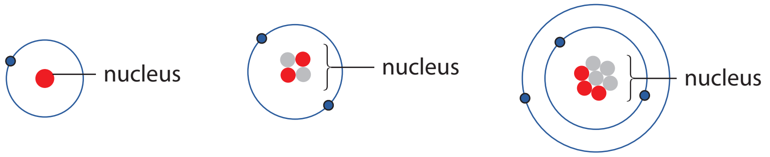
HELPFUL NOTES

Proton (atomic) number = number of protons in an atom

Nucleon (mass) number = total number of protons and neutrons in the nucleus

Figure 19.9 shows the structures of three atoms with different proton numbers. Take note of the number of electrons, protons and neutrons in each atom and their corresponding proton number Z and nucleon number A.

Key
- electron
- proton
- neutron



Nuclide notation	${}^{1}_{1}\mathrm{H}$	${}^{4}_{2}\mathrm{He}$	${}^{7}_{3}\mathrm{Li}$
Atom	Hydrogen	Helium	Lithium
Number of electrons	1	2	3
Number of protons	1	2	3
Number of neutrons	0	2	4
Proton number *Z*	1	2	3
Nucleon number *A*	1	4	7

Figure 19.9 *Simplified atomic structures of the three lightest elements*

Worked Example 19A

The nucleus of an element is represented by ${}^{131}_{53}X$.

(a) How many electrons does the neutral atom contain?

(b) How many neutrons does the nucleus contain?

Solution

(a) The proton number $Z = 53$. So, the number of protons is 53.
In a neutral atom, the number of electrons must equal the number of protons. Hence, the number of electrons is 53.

(b) The nucleon number $A = 131$. So, the number of neutrons is $131 - 53 = 78$.

ENRICHMENT *THINK*

Figure 19.10 shows three isotopes of the element carbon.

1 Which isotope is the heaviest? Explain why.

2 Which isotope is the least stable? Explain why.

Isotopes

Isotopes of an element are the atoms that have the same number of protons but different number of neutrons in the nucleus.

Figure 19.10 shows the nuclide notation for three atoms of the same element carbon. How many electrons and protons does each atom have? How many neutrons does each atom have?

${}^{12}_{6}\mathrm{C}$ ${}^{13}_{6}\mathrm{C}$ ${}^{14}_{6}\mathrm{C}$

Figure 19.10 *Isotopes of the same element have the same proton number but different nucleon numbers.*

The atoms have the same proton number, i.e., each atom has six protons. All atoms of the same element have the same number of protons. However, the number of neutrons is different for each atom. There are six neutrons in ${}^{12}_{6}\mathrm{C}$, seven neutrons in ${}^{13}_{6}\mathrm{C}$ and eight neutrons in ${}^{14}_{6}\mathrm{C}$. The three atoms are *isotopes* of the same element.

Many elements have isotopes. An element may have more than one isotope. Carbon has three naturally occurring isotopes as shown in Figure 19.10. Hydrogen also has three naturally occurring isotopes, which include deuterium and tritium. Isotopes of the same element have identical chemical properties.

ENRICHMENT THINK

Why do you think isotopes of the same element have identical chemical properties?

Let's Practise 19.2

1 State the relative charge of
   (a) a proton;
   (b) a neutron;
   (c) an electron.

2 The following statement describes the nucleus of atom *X*.
   The proton number Z of atom X is 17. The nucleon number is 35.
   (a) State the meanings of the underlined terms.
   (b) Write down the nuclide notation for the nucleus of this atom.
   (c) How many neutrons are in the nucleus?
   (d) Atom *Y* has the same proton number 17, but its nucleon number is 37. Based on this information, how is *X* related to *Y*?

3 **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

TWB LINK

Exercises 19B, pp. XX–XX

S

19.3 Nuclear Fission and Nuclear Fusion

In this section, you will learn the following:
- Describe the processes of *nuclear fission* and *nuclear fusion*. Include nuclide equations and mass and energy changes.
- Know the relationship between the proton number and the relative charge on a nucleus.
- Know the relationship between the nucleon number and the relative mass of a nucleus.

What is nuclear fission?

A neutron is a small particle that has no charge. It can get close to a positively charged atomic nucleus without being repelled by it. Scientists used neutrons to probe the nucleus of various elements. They carried out experiments similar to hitting a metal foil with α-particles but used neutrons instead.

The uranium-235 atom, ${}^{235}_{92}U$, has a big nucleus consisting of 235 nucleons. It has 92 protons and 143 (235 – 92) neutrons.

In 1938, scientists experimented with hitting uranium-235 with neutrons. The nucleus split into two almost equal parts and released more neutrons. A lot of energy was also released in the process. This splitting of the atomic nucleus is called *nuclear fission*.

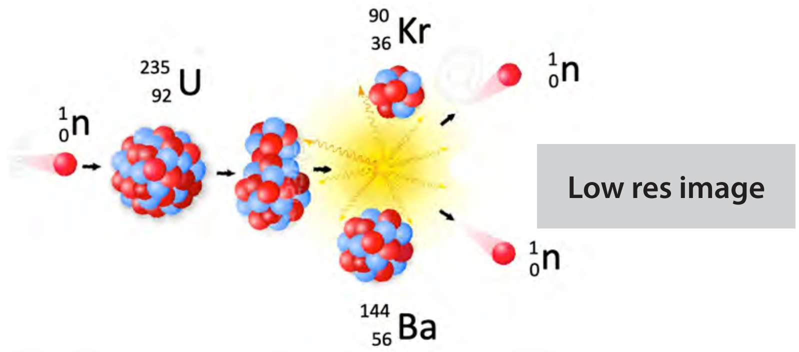
Nuclear fission is a process in which the nucleus of an atom splits (usually into two parts) and releases a huge amount of energy.

WORD ALERT

Probe: examine or investigate in detail

Fission: break up into parts

What happens to the split nucleus during a nuclear fission? The original atom becomes atoms of two different elements. This is a type of nuclear reaction. It can be represented by a nuclide equation as shown in Figure 19.11.



$$^{1}_{0}\text{n} + ^{235}_{92}\text{U} \rightarrow ^{144}_{56}\text{Ba} + ^{90}_{30}\text{Kr} + 2\,^{1}_{0}\text{n} + \text{energy}$$

Figure 19.11 *During a nuclear fission, a massive nucleus splits into smaller nuclei, releasing a huge amount of energy.*

In a nuclear reaction, *the total number of nucleons before and after the reaction is the same*. Add up the nucleon numbers on the left-hand side of the nuclide equation in Figure 19.11. It should equal the sum of the nucleon numbers on the right-hand side. The total number of nucleons before fission is 1 + 235 = 236. After fission, the total number of nucleons is 144 + 90 + 2(1) = 236.

The total relative charge before and after should also be the same.

What is the relative charge on the nucleus of an atom? Recall that the relative charge on each proton is +1. The relative charge on a neutron is 0. The proton number *Z* gives the number of protons in the nucleus.

The **relative charge on the nucleus** is the same as the proton number *Z* of the nucleus.

In Figure 19.11, the total relative charge before fission is 0 + (+92) = +92.

After fission, the total relative charge is 56 + (+36) + 2(0) = +92.

In a nuclear fission, there are a number of possible fission products. Therefore, there are a number of possible nuclide equations.

For example: $^{235}_{92}\text{U} + ^{1}_{0}\text{n} \rightarrow ^{139}_{56}\text{Ba} + ^{94}_{36}\text{Kr} + 3\,^{1}_{0}\text{n} + \text{energy}$

Check that the total number of nucleons and the total relative charge before and after the reaction are the same.

Worked Example 19B

In the following nuclide equation, what are the missing nucleon number *A* and proton number *Z*?

$^{233}_{92}\text{U} + ^{1}_{0}\text{n} \rightarrow ^{137}_{54}\text{Xe} + ^{A}_{Z}\text{Sr} + 3\,^{1}_{0}\text{n}$

Solution

Before fission, total nucleon number = 233 + 1 = 234

After fission, total nucleon number = 137 + *A* + 3(1) = 140 + *A*

Equating the total nucleon number before and after fission, 140 + *A* = 234

$\Rightarrow \therefore A = 94$

Before fission, total relative charge = (+92) + 0 = +92

After fission, total relative charge = (+54) + *Z* + 0 = (+54) + *Z*

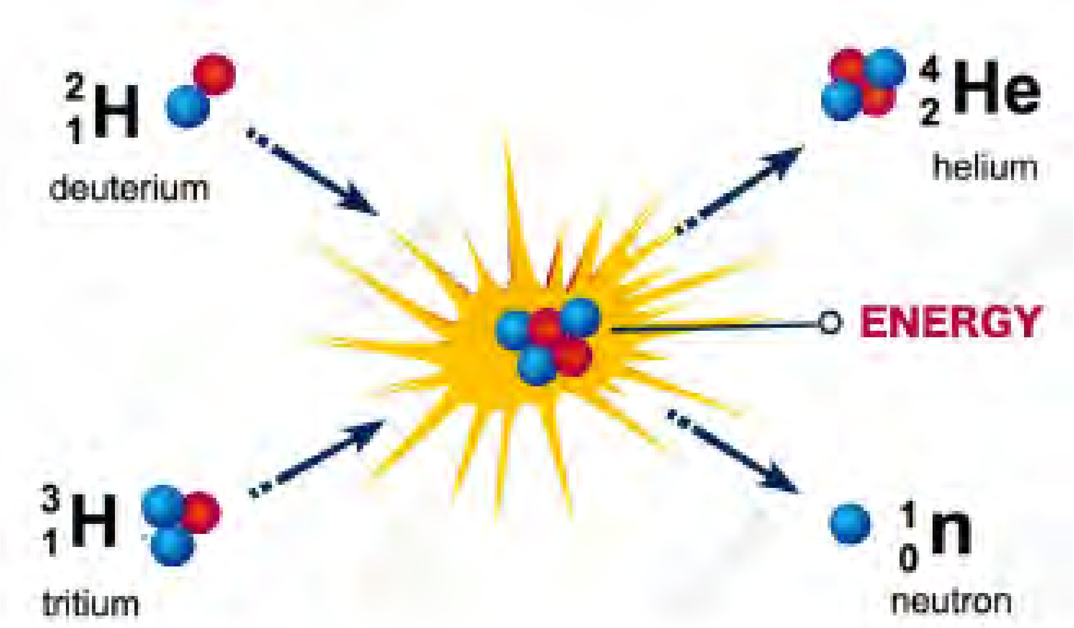
Equating the total relative charge before and after fission, 54 + *Z* = 92

$\Rightarrow \therefore Z = 38$

What is nuclear fusion?

Nuclear fusion is a process in which two light atomic nuclei combine to form one heavier atomic nucleus, releasing a huge amount of energy.

Figure 19.12 shows an example of a nuclear fusion reaction.



Low res image

$$^2_1H + ^3_1H \rightarrow ^4_2He + ^1_0n + \text{energy}$$

Figure 19.12 *Two hydrogen isotopes combine to form a larger helium atom in a nuclear fusion reaction.*

Just like in nuclear fission, the total number of nucleons before and after the fusion is the same. The total charges before and after is also the same.

Where does nuclear energy come from?

Nuclear energy is potential energy stored in the nucleus. This energy is converted from mass.

Nuclear scientists use relative mass (in atomic mass units) instead of the kilogram to measure the mass of a nucleus because it is very small. By definition, the mass of the nucleus of the carbon-12 atom is 12 atomic mass units. There are 12 nucleons in the nucleus of the carbon-12 atom. So, the relative mass of each nucleon should be 1 atomic mass unit.

However, very precise measurements show that the relative mass of a neutron which is not in a nucleus is slightly larger than 1 atomic mass unit. Similarly, the relative mass of a proton which is not combined in a nucleus is slightly larger than 1 atomic mass unit. So the total mass of the 12 nucleons that make up the carbon-12 nucleus is actually slightly larger than the mass of the nucleus itself.

This fact is true of all nuclei — the total mass of the nucleons that make up a nucleus is slightly larger than the mass of the nucleus itself.

What happens to the missing mass? It is converted to the energy that holds the nucleons together. This is the potential energy stored in the nucleus. During a nuclear reaction (nuclear fission or nuclear fusion), the neutrons and protons rearrange to form new nuclei. As a result, there is a very small change in mass. A huge amount of energy is released as a result of mass–energy conversion.

WORD ALERT

Fusion: joining of individual parts to become one

QUICK CHECK

In both nuclear fission and nuclear fusion, the total number of nucleons before and after each process is the same.

True or false?

HELPFUL NOTES

The mass–energy conversion of a nuclear fission is governed by the famous Einstein equation: $E = mc^2$

WORD ALERT
Ejected: forced or thrown out

In a nuclear fission, the total mass of the products (new nuclei and ejected neutrons) is smaller than the total mass of the original nucleus and neutron that hit it. In forming fission products, a lot of energy is released from the total reduced mass. Nuclear power stations use nuclear fission to generate energy (Figure 19.13).

Similarly, in nuclear fusion, the total mass of the two light nuclei before the fusion is more than the total mass of the heavier nucleus and the ejected neutron. The difference in mass is converted to energy released in the fusion process.

However, nuclear fusion is harder to achieve. The nucleus of an atom is positively charged. Like charges repel. In order for two positively charged nuclei to combine, they must overcome the strong repulsive force. Nuclear fusion takes place naturally at very high temperatures and pressures in the Sun. Unfortunately, nuclear fusion has only been used destructively in the hydrogen bomb (Figure 19.14). Scientists are trying to build nuclear fusion reactors that can be safely used.

Table 19.1 summarises the particles represented by $^A_Z X$.

Figure 19.13 *A nuclear power plant harnesses the energy released from nuclear fission.*

Table 19.1 *Summary of atomic particles*

Particle	Charge (relative charge)	Approximate mass (atomic mass unit)	Number of particles in nucleus
Proton	+1	1	Z
Neutron	0	1	$A - Z$
Electron	–1	$\frac{1}{2000}$	Z
Nucleus	$+Z$	A	

PHYSICS WATCH
Scan this page to watch a clip about the need to use nuclear energy responsibly.

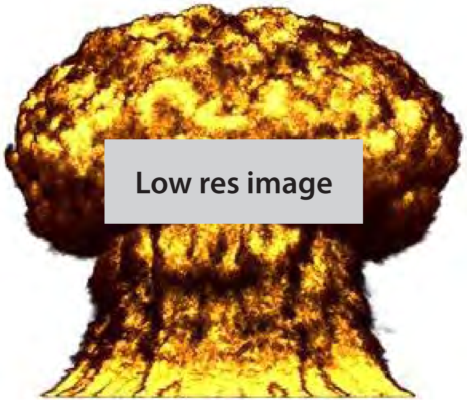


Figure 19.14 *The hydrogen bomb releases a huge amount of energy from nuclear fusion.*

Let's Practise 19.3

1 Table 19.2 compares two nuclide equations. Complete the table with suitable words from the list below.

nuclear fusion, nuclear fission, mass, number of nucleons, energy, charges, heavy nucleus split into lighter nuclei, lighter nuclei combine to form heavier nucleus

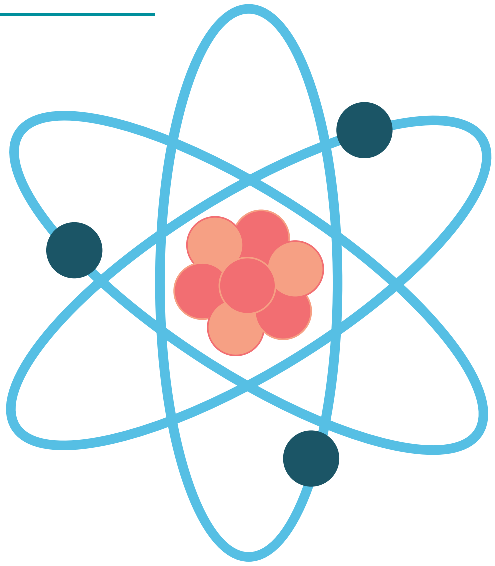
You may use some words more than once. The first has been done for you.

Nuclide equation	$^{239}_{94}Pu + ^1_0n \rightarrow ^{137}_{54}Xe + ^{103}_{40}Zr + ^1_0n$	$^2_1H + ^2_1H \rightarrow ^3_2He + ^1_0n$
Description of process	Heavy nucleus split into lighter nuclei	
Name of process		
Total ________ before	240	4
Total ________ after	240	4
Total ________ before	+94	+2
Total ________ after	+94	+2
Total ________ before compared to after	greater and so ________ released	greater and so ________ released

2 **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

LINK
Exercises 19C–19D, pp. XX–XX
Exercise19E Let's Reflect, p. X

Let's Map It



Geiger and Marsden experiment (Rutherford's scattering)

provides insights into

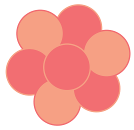
THE NUCLEAR ATOM

can

Negatively charged electrons

consists of

Positively charged nucleus

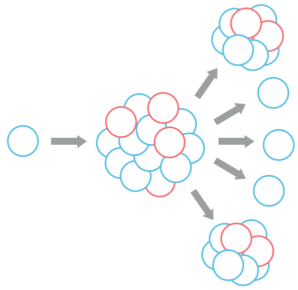


contains

Protons
- Positively charged
- Proton number Z

Nucleons
- 2 types of particles, protons and neutrons
- Nucleon number A

Neutrons
- No charge
- Number of neutrons (A-Z)



Nuclide notation

$$^{A}_{Z}X$$

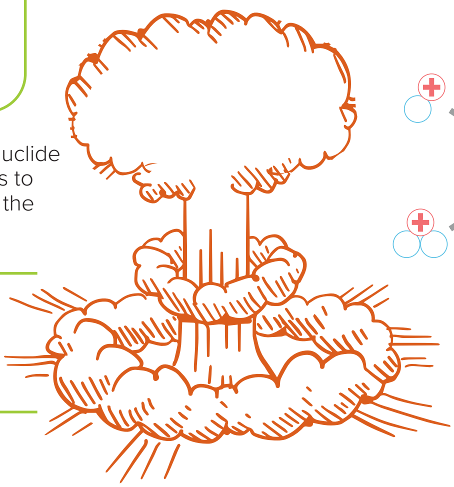
- Element *X*
- Nucleus has *Z* protons and *A* – *Z* neutrons

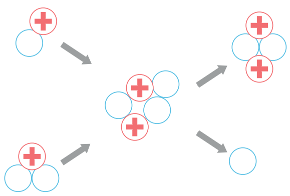
used to represent

Isotopes of elements
- Same proton number Z
- Different nucleon number A

used in nuclide equations to describe the

Nuclear processes of
- Nuclear fission
- Nuclear fusion





Let's Review

Section A: Multiple-choice Questions

1 Which of the following statements correctly describe the structure of an atom?

A An atom consists of positively charged protons and negatively charged electrons tightly bound together.
B An atom consists of positively charged protons and negatively charged neutrons tightly bound together.
C An atom consists of a positively charged nucleus and negatively charged electrons in orbit around the nucleus.
D An atom consists of a positively charged nucleus and negatively charged neutrons in orbit around the nucleus.

2 How does a neutral atom become a positive ion?

A It gains protons. **B** It loses protons.
C It gains electrons. **D** It loses electrons.

3 S The scattering of α-particles by thin metal provides evidence for

A a nucleus consisting of protons and neutrons.
B a nucleus that is charged.
C electrons carrying negative charges.
D neutrons not carrying any charge.

4 An atom has proton number $Z = 19$ and nucleon number $A = 40$. Which of the following rows describes the composition of the neutral atom?

	Number of protons	*Number of electrons*	*Number of neutrons*
A	40	40	19
B	19	21	40
C	40	21	19
D	19	19	21

5 Which of the following nuclides has equal number of neutrons and protons?

A ${}^{1}_{1}H$ **B** ${}^{6}_{3}Li$
C ${}^{10}_{4}Be$ **D** ${}^{17}_{8}O$

6 Which pairs of nuclides are isotopes?

A ${}^{35}_{17}X$ and ${}^{37}_{17}Y$ **B** ${}^{35}_{17}X$ and ${}^{79}_{35}Y$
C ${}^{37}_{17}X$ and ${}^{37}_{20}Y$ **D** ${}^{79}_{35}X$ and ${}^{81}_{37}Y$

Section B: Short-answer and Structured Questions

1 The nuclide notation for an atom is ${}^{14}_{7}N$.

(a) What does the number 14 represent?
(b) What does the number 7 represent?
(c) The nuclide notation for another atom of the same element is ${}^{15}_{7}N$. Explain how the two atoms can be of the same element.

2 Figure 19.15 shows the structures of two atoms *X* and *Y*. One of the atoms is not a neutral atom.

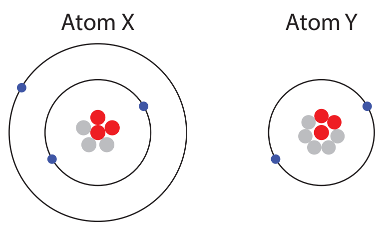


Figure 19.15

(a) Complete the key to the Figure 19.14.

electron
____
____

(b) Which atom is neutral?
Give the nuclide notation for this atom.
(c) Explain why the atoms in Figure 19.8 belong to the same element.

3 S In a nuclear reactor, an atom of uranium-235 undergoes nuclear fission.

(a) Explain what is meant by *nuclear fission*.
(b) Describe how energy is produced by the fission of an atom of uranium-235.

4 S A nuclear reaction is represented by the following nuclide equation:

$${}^{1}_{1}H + {}^{2}_{1}H \rightarrow {}^{3}_{2}He + \text{energy}$$

(a) Explain the type of process represented by the nuclide equation.
(b) Energy is released by the process. Describe the changes that result in energy being released.

CHAPTER

20 Radioactivity

Toshiro, a Japanese pilot, spends a lot of time in the sky at altitudes between 6000 to 12000 metres. He has clocked up to 1000flight hours per year for the past 12 years. That's more than 10 000 flight hours! Before this, Toshiro used to clock up to 1650 flight hours per year.

Pilots are being advised to reduce the amount of working time spent on long flights and flights that are at high altitudes. They are even told not to fly frequently over the two poles — the North Pole and the South Pole!

What are they trying to avoid?

Radiation!

PHYSICS WATCH

Scan this page to watch a clip about radioactive exposure.

QUESTIONS

- What is the nature of the radiation that pilots are trying to avoid?
- Where do you think the radiation comes from?
- How does following the advice helps pilots?

20.1 Detection of Radioactivity

In this section, you will learn the following:

- Know what is meant by *background radiation*.
- Know the sources that make a significant contribution to background radiation, including radon gas (in the air), rocks and buildings, food and drink and cosmic rays.
- Know that ionising nuclear radiation can be measured using a detector connected to a counter.
- Use count rate measured in counts/s or counts/min.
- S Use measurements of background radiation to determine a corrected count rate.

What is background radiation?

Radiation is all around us. We are commonly exposed to electromagnetic radiation. Examples are visible light and infrared light from the Sun, and microwaves from mobile phones. These are non-ionising radiation. There are also other types of radiation which are ionising.

Ionising radiation is radiation with high energies that can *knock off electrons from atoms to form ions*. Very high frequency ultraviolet, X-rays and gamma rays are examples of ionising electromagnetic radiation. High-energy particles from cosmic rays and from naturally occurring radioactive materials are examples of ionising nuclear radiation.

Background radiation is *ionising nuclear radiation* in the environment when no radioactive source is deliberately introduced. Sources of background radiation can be natural or artificial (Table 20.1).

ENRICHMENT INFO

Cosmic Rays

Cosmic rays come from the Sun and other space objects outside the Solar System, such as distant galaxies. They are not like light rays. They consist mainly of protons and a small percentage of other subatomic particles.

The Earth's atmosphere reduces most of the energy of cosmic rays. When cosmic rays collide with the Earth's atmosphere, less energetic particles are created. At ground level, exposure to cosmic rays is much less than at higher levels above sea levels.

Table 20.1 Sources of background radiation

Natural sources	Artificial sources
• Rocks • Radon gas in the air • Food and drink (e.g. foods high in potassium such as banana contain small amounts of radioactive potassium-40) • Cosmic rays	• Medical X-rays • Building materials • Waste products from nuclear power stations

Natural sources make a significant contribution to background radiation. At ground level, the amounts of background radiation are usually well below the levels that the human body can tolerate.

Figure 20.1 The people in the photos are exposed to background radiation. For each situation, can you identify the sources of the background radiation?

How do we measure ionising nuclear radiation?

Ionising nuclear radiation can be measured using a detector connected to a counter (Figure 20.2).

To measure the background radiation, follow these steps:

1. Remove all known radioactive sources and set the counter to zero.
2. Start the counter and a stopwatch.
3. Stop the counter after 10 minutes and record the number of counts.
4. Divide the number of counts by 10 to obtain the number of counts per minute.
5. Repeat your measurement at least once to obtain an average value.

Alternatively, record the number of counts for a longer time interval, for example, 20 minutes.

The background count rate is measured in **counts per minute (counts/min)**. When the count rate is high, the counts are measured for a shorter time, for example, 30 seconds. The average count rate in such a case is measured in counts per second (counts/s).

Figure 20.2 A detector attached to a counter is used to measure ionising nuclear radiation.

S When carrying out any measurements with radioactive sources, you should first measure the background radiation. Subtract this background count rate from your measurements to obtain the corrected count rate for the radioactive source.

Worked Example 20A

(a) A teacher turned on a radiation detector and observed the number of counts at 10-minute intervals. She recorded her observations as follows: 198, 180, 175, 200. Determine the average background count rate.

(b) Next, the teacher carefully placed the detector in front of a radioactive source. She measured the number of counts for 30 seconds. It was 1243. Calculate the count rate for the radioactive source in counts/s.

(c) S What was the corrected count rate for the radioactive source in counts/min?

Solution

(a) Average number of counts for 10 minutes $= \frac{198 + 180 + 175 + 200}{4} = 188$

Average background count rate $= \frac{188}{10} = 19$ counts/min

(b) Count rate of the radioactive source $= \frac{1243}{30} = 41$ counts/s

(c) S Count rate of radioactive source $= \frac{1243}{0.5} = 2486$ counts/min (30 s = 0.5 min)

Corrected count rate = 2486 – 19 = 2467 counts/min

QUICK CHECK

When measuring ionising nuclear radiation from a radioactive source, the counter will give the true count rate.

True/false?

Let's Practise 20.1

1 What is background radiation?
2 Name **two** natural sources of background radiation.
3 A student turned on a radiation detector for 20 minutes. The counter showed a count of 420. What was the background radiation?
4 S In an experiment, the number of counts from a radioactive source was measured for five minutes. It was 120. The background count was 20 counts/min. What was the corrected count rate for the radiation from the radioactive source?
5 **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

LINK TWB

Exercise 20A, pp. XX–XX

20.2 Nuclear Emission

In this section, you will learn the following:

- Describe the emission of radiation from a nucleus as spontaneous and random in direction.
- Identify alpha (α-), beta (β-) and gamma (γ-) emissions from the nucleus by recalling their nature, their relative ionising effects and their relative penetrating abilities.
- S Describe the deflection of α-particles, β-particles and γ-radiation in electric fields and magnetic fields.
- S Explain their relative ionising effects with reference to kinetic energy and electric charge.

How is radiation emitted from a nucleus?

If you measure background radiation at one-minute intervals, you will observe that the count rate is always different for successive minutes. This is not because of errors in counting. The count rate will always be different. Why is this so?

The radiation emitted by a radioactive nucleus is *spontaneous* and *random in direction*. It is not possible to make the radioactive nucleus emit radiation by heating, cooling, chemical means or any other method. There is no way to predict when a radioactive nucleus will emit radiation. It is also impossible to know the direction in which the emitted radiation will leave a nucleus. This is why we need to make measurements over a sufficiently long period of time to obtain an average count rate.

WORD ALERT A-Z

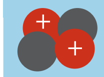
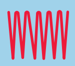
Spontaneous: happening suddenly

Figure 20.3 *How does popping popcorn simulate radioactive emission?*

What are the three types of nuclear emission?

There are three types of nuclear emission: *alpha (α-) particles, beta (β-) particles* and *gamma (γ-) rays*. Their properties are shown in Table 20.2.

Table 20.2 *The three types of nuclear emission*

Nuclear emission	Nature	Relative ionising effect	Relative penetrating ability
α-particles  $^{4}_{2}\alpha$	An **α-particle** consists of two protons and two neutrons tightly bound together without any orbiting electrons. It is identical to a *helium nucleus*.	Highest	• Least • They are easily absorbed by a piece of paper, a thin aluminium foil or human skin.
β-particles ⊖ $^{0}_{-1}\beta$	A **β-particle** is a fast-moving *electron* ejected from a radioactive nucleus.	Medium	• Medium • They are absorbed by a few-mm-thick aluminium.
γ-rays 	A **γ-ray** is electromagnetic radiation emitted by a nucleus with excess energy.	Least	• Highest • They pass through most materials easily and are absorbed by a few-cm-thick lead or very thick concrete.

Worked Example 20B

An experiment was set up to investigate the penetrating power of radiation from a radioactive source (Figure 20.4).

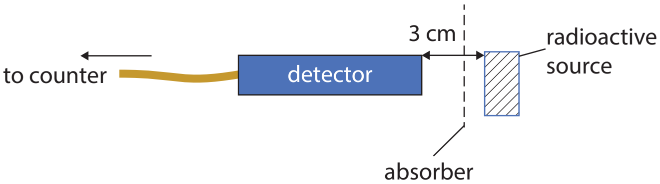


Figure 20.4

Table 20.3 shows the results.

Table 20.3

Background count	25 counts per minute
Count with source only	4200 counts per minute
Count with source and paper absorber	4180 counts per minute
Count with source and 3-mm-thick aluminium absorber	1200 counts per minute

What type or types of radiation does the radioactive source emit?

Solution

No α-particles are emitted because the count rate with the paper absorber is about the same as without any absorber. The emission is partially absorbed by the 3-mm-thick aluminium — so this must be the β-particles. Some emission is not absorbed because the count rate is quite high at 1200 counts per minute while the background count is only 25 counts per minute. This must be due to γ-emission from the source. The radioactive source emits β-particles and γ-rays.

Relative ionising effects of nuclear emission

An ion is formed from a neutral atom when an electron leaves the atom. Energy has to be transferred to the electron for it to leave the atom.

α- and β-particles are fast-moving charged particles. They have large amounts of kinetic energy. α-particles have a bigger amount of kinetic energy than β-particles. Therefore, they have a bigger ionising effect.

There is electrical force between the moving charged particles and the charged electrons in the atoms. The electrical force transfers energy to the electrons in the atom from the kinetic energy of the moving particles. The bigger the force, the more energy can be transferred. Table 20.3 shows that an α-particle has twice the amount of charge of a β-particle. It has a bigger force than a β-particle. Thus, α-particles form more ions within a short distance than β-particles.

Table 20.4 *Relative charges and mass of nuclear emission*

Nuclear emission	Relative charge	Mass (atomic mass units)
α-particles	+2	4
β-particles	–1	$\frac{1}{2000}$
γ-rays	0	0

γ-rays are electromagnetic waves. They do not have any charge or mass. They transfer nuclear energy from the radioactive nuclei. γ-rays have the least ionising effect. α-particles have the greatest ionising effect because of its +2 relative charge and high amount of kinetic energy.

What happens when α-particles, β-particles and γ-rays travel through an electric field?

Figure 20.5 shows three different sources of nuclear radiation in a strong electric field. The path of each type of nuclear radiation is deflected differently. Can you identify the type of nuclear radiation? (Hint: What type of charge is carried by each type of nuclear radiation?)

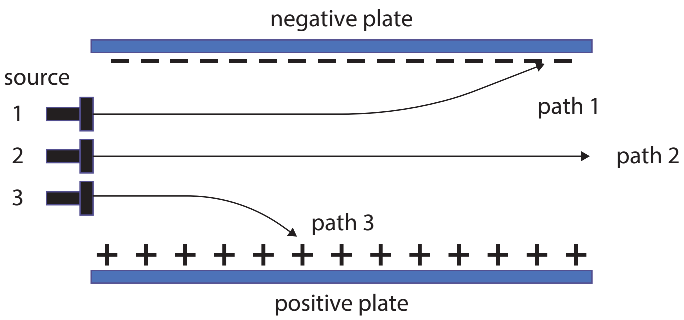


Figure 20.5 *Nuclear radiation passing through an electric field*

Source 1 emits α-particles. The positively charged particles are attracted to the negative plate (path 1). The deflection is not as much as path 3 because they have a relatively big mass.

Source 3 emits β-particles. The negatively charged electrons are attracted towards the positive plate (path 3). The deflection is more because they have a small mass.

Source 2 emits γ-rays which are not deflected (path 2) because they are electromagnetic waves.

What happens when α-particles, β-particles and γ-rays travel through a magnetic field?

Figure 20.6 shows the paths of three different types of nuclear radiation in a magnetic field. The magnetic field is coming out of the page. (The dots represent the pointed end of arrows coming out of the page.) Can you identify the types of nuclear radiation? (Hint: determine the direction of the force on a stream of charged particles in a magnetic field.)

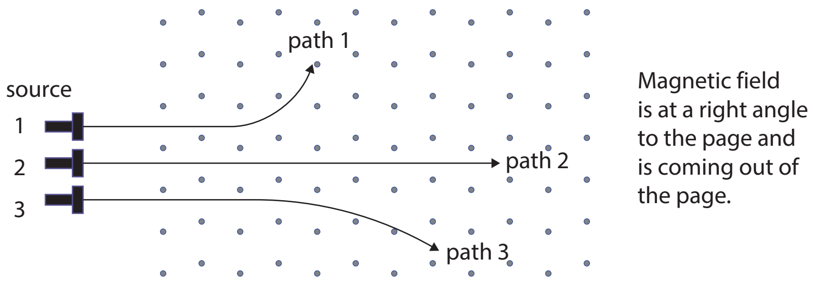


Figure 20.6 *Nuclear radiation passing through a magnetic field*

Source 2 emits γ-rays which are not deflected by the magnetic field because they do not carry any charge.

Source 1 emits β-particles. The particles are deflected upwards since they are negatively charged. They are deflected more than the alpha particles in path 3 because they have smaller mass.

Source 3 emits α-particles which are deflected downwards and less than the particles in path 1.

Let's Practise 20.2

1 A student was trying to measure the radiation from a radioactive source. He took readings for a short time. His readings were as follows:

Counts/s: 520 530 510 515 540

The student suggested that the counter was faulty because the readings kept changing. What explanation can you give for the changing count rate?

2 Draw lines to match the type of nuclear radiation (A) to the correct nature (B), relative ionising effect (C) and relative penetrating abilities (D):

A	B	C	D
α	Electromagnetic radiation	Least ionising	Most penetrating
β	Negatively charged small particles	Most ionising	Medium penetrating
γ	Positively charged particles with high kinetic energy	Medium ionising	Least penetrating

3 **(a)** S The radiation from a radioactive source is not deflected in an electric field or in a magnetic field. What is this radiation?

(b) What type or types of nuclear emission will be defected in an electric field and in a magnetic field? How can you verify the type of emission by observing its deflection?

4 S What two properties of α-particles explain their strong ionising effect?

5 **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

LINK TWB

Exercise 20B, pp. XX–XX

20.3 Radioactive Decay

In this section, you will learn the following:

- Know what is meant by *radioactive decay* and that the changes involved are spontaneous and random.
- State that what happens to the nucleus during α-decay or β-decay.
- S Know why isotopes of an element may be radioactive.
- S Describe the effect of α-decay, β-decay and γ-emissions on the nucleus.
- S Use decay equations, using nuclide notation, to show the emission of α-particles, β-particles and γ-radiation.

What is radioactive decay?

Radioactive sources contain *unstable* nuclei. These nuclei are unstable because they change spontaneously and randomly.

A change in an unstable nucleus can result in the emission of α-particles or β-particles and/or γ-radiation. This nuclear process is called **radioactive decay**.

It is impossible to predict which nucleus or when a particular nucleus will decay because radioactive decay is *spontaneous and random*. However, all nuclei of the same isotope will emit the same type of nuclear radiation.

- When a nucleus undergoes **α-decay**, it emits an *α-particle*.
- When a nucleus undergoes **β-decay**, it emits a *β-particle*.

During α- or β-decay, the nucleus changes to that of a different element.

WORD ALERT A-Z

Nuclei: plural of nucleus

Decay: break down into smaller parts

Why are some isotopes radioactive?

The nuclei of some isotopes like uranium($^{238}_{92}U$) and caesium ($^{137}_{55}Cs$) are very **massive**. Such a massive nuclide has more than a hundred nucleons packed in its nucleus. These nuclei tend to be unstable. They can change into lighter nuclei by emitting α-particles.

The element carbon has three natural isotopes: $^{12}_{6}C$, $^{13}_{6}C$ and $^{14}_{6}C$. Which nuclide has the most neutrons? By looking at the nucleon number, we know it is carbon-14. Carbon-14 has eight neutrons, which is more than the six protons in the nucleus. Similarly, the nuclide sodium-24 ($^{24}_{11}Na$) has 13 neutrons but only 11 protons. These nuclides with excess neutrons are unstable. They can change into nuclei with fewer excess neutrons by emitting β-particles.

How does α-decay make a nucleus more stable?

When a very massive nuclide such as radon-224 decays by emitting an α-particle, it changes into a nucleus of a lighter element. This nucleus has a nucleon number *A* smaller by 4 and proton number *Z* smaller by 2. The new element formed is polonium. How does this happen? The nuclide equation below shows how radon-224 undergoes α-decay:

nucleon number decreases by 4

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

proton number decreases by 4

During α-decay, the nucleus ejects four nucleons consisting of two protons and two neutrons. The nucleus now has four fewer nucleons. The four ejected nucleons form a helium nucleus. This helium nucleus is referred to as an α-particle and can simply be written as $^{4}_{2}\alpha$. The decay equation can then be written as:

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

Although polonium is less massive than radon, it is still not stable. It further decays by emitting α-particles to become the lead nuclide $^{214}_{82}Pb$.

How does β-decay make a nucleus more stable?

A β-particle is a negatively charged electron. However, there are no electrons in the nucleus of an atom. So how can a nucleus emit an electron?

The process is complex and involves another extremely small particle. To simplify, the following describes what happens during a β-decay:

- A neutron changes into a proton and an electron (neutron → proton + electron).
- The proton remains in the nucleus. The electron is emitted as a β-particle.
- As a result, *the proton number Z increases by one* while the *nucleon number A remains the same*.

As an example, let's take a look at carbon-14 undergoing β-decay as shown below:

nucleon number remains the same

$$^{14}_{6}C \rightarrow \, ^{14}_{7}N + \, ^{0}_{-1}\beta$$

proton number increases by 1

WORD ALERT

Massive: has large mass

QUICK CHECK

The nuclide equation for α-particle decay of polonium is as follows:

$$^{218}_{84}Po \rightarrow \, ^{214}_{82}Pb + \, ^{4}_{2}\alpha$$

True or false?

When carbon-14 emits a β-particle, it changes into the nitrogen nuclide with seven neutrons and seven protons. Before the decay, the carbon nuclide has eight neutrons but only six protons. The new nitrogen nuclide does not have excess neutrons compared to the number of protons.

The lead nuclide $^{214}_{82}Pb$ decays by β-emission to form the nuclide bismuth $^{214}_{83}Bi$. Try writing out the nuclide equation for this decay. Check your answer in the following discussion on γ-emission.

How does γ-emission make a nucleus more stable?

After a nucleus emits an α- or a β-particle, the nucleus may have excess energy. It releases this excess energy by emitting γ-rays. For example, when the lead nuclide $^{214}_{82}Pb$ decays, the nuclide, bismuth $^{214}_{83}Bi$ is left with excess energy. This excess energy is released as γ-emission. Both the number of protons and the number of neutrons in the nucleus are not changed in the process. During γ- emission, the proton number *Z* and the nucleon number *A* remain the same.

The two types of emission can be represented by the following nuclide equations:

$$^{214}_{82}Pb \rightarrow {}^{214}_{83}Bi^{*} + {}^{0}_{-1}\beta$$

$$^{214}_{83}Bi^{*} \rightarrow {}^{214}_{83}Bi + \gamma$$

The asterisk * is used to indicate that a particular nucleus has excess energy (or is in an excited state). The equations are usually combined into one:

$$^{214}_{82}Pb \rightarrow {}^{214}_{83}Bi + {}^{0}_{-1}\beta + \gamma$$

Similarly, when radium decays to radon, the radon nucleus is left with excess energy, which it releases as γ-radiation:

$$^{226}_{88}Ra \rightarrow {}^{222}_{86}Rn + {}^{4}_{2}\alpha + \gamma$$

There are some rare artificial isotopes that emit only γ-rays, like the unstable technetium-99m. (The 'm' stands for 'metastable'.)

$$^{99m}_{43}Tc \rightarrow {}^{99}_{43}Tc + \gamma$$

Table 20.5 summarises the changes to the nucleus during radioactive decay.

Table 20.5 *What happens to the nucleus during radioactive decay*

Type	Effect on nucleus	Decay equation
α-decay	• Loses two neutrons and two protons • Becomes a less massive nucleus of a different element	$^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}\alpha$
β-decay	• One neutron in nucleus changes into a proton and an electron; proton remains in the nucleus, electron is emitted (β-particle) • Becomes the nucleus of a different element with fewer excess neutrons	$^{A}_{Z}X \rightarrow {}_{Z+1}^{A}Y + {}^{0}_{-1}\beta$
γ-emission	• Releases excess energy • No change in atomic number or mass number	$^{A}_{Z}X \rightarrow {}^{A}_{Z}X + \gamma$ or $^{A}_{Z}X^{*} \rightarrow {}^{A}_{Z}X + \gamma$

Let's Practise 20.3

1 Complete the sentences:

(a) ________________ is a change in an unstable nucleus that can result in the emission of α-particles or β-particles and/or γ-radiation. These changes are ________________ and ________________.

(b) During α- or β-decay, the nucleus changes to that of a different ________________.

2 S What two types of isotopes may be radioactive?

3 S Complete the sentences:

(a) When a nucleus emits an α-particle, its nucleon number ________________ and its proton number ________________.

(b) When a nucleus emits a β-particle, its nucleon number ________________ and its proton number ________________. It now has ________________ excess neutrons.

4 S Write the nuclide equations for the following two processes:

(a) $^{238}_{92}U$ decays to Th by emitting an α-particle and γ-radiation.

(b) $^{137}_{55}Cs$ decays to Ba by emitting a β-particle and γ-radiation.

5 **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

TWB LINK

Exercise 20C, pp. XX–XX

20.4 Half-life

In this section, you will learn the following:

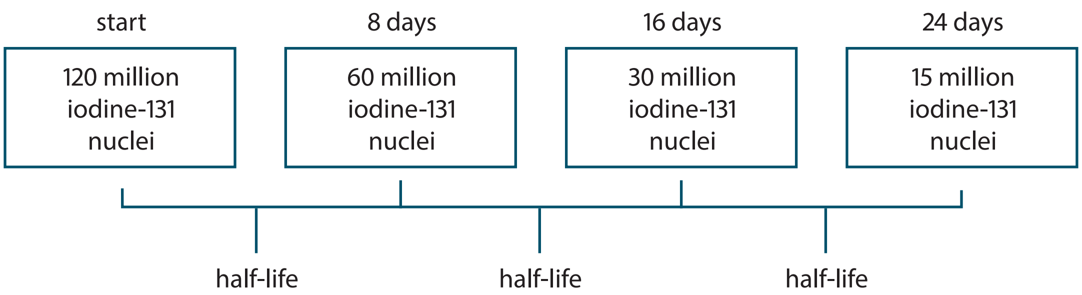
- Define the half-life of a particular isotope.
- Recall and use the definition of half-life in simple calculations.
- S Calculate half-life from data or decay curves from which background radiation has not been subtracted.
- S Explain how the type of radiation emitted and the half-life of an isotope determine which isotope is used for applications.

What is half-life?

Nobody knows exactly when a particular nucleus will decay. However, every isotope has a definite rate of decay which cannot be changed by heating, cooling or any other methods. We can make predictions about the decay of a large number of nuclei of a particular isotope because it has a fixed *half-life*.

The **half-life** of a radioactive isotope is the time taken for half the nuclei of that isotope in any sample to decay.

For example, the half-life of iodine-131 is eight days. Suppose there are 120 million iodine-131 in the beginning. Observe the number after 8 days, 16 days and 24 days. The results are as shown:



HELPFUL NOTES

The half-life of an isotope can also be understood as the time taken for the count rate of the radioactive emission to fall by half.

Experimentally, the time taken for the count rate of the radioactive emission to fall by half is the half-life of the isotope. The graph of count rate against time is called the **decay curve** (Figure 20.7).

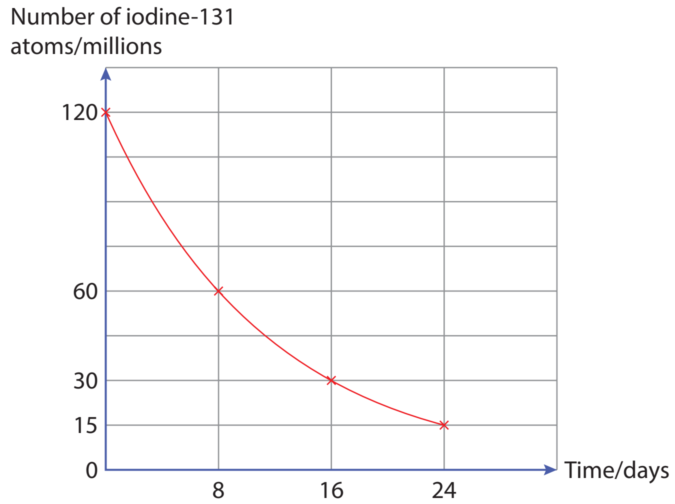


Figure 20.7 *Decay curve*

ENRICHMENT *THINK*

Technetium 99 has a half-life of 215 000 years. Its isomer, Technetium 99m, has a half-life of six hours.

Which of the two is suitable to be used as a medical tracer for scanning the internal organ of a patient? Explain why.

Worked Example 20C

In an experiment, a radiation detector was placed close to a radioactive source. The count rate was measured at five-minute intervals for 30 min. The results for the first 20 min are shown in Table 20.6.

Table 20.6

Time/min	0	5	10	15	20
Count rate Counts / min	12 012	8558	6098	4344	3095

(a) Use the data to estimate the half-life of the radioactive source.

(b) What could be the approximate count rate at the end of 30 min?

Solution

(a) At the start of the experiment, the count rate was 12 012 counts/min. Half of this rate is about 6000 counts/min. From the table, the count rate decreases to 6098 counts/min after 10 min. Therefore, the half-life of the radioactive source is about 10 min.

(You can check to see that after another 10 min (i.e. time = 20 min), the count rate is further halved from about 6000 to 3000 counts/min.)

(b) The half-life is 10 min. At the end of 20 min, the count rate was about 3000 counts/min. So, in the next 10 minutes (i.e. at the end of 30 min), this rate would be halved to 1500 counts/min.

Worked Example 20D

The decay curve of a radioactive isotope is shown in Figure 20.8. Use the graph to estimate the half-life of the isotope.

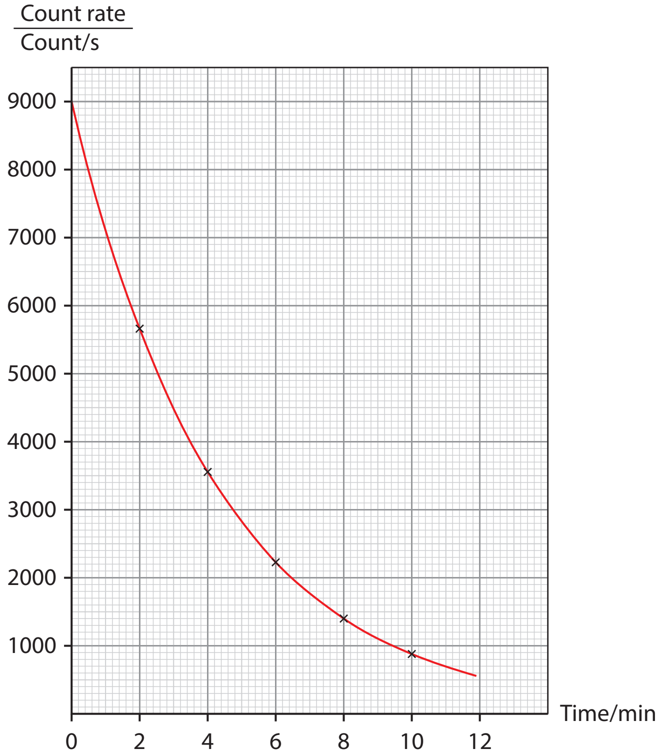


Figure 20.8 *Decay curve for a radioactive isotope*

Solution

The solution is shown in Figure 20.9 From the decay curve, the half-life is 3 min.

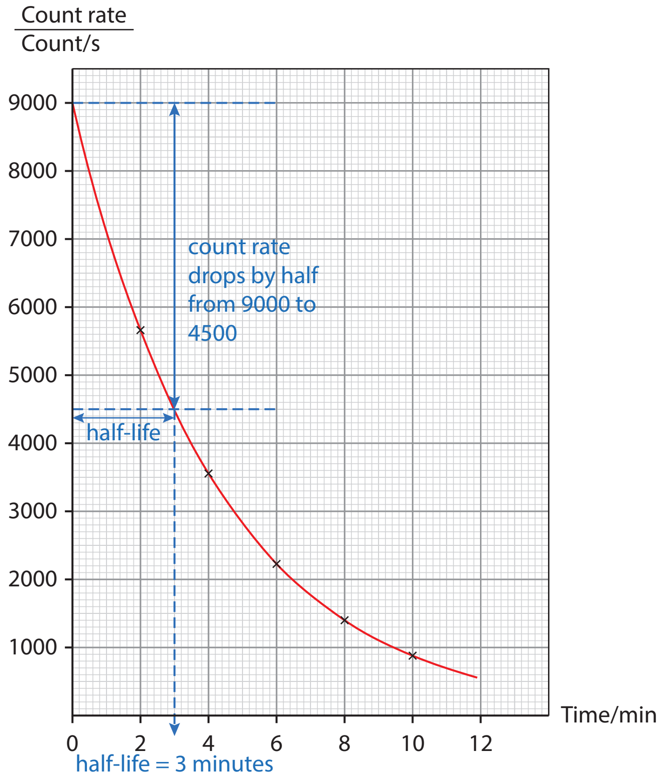


Figure 20.9 *Determining the half-life of an isotope from a decay curve*

In Worked Examples 20C and 20D, the count rates are very high. Now consider the decay curve in Figure 20.10. Why does the count rate remain at about 20 counts/min after some time?

The almost constant count rate of 20 counts/min is due to the background radiation. In this example, the small sample has completely decayed. What is the half-life of this isotope? From the decay curve in Figure 20.11, the half-life is 20 min.

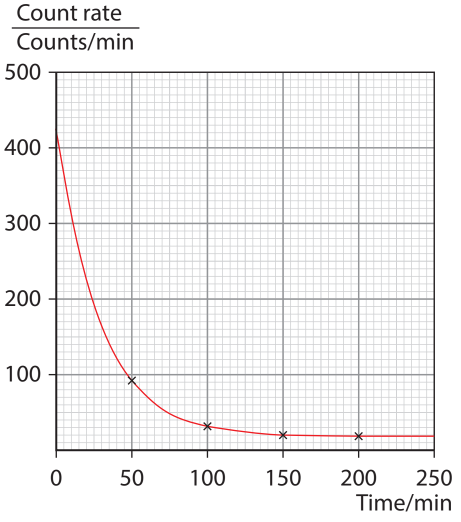


Figure 20.10 Decay curve from which background radiation has not been subtracted

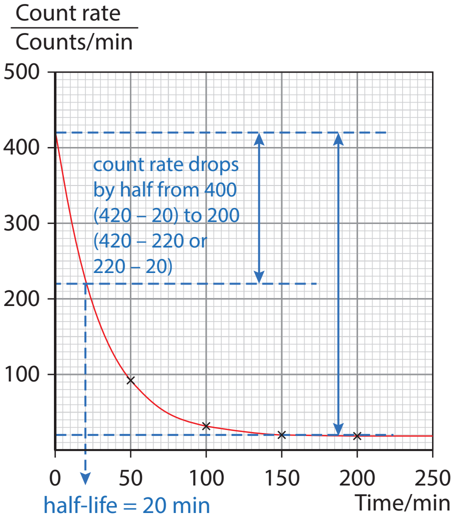


Figure 20.11 Determining the half-life from decay curve from which background radiation has not been subtracted

Worked Example 20E

In an experiment to measure the half-life of an isotope, the count rate was measured at 10-min intervals for 40 min. The results are shown in Table 20.7.

Table 20.7

Time/min	0	10	20	30	40
Count rate / Counts / min	423	305	219	165	124

The background count rate was 20 counts/min.

(a) Determine the corrected count rates.

(b) Estimate the half-life of the isotope.

Solution

Subtract 20 from each count rate to obtain the corrected count rate.

Table 20.8

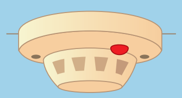
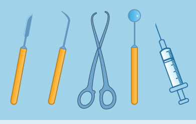
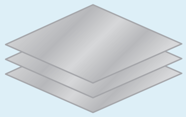
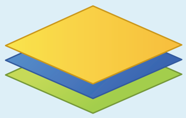
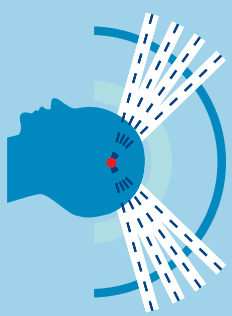
Time/min	0	10	20	30	40
Count rate / Counts / min	403	285	199	145	104

The starting count rate was about 400 counts/min. Half of this quantity is 200 counts/min. From Table 20.8, the count rate falls to this value after about 20 min. So, the half-life is about 20 min.

What are the uses of radioactivity?

Radioactive isotopes have many practical uses. Table 20.9 shows how the half-life and the type of radiation emitted determine which isotope is used for a particular application.

Table 20.9 *Some applications of radioactivity*

Application	How it works	Requirements	
		Type of radiation	Half-life
Household fire (smoke) alarm 	When there are smoke particles, the alarm sound because an ionising current is interrupted.	α-particles have the highest ionising ability and they are easily stopped by smoke particles. Isotope must emit α-particles.	
Irradiating food to kill bacteria 	Radiation penetrates food and kills bacteria.	γ-rays have the highest penetrating ability. Isotope must emit γ-rays.	Long (more than a few years) so that a small quantity can last a long time
Sterilisation of equipment 	γ-rays pass through sealed packages of medical equipment such as dressing, syringes and needles	Isotope must emit γ-rays.	
Measuring and controlling the thickness of materials 	• Radiation passes through continuous roll of materials. • Thickness is indicated by change in count rate.	α-particles cannot be used. They are easily absorbed. Whether to use β-particles or γ-rays depends on the type of material.	
	Thin materials such as paper and plastic film	β-particles can pass through these materials though some will be absorbed. Count rate will depend on thickness. γ-rays pass through too easily to show changes in count rate. Isotope should emit β-particles.	Long so that a small quantity can last for some time
	Materials such as metal plates	β-particles will be completely absorbed. Isotope should emit γ-rays.	
In medicine — diagnosis and treatment of cancer 	For cancer diagnosis, small doses of isotopes that emit γ-rays are taken into the body. Gamma cameras are used to obtain images for diagnosis. For cancer treatment, isotopes are inserted near the cancerous growth. γ-rays damage cancer cells, controlling and even stopping their growth.	Isotope must emit γ-rays.	Short (at most a few hours) so that they will not remain in the body
	Iodine-131 is used to treat thyroid cancer. It emits α-particles that destroy thyroid cells including the cancer cells.	Iodine -131 emits α-particles.	Short, 8 days

ENRICHMENT *ACTIVITY*

Doctors use radioactive isotopes called tracers to identify abnormal body processes. Tracers emit α-particles, β-particles or γ- rays and can be used to follow the path of a single element around the body.

In small groups, discuss and make a list of the advantages and disadvantages of using tracers in medicine. Present your list to the class.

Let's Practise 20.4

1 The *half-life* of a particular radioactive isotope is 15 h. A counter recorded a count rate of 8800 counts/min. It continues to record the count rate for the next 45 h.

(a) What is half-life?

(b) After how long will the count rate be about 4400 counts/min?

(c) What will be the approximate count rate at the end of 45 h?

2 S On a particular day, the background count was 25 counts/min. A student measured the radiation from a radioactive isotope for 20 min. The counter showed the total number of counts as 2800. What was the count rate for the radiation from the isotope?

3 S You need to choose a radioactive isotope for a particular application. Explain the **two** properties you need to consider when making your choice.

4 **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

LINK TWB
Exercise 20D pp. XX–XX

20.5 Safety Precautions

In this section, you will learn the following:

- State the effects of ionising nuclear radiations on living things.
- Describe how radioactive materials are moved, used and stored in a safe way.
- S Explain safety precautions for all ionising radiation.

How does ionising nuclear radiation affect living things?

Ionising nuclear radiation damages living cells. The energy carried by the radiation *can kill cells and cause mutation and cancer* (Figure 20.12).

During World War II, two Japanese cities, Hiroshima and Nagasaki, were exposed to a large amount of ionising nuclear radiation released by atomic bombs. Mutations in the genes of many survivors led to children with disabilities and health problems. The Chernobyl nuclear reactor accident in 1986 caused a large leakage of radioactive dust into the air, which led to health problems in people, livestock and plants.

In more recent times, another nuclear plant disaster had occurred. The Fukushima nuclear plant was destroyed by a tsunami in 2011. The Japanese were once again exposed to nuclear radiation. People had to abandon places contaminated by the radiation (Figure 20.13).

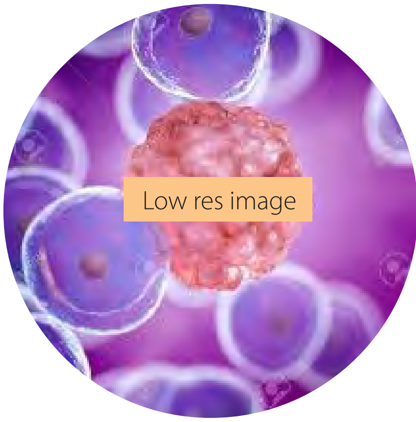


Figure 20.12 *Radiation can cause a healthy cell to become cancerous.*

Figure 20.13 *Radiation hotspot in Kashiwa, Japan*

How do we handle radioactive materials safely?

When using radioactive materials, use gloves and tongs. Wear protective clothing such as lab coats, shoe covers and safety glasses to prevent contamination. When moving a radioactive source, make sure it is in a suitable container to prevent exposure to nuclear radiation. For example, a sample of isotope that emits γ-rays must be stored in a lead box.

All radioactive materials should be kept in sealed and clearly labelled lead boxes. This is to prevent nuclear emissions from escaping into the air. The boxes should be kept in a secure place that is not easily accessible by anyone.

WORD ALERT

Accessible: easily within reach

S What safety precautions can be taken to prevent overexposure to ionising radiation?

Below are three important ways to control exposure to ionising radiation:

- *Reduce exposure time*: For example, complete the experimental setup first before introducing the radioactive source. Carry out experiments involving radioactive materials only in designated locations. These locations should only be used for work that requires the use of ionising radiation.
- *Increase distance between source and living tissue*: The intensity of all ionising radiation decreases with distance. Use long tongs or remote-controlled devices to increase the distance between radioactive materials and your body.
- *Shielding*: Use materials that absorb ionising radiation to protect your body. For example, use lead-lined gloves and suits, and thick concrete walls and lead-lined doors for rooms in which ionising radiation is used.

Let's Practise 20.5

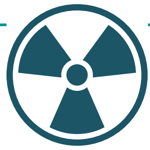
1 State **two** negative effects of ionising nuclear radiations on living things.
2 What kind of box is suitable to store radioactive sources in a safe way?
3 S State **three** ways to control exposure to ionising radiation.
4 **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

TWB LINK

Exercises 20E–20F, pp. XX–XX

Exercise 20G Let's Reflect, p. X

Let's Map It



RADIOACTIVITY

Background radiation from sources including
- radon gas in the air
- rocks and buildings
- food and drink
- cosmic rays

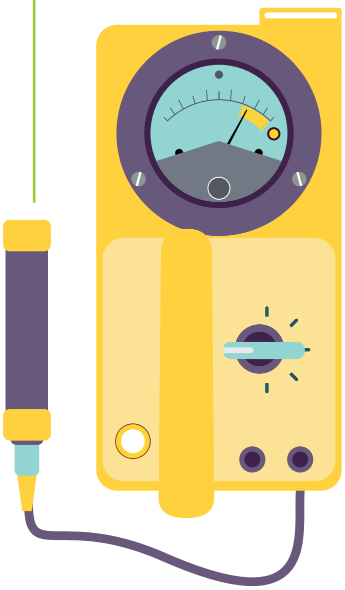
causes

Safety precautions
- Reduce exposure time
- Increase distance from source
- Shield from source

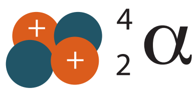
can be measured using

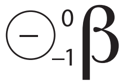
Electronic detector connected to a counter

- Measures count rate in **counts/s** or **counts/min**
- (S) **Corrected count rate** = count rate - background count rate

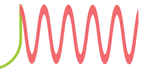


Three types of nuclear emission





- **Alpha (α-) particle:** two protons and two neutrons
- **Beta (β-) particle:** fast-moving electron
- **Gamma (γ-) ray:** electromagnetic radiation



- Spontaneous and random emission
- Relative penetrative power
- (S) Relative ionisation power
- (S) Deflection in electric and magnetic fields

Radioactive decay from unstable nucleus

(S) Decay equations
- **α-decay**

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

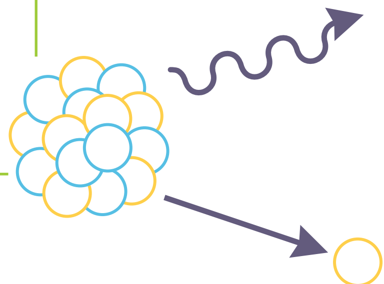
  $^{A}_{Z}X \rightarrow {}_{Z+1}^{A}Y + {}^{0}_{-1}\beta$
- **γ-emission**

  $^{Am}_{Z}X \rightarrow {}^{A}_{Z}X + \gamma$

  Or

  $^{A}_{Z}X^{*} \rightarrow {}^{A}_{Z}X + \gamma$

Half-life
- Time taken for half the nuclei of that isotope in any sample to decay.



Let's Review

Section A: Multiple-choice Questions

1 Background radiation is

A electromagnetic radiation from the Sun.
B microwave radiation from mobile phones and wireless Internet.
C ionising nuclear radiation from radioactive sources left in the laboratory.
D ionising nuclear radiation in the laboratory when there is no radioactive source present.

2 Which atoms in a sample of radioactive isotope will decay first?

A Half the atoms inside the sample
B Atoms that have lost their electrons
C Atoms near the surface because they are exposed to air
D No particular atoms because the process is random

3 Which statement about α-particles is correct?

A They emit gamma rays.
B They travel as electromagnetic waves.
C They are **not** ionising nuclear radiation.
D They are the least penetrating of the nuclear emission.

4 (S) Which statement about γ-emission is correct?

A They are emitted by β-particles.
B They travel at the same speed as visible light in air.
C They travel at the same speed as β-particles emitted by the same nuclei.
D The atomic number of the nucleus increases by one when it emits γ-radiation.

5 A radioactive isotope decays by emitting β-particles. What happens to an atom of the isotope when it decays?

A It gains electrons.
B It loses electrons.
C It becomes a β-particle.
D It changes into another element.

6 (S) The equation represents radioactive decay:

$^{227}_{89}Ac \rightarrow ^{227}_{90}Th + Y$

What does *Y* represent?

A neutron
B α-particle
C β-particle
D γ-emission

7 There is 80 mg of radioactive chemical in a container. The half-life of the radioactive chemical is 5 years. The chemical decays into a stable compound. How much of the chemical is still radioactive at the end of 10 years?

A 8 mg
B 16 mg
C 20 mg
D 40 mg

8 (S) A student was investigating the activity of a radioactive source. When the radiation detector was placed next to the source, the count rate was 750 counts/min. The half-life of the source was 10 min. The background count rate was 30 counts/min. What was the count rate after 20 min?

A 180 counts/min
B 195 counts/min
C 210 counts/min
D 225 counts/min

9 (S) The isotope technetium-99m emits only γ-rays. Its half-life is six hours. It is used for detecting cancer because it

A has a short half-life.
B is a cheap source of γ-rays.
C will emit radiation for only six hours.
D takes about six hours to detect cancer cells.

10 A radioactive chemical decays by emitting β-particles and γ-rays. What type of material should be used for the container?

A lead
B plastic
C cardboard
D aluminium

Let's Review

Section B: Short-answer and Structured Questions

1 In a school laboratory, a student turns on a radiation detector for 20 min. The counter reads 440 counts. There is no radioactive material in the laboratory.

(a) What is the count rate for the radiation?

(b) What are **two** possible sources for the radiation that the detector measures?

(c) What is the name for the radiation?

2 A particular radioactive isotope decays by emitting α-particles. It has a half-life of 430 years.

(a) What is an α-particle?

(b) What does *half-life of 430 years* mean?

(c) Another radioactive isotope decays by emitting β-particles. State **two** ways in which β-particles are different from α-particles.

3 S A radioactive source is placed in a strong electric field. Figure 20.14 shows the path of the emission from the radioactive source.

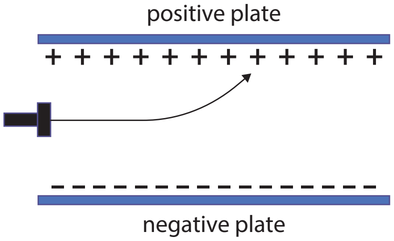


Figure 20.14

(a) Identify the type of emission. Explain your answer.

(b) Complete Figure 20.15 to show the effect on the radiation when the source is placed in a strong magnetic field. The magnetic field is at a right angle to the paper and is going into the paper.

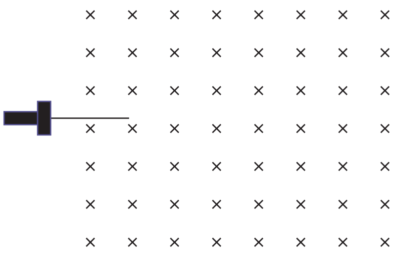


Figure 20.15

(c) Explain why long tongs should be used to pick up the source.

4 S Radioactive cobalt-60, $^{60}_{27}Co$, decays by β-emission to the element nickel (Ni) and emits γ-radiation.

(a) Write down the equation representing this decay.

(b) The half-life of cobalt-60 is 5.3 years. A container contains 16 mg of radioactive cobalt-60. After how many years will the amount of radioactive cobalt-60 be reduced to 1 mg?

5 S The isotope americium-241, $^{241}_{95}Am$, has a half-life of 430 years. It decays to form $^{237}_{93}Np$. It is commonly used in smoke detectors that makes use of ionisation. The alarm sounds when smoke breaks the flow of ions.

(a) What type of radiation does americium-241 emit that makes it suitable for use in smoke detectors? Explain the property that makes it suitable.

(b) Suggest another reason (other than the type of radiation) that makes this isotope a good choice for use in smoke detectors.

(c) In such a smoke detector, a very small quantity of americium-241 is encased in a layer of foil and ceramic. Explain why this will prevent the radiation from harming the user.

CHAPTER 21

Earth and the Solar System

PHYSICS WATCH

Scan this page to watch a clip of how the photo of Earthrise was captured.

QUESTIONS

- Why do you see only half of the Earth?
- Where on the Earth is it daytime and where is it night?
- In which direction is the Sun?
- Why do you think this photograph had a profound effect on people's feelings about the Earth? How does it affect you?

In 1968, Apollo 8 left the Earth and went into orbit round the Moon before returning to Earth. It was the first spacecraft to do so while carrying astronauts. The three crew members were looking for a future landing site on the Moon. They were photographing the brown-grey moon rocks when they noticed the Earth coming into view at another window of the spacecraft. Bill Anders, one of the astronauts, took a colour photo which is now known as 'Earthrise'. The photo had a profound effect on people's feelings about the Earth at that time.

21.1 The Earth

In this section, you will learn the following:

- Know that the Earth is a planet that rotates on its tilted axis once in about 24 hours. Use this to explain observations of the apparent daily motion of the Sun and the periodic cycle of day and night.
- Know that the Earth orbits the Sun once in about 365 days. Use this to explain the periodic nature of the seasons.
- Know that the Moon takes about one month to orbit the Earth. Use this to explain the Moon's phases.
- S Define *average orbital speed* and use the equation $v = \frac{2\pi r}{T}$.

How does the Earth move?

The Earth is a **planet**. Planets orbit a star. Our star is the Sun.

The Earth takes about 365 days or one **year** to orbit the Sun. Every time you celebrate your birthday, you have travelled one more time around the Sun! How many times have you travelled around the Sun?

The Earth also rotates on its axis and it takes about 24 hours or one **day** *to rotate once*. The Earth's *axis is tilted* at an angle of about 23.5 degrees towards the plane of its orbit.

ENRICHMENT INFO

Leap Years

Our calendars have 365 days in a year. The Earth takes closer to 365 days and six hours to travel once around the Sun. In four years, the difference between the orbit time and calendar time adds up to 24 hours. So, in every four years, an extra day is added to the calendar making a leap year. In a leap year, February has 29 days instead of 28 days.

How does day and night come about?

Stars produce energy by nuclear fusion and give out light so they shine brightly. A planet only shines when the light from a star lands on it.

The Sun shines on the half of the Earth that is facing it. This half experiences daytime. The other half is in darkness, which experiences night-time. In 24 hours, the Earth spins once and we move from the light into darkness and back into the light again.

On the Earth, we see the Sun move across the sky from East to West. This apparent movement is because the Earth is spinning about its axis as it orbits the Sun.

WORD ALERT

Apparent: can be observed

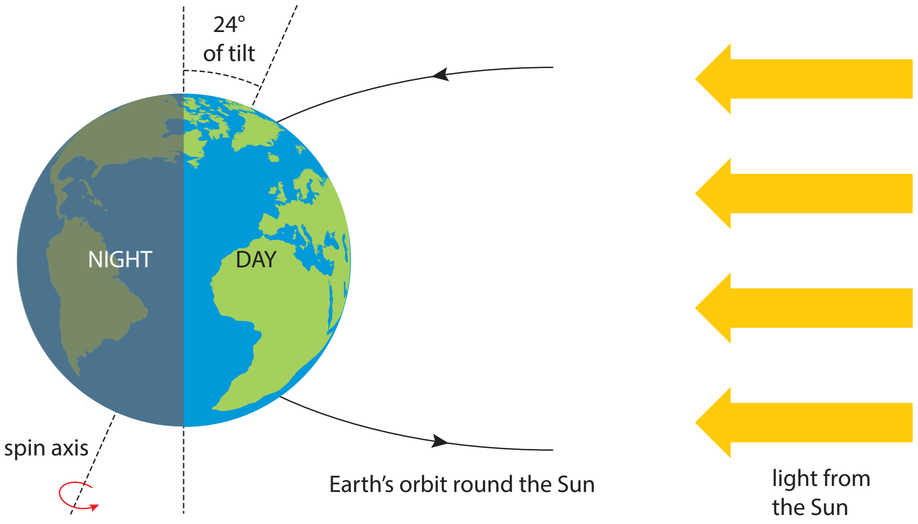


Figure 21.1 *The day and night cycle is due to the Earth's rotation about its tilted axis.*

What is a season?

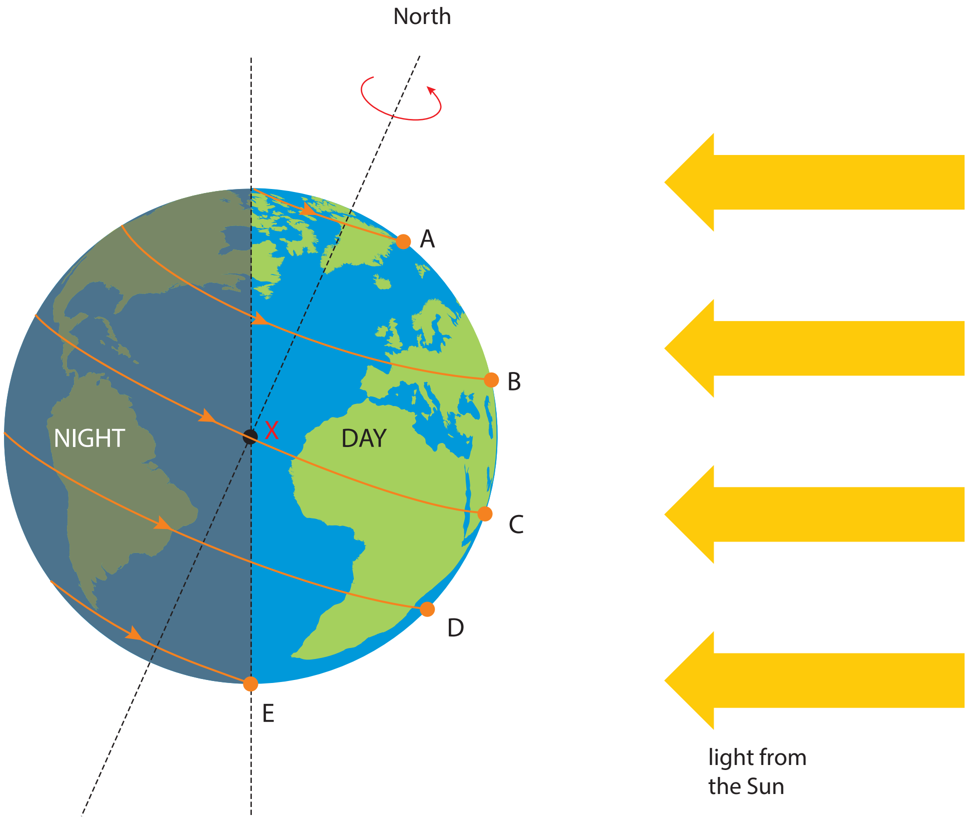
Temperate countries have different weather patterns at different times of the year. These weather patterns are called **seasons**. There are four seasons every year — spring, summer, autumn and winter.

Seasons occur because the Earth orbits the Sun on a tilt. At different times of the year, places on the Earth receive different amounts of the Sun's rays.

Figure 21.2 shows how the tilt of the Earth's axis affects the periods of daytime and night-time. Here, the North Pole is tilted directly towards the Sun.

WORD ALERT

Temperate: having moderate climate, experienced by countries between the tropics and the polar regions of the Earth



QUICK CHECK

Refer to Figure 21.2.

Point X is experiencing dawn. Night has just ended and daytime is starting.

True or false?

A is at the Arctic Circle. Places north of this circle will be in daylight for 24 hours and the Sun never sets.

B is in the temperate zone between **A** and **C**. Places here have longer days and shorter nights.

C is on the Equator. Places around the Equator have equal periods of daytime and night-time.

D is in the temperate zone between **C** and **E**. Places here have shorter days and longer nights.

E is at the Antarctic Circle. Places south of this circle will be in darkness for 24 hours and the Sun never rises.

Figure 21.2 *The tilt of the Earth's axis causes different parts of the Earth to have different lengths of daytime and night-time.*

Figure 21.3 shows the Earth in its orbit at different times of the year and the corresponding seasons for the Northern Hemisphere.

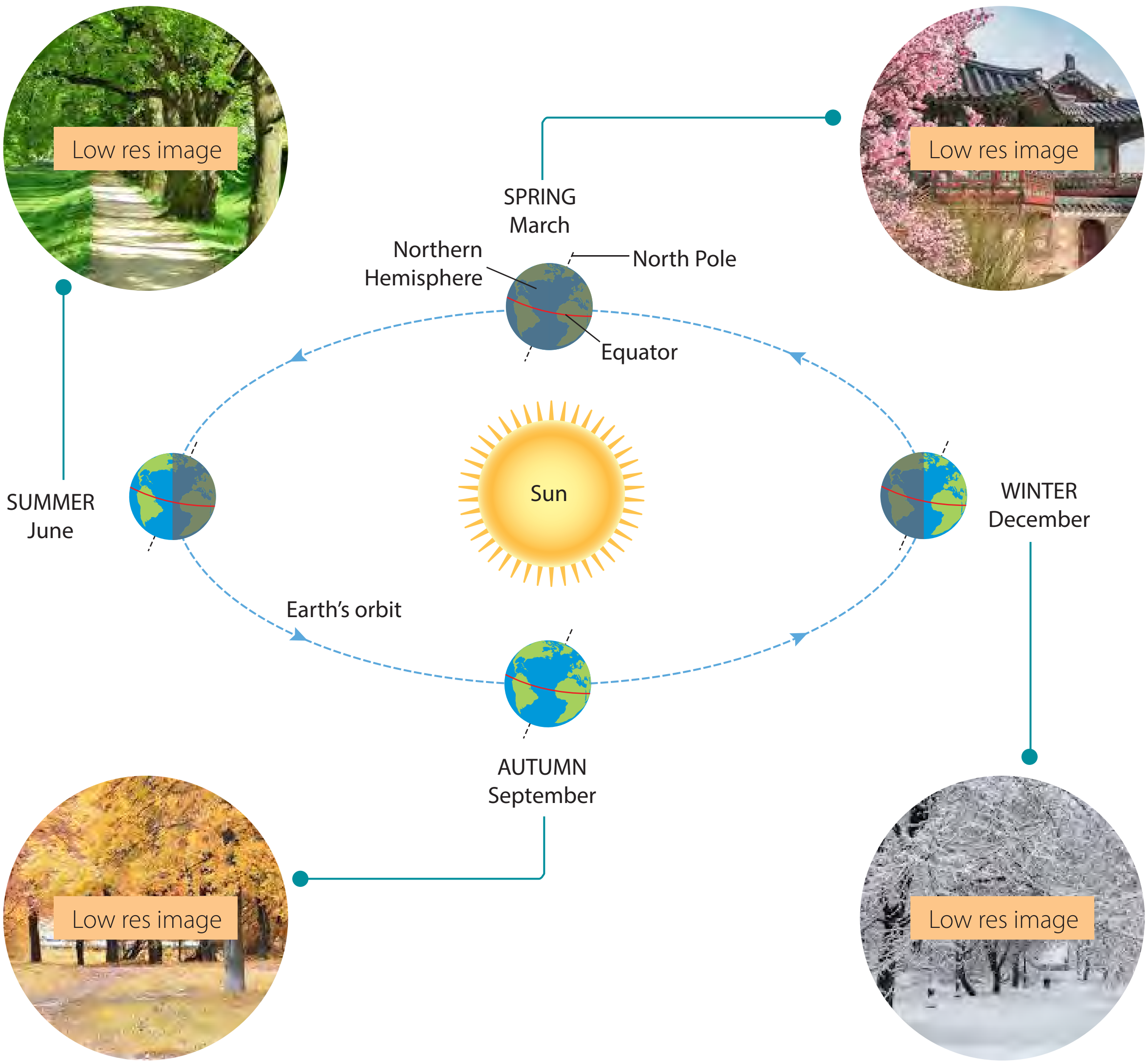


Figure 21.3 *The seasons in the Northern Hemisphere (not to scale).*

ENRICHMENT ACTIVITY

Figure 21.3 is certainly not drawn to scale. Try this to see why!

Earth's radius = 6×10^6 m
Sun's radius = 7×10^8 m

Radius of Earth's orbit = 1.5×10^{11} m

If the Sun's radius was reduced to 5mm, what would the distance between the Sun and the Earth be to the same scale? On this same scale, what would the Earth's radius be?

In the months around June, the tilt of the North Pole is towards the Sun. As shown in Figure 21.3, the Northern Hemisphere, above the Equator, will have long days and short nights. It is hotter because the Sun rises higher in the sky and there are more hours of sunshine. This is the summer season.

As the orbit continues, the Earth's axis no longer tilts towards the Sun. In September, the Northern Hemisphere is tilted in the direction of travel. The days gradually become shorter and the nights longer. Shorter days mean cooler temperatures, and it is autumn.

Around December, the tilt of the North Pole will be away from the Sun. In the Northern Hemisphere, the days will be shortest and the nights longest. Fewer hours of sunlight and the Sun rises lower in the sky means it will be colder. This is winter.

In March, the Northern Hemisphere is tilted in the direction of travel again. The days gradually become longer and the nights shorter. The land will be warming up again as spring arrives.

QUICK CHECK

Look at the Southern Hemisphere in Figure 21.3. It will be winter in June and summer in December.

True or false?

How does the Sun appear to move during the day?

Remember that the Sun appears to move across the sky because the Earth is spinning about its axis as it orbits the Sun. The Earth spins from West to East, so the Sun appears to rise in the East and set in the West.

At the Equator, the Sun always rises due east and sets due west, so the days and nights are always 12 hours long. The Sun is almost directly overhead at midday all year. Places near the Equator have little seasonal change because the Sun's position in the sky does not change very much all year.

In the Northern Hemisphere, the Sun's path across the sky is longer in summer than in winter. Also, the Sun rises higher in the sky in summer than in winter.

Light from the Sun is more intense when it is higher in the sky as the rays spread over a smaller area of the Earth.

Figure 21.4 shows the apparent motion of the Sun in the sky for Manchester in the UK. Manchester is about 53 degrees north of the Equator. On the longest day of the year, June 21st, there is 17 hours between sunrise and sunset. On the shortest day, December 21st, there is only 7.5 hours of daylight.

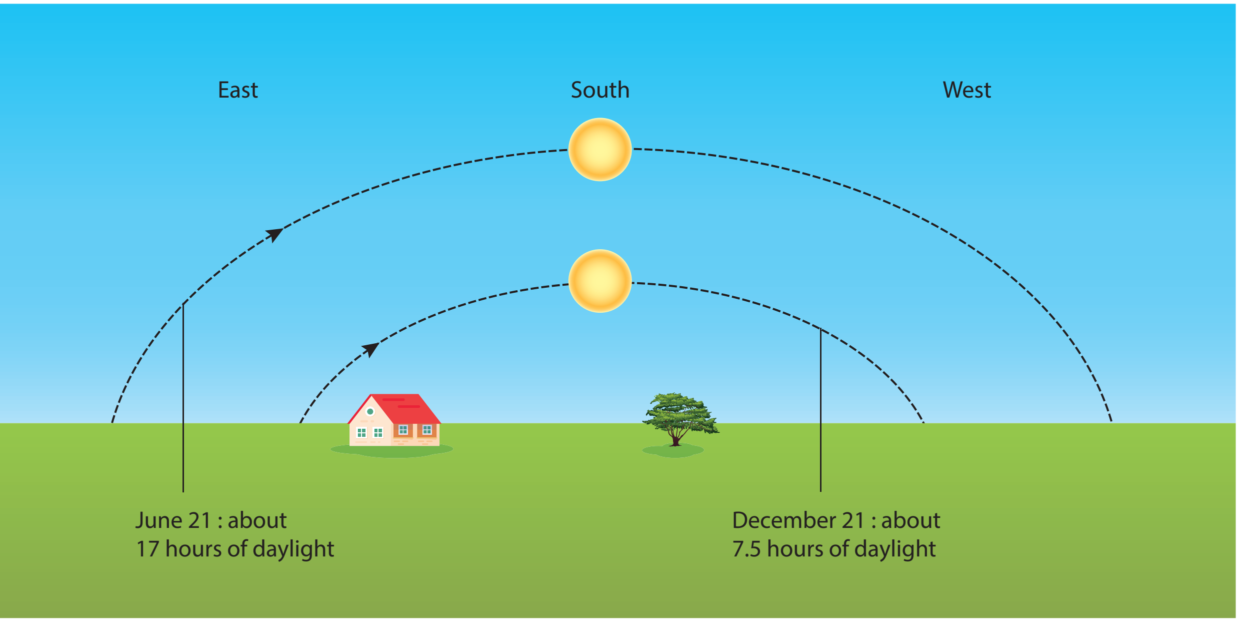


Figure 21.4 *The Sun's apparent movement across the sky 53 degrees north of the Equator.*

Why does the Moon's appearance change?

Some planets have *natural satellites* or *moons* that orbit them as they orbit the Sun. The Earth has one natural satellite called the **Moon**. Like the planets, moons do not give out light. We only see the Moon's surface when light is reflected back from it.

The Moon takes approximately 28 days to orbit the Earth once. It orbits the Earth with the same side facing the Earth as it travels round.

HELPFUL NOTES

You must **never** look directly at the Sun. A glass lens can focus the Sun's rays to set fire to paper. Your eye lens would focus the Sun's energy onto the light sensitive cells of your eye and damage them.

PHYSICS WATCH

Scan this page to watch how the Sun appears to move across the sky. They are taken at the same place on the longest day and the shortest day.

What differences do you expect to see?

QUICK CHECK

The Sun moves across the sky in the daytime because it is orbiting around the Earth.

True or False?

ENRICHMENT *ACTIVITY*

Make a record of the Moon's appearance. Observe the Moon every day for 28 days. Note the date and the time you made the observation. Draw a circle to represent the Moon and shade in the dark part to record its appearance. Use Figure 21.5 on page 352 to show where the Moon is in its orbit round the Earth.

ENRICHMENT INFO

The Sun is about 400 times further from the Earth than the Moon. The Sun's diameter is about 400 times greater than the Moon's. So, the Sun and Moon appear to be the same size in the sky.

Occasionally, for some places on Earth, a new Moon coincides exactly with the Sun. The Moon completely blocks out the Sun. This is called a *total eclipse*. The Sun disappears and daytime turns to night-time for a few minutes.

The appearance of the Moon in the sky changes from day to day. This depends on the Moon's position relative to the Sun and the Earth. The different appearances are known as the **phases of the Moon**.

Study Figure 21.5. The Earth, with the Moon at different positions in its orbit (inner circle), is shown as viewed *from above the North Pole*. The Moon is also shown as how it appears *from the Earth* at those different positions (outer circle).

One half of the Moon is in sunlight, so the Moon is always half-illuminated. When the Moon is in position 1, the bright half of the Moon is facing the Earth. On the Earth, you would see a bright round **full Moon** in the sky at night.

As the Moon continues its orbit, less and less of the bright half of the Moon is facing the Earth, and more and more of the dark side of the Moon is seen. Positions 2, 3 and 4 in Figure 21.5 shows how the Moon appears from Earth as the bright part is getting smaller or **waning**.

In position 5, the dark side of the Moon is facing the Earth. This is called the **new Moon**. It is only illuminated by a little light reflected from the Earth. This occurs in daytime so the new Moon is not visible.

In the rest of its orbit, more and more of the bright part of the Moon can be seen from the Earth. The Moon is said to be **waxing**.

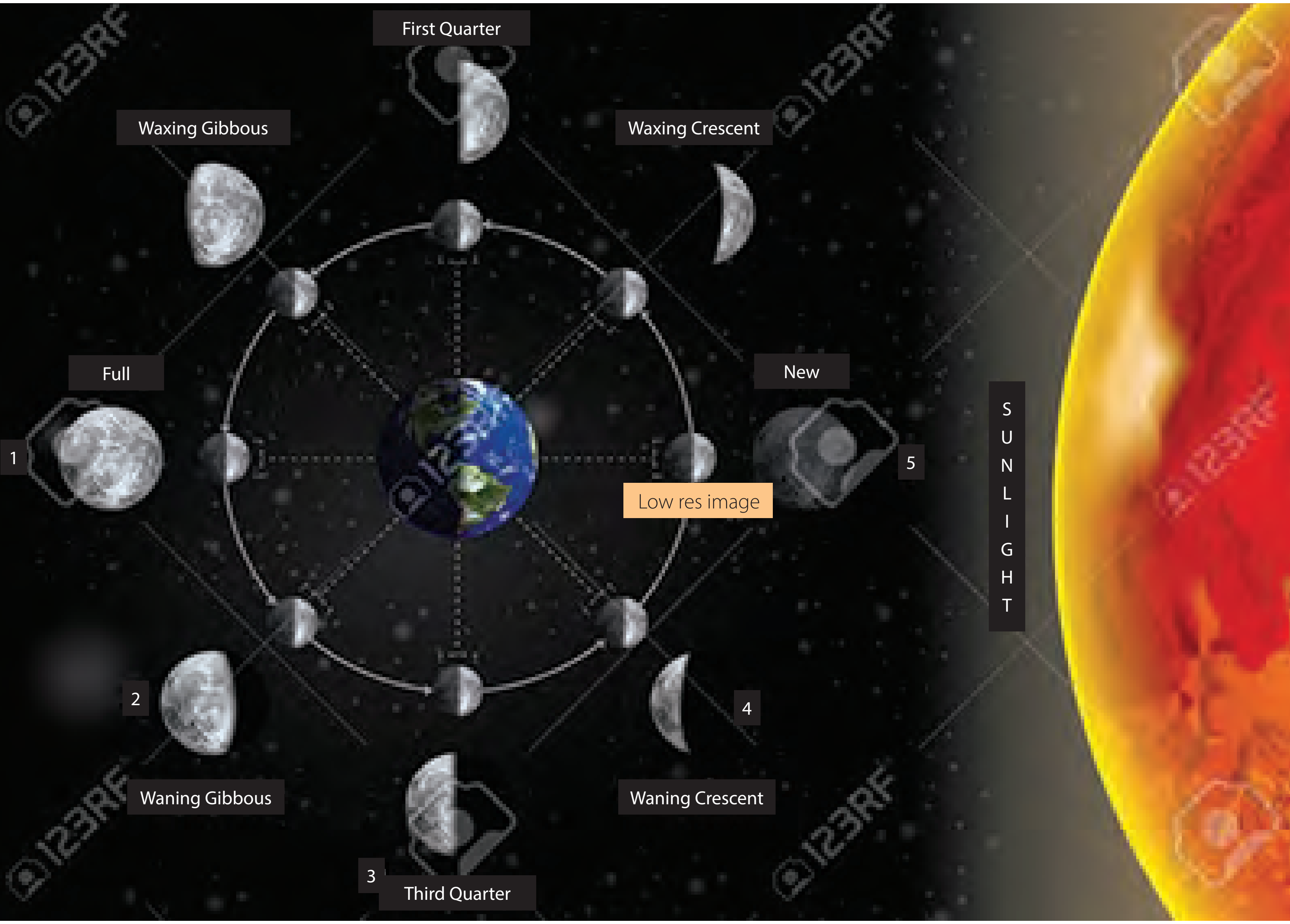


Figure 21.5 *The phases of the Moon (not to scale).*

How quickly is the Moon orbiting the Earth?

Remember that speed is distance travelled per unit time and average speed is given by the equation:

$v = \frac{s}{t}$ where v = average speed (in m/s)

s = total distance travelled (in m)

t = total time taken (in s)

For a circular orbit, the total distance for one orbit would be the circumference of a circle.

Circumference = $2\pi r$ where r = average orbital radius

The Moon's orbit around the Earth is a slightly squashed circle called an *ellipse*.

But if we use the average radius of the orbit, we can use the following equation for the **average orbital speed**:

$\mathbf{v = \frac{2\pi r}{T}}$ where v = average orbital speed (in m/s)

r = average orbital radius

T = orbital period

Worked Example 21A

It takes 27.3 days for the Moon to travel once around the Earth. The average radius of the Moon's orbit is 385 000 km. Calculate the average orbital speed of the Moon.

Solution

First, we must convert the units.

Average radius = 385 000 km = 3.85×10^8 m

Orbital period = $27.3 \times 24 \times 60 \times 60 = 2.36 \times 10^6$ s

Average orbital speed = $\frac{2\pi r}{T} = \frac{2(3.85 \times 10^8)}{2.36 \times 10^6} = 1.03 \times 10^3$ m/s

> **LINK**
>
> Recall what you have learnt in Chapter 2 about speed and average speed.

Let's Practise 21.1

1 Choose from the words below to complete the sentences.

natural satellite *planet* *star*

The Earth is a ________ which orbits a ________ called the Sun.
The Moon is a ________ of the Earth.

2 State how many times the Earth spins on its axis every year.

3 Which is the correct reason for the Sun's apparent movement across the sky every day?

A The Sun's rotation about its axis.

B The Earth's rotation about its axis.

C The Sun's rotation around the Earth.

D The Earth's rotation around the Sun.

4 State whether each of these statements is true or false.

(a) A new Moon occurs when the dark side of the Moon faces the Earth.

(b) A full Moon occurs when the dark side of the Moon faces the Earth.

(c) A first quarter Moon occurs when half of the bright side is seen and this part is decreasing.

(d) A waxing crescent Moon occurs when a sliver of the bright side is seen and this part is increasing.

> **WORD ALERT**
>
> **Sliver:** small, thin and narrow part of something

LINK TWB
Exercise 21A, pp. XX–XX

5 Ⓢ The International Space Station orbits the Earth 410 km above its surface. It takes 92 minutes to complete one orbit. Work out its average orbital speed in m/s. (Take the radius of the Earth to be 6 400 km.)

6 **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

21.2 The Solar System

In this section, you will learn the following:

- Describe the Solar System.
- Know the physical difference between the four planets nearest to the Sun and the four planets furthest from the Sun. Explain this difference.
- Know what affects the strength of a planet's gravitational field.
- Know that planets orbit the Sun due to the mass of the Sun.
- Know that the Sun's gravitational attraction keeps an object in orbit around the Sun.
- Calculate the time it takes for light to travel between objects in the Solar System.
- Ⓢ Know that planets, minor planets and comets have elliptical orbits and that the Sun is not at the centre except when the orbit is nearly circular.
- Ⓢ Know that an object in an elliptical orbit travels faster when closer to the Sun and explain this using the conservation of energy.
- Ⓢ Analyse and interpret planetary data.
- Ⓢ Know how the Sun's gravitational field decreases with distance and how this affects the orbital speed of the planets.

How was the Solar System formed?

The Earth, Sun and Moon are part of our Solar System. Figure 21.6 shows the main known objects lined up. The diagram is certainly not to scale — most of the Solar System is empty space.

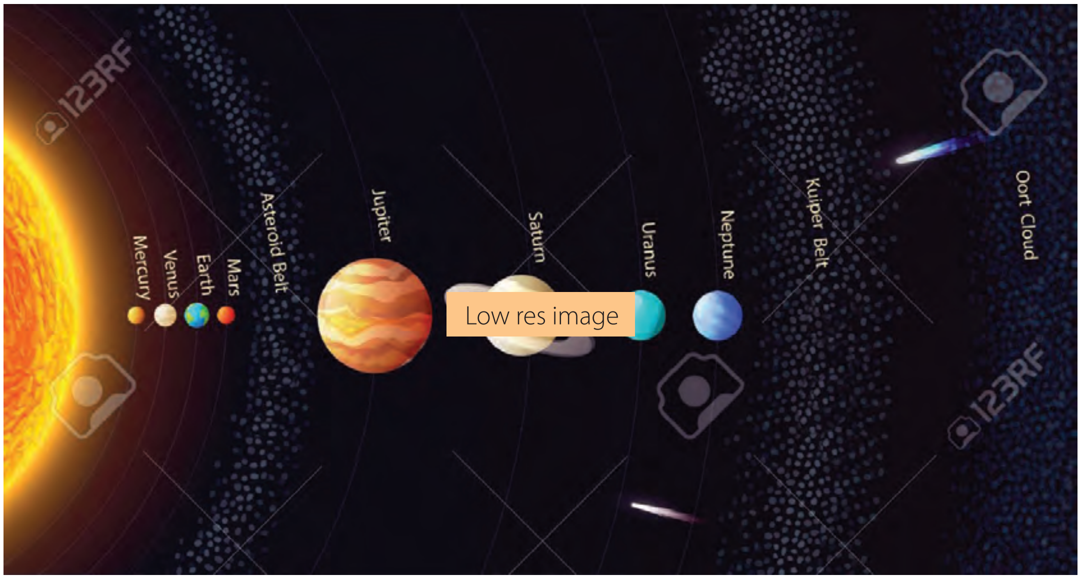
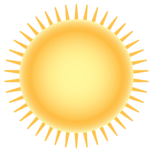


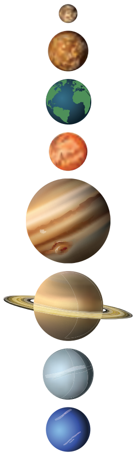
Figure 21.6 Diagram showing the main objects in our Solar System

Table 21.1 gives more information about the main objects in our Solar System.

Table 21.1 *Main objects in our Solar System*



One star called the **Sun** is at the centre of our Solar System.

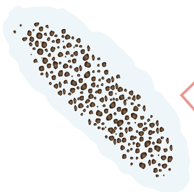


Eight **planets** orbit the Sun.

- In order of their distance from the Sun, these are called Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus and Neptune.
- Mercury, Venus, Earth and Mars are smaller rocky planets. Jupiter, Saturn, Uranus and Neptune are larger planets made from gas and ice.

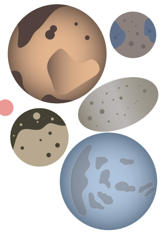
Most of the eight planets have one or several moons. A **moon** is a natural satellite which orbits a planet. The Earth has just one moon. Saturn has over 50 moons.

The **asteroid belt** between Mars and Jupiter contains many asteroids. Ceres is the only object in the asteroid belt which is large enough to be classified as a dwarf planet.

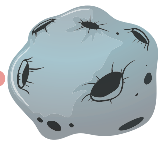


The **Oort cloud** is thought to contain icy rocks and dwarf planets like the Kuiper belt. It is also home to comets with orbit times longer than 200 years.

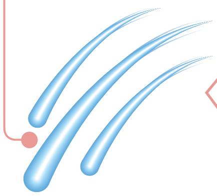
Other objects in the Solar System that orbit the Sun are **minor planets** which include:



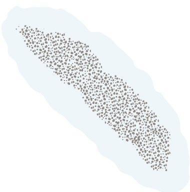
Dwarf planets — these are less massive than the eight planets but are also almost spherical. Their gravity is not enough to attract nearby matter, so there may be other objects in their orbit. Pluto is a dwarf planet in the Kuiper belt with a very elliptical orbit.



Asteroids — these are irregularly shaped lumps of rock left over from the formation of the Solar System. Asteroids have elliptical orbits.



Comets — these are lumps of frozen gases and dust left over from the birth of the Solar System and they have very elliptical orbits.



The **Kuiper belt** beyond Neptune contains more leftovers from Solar System. It has asteroids and other dwarf planets as well as Pluto. Comets with orbit times of less than 200 years, such as Halley's comet, originate here.

About 4.6 billion years ago, the Solar System was formed from a swirling cloud of gas and dust in space. These clouds called **nebulae** consist of mainly hydrogen plus a mixture of heavier elements. The particles in the cloud were attracted to each other because of the force of gravity between them.

Gradually, the cloud began to collapse which made it spin faster. Gravitational potential energy became kinetic energy as the particles began to move. Then kinetic energy became heat energy as they crashed together. A hot spinning mass called a **protostar** was formed at the centre of a swirling disc of gas and dust. The swirling disc is called an **accretion disc**.

Accretion is the accumulation of particles into a massive object by gravitational attraction.

Eventually, the protostar became dense and hot enough for nuclear fusion to occur at its centre. It became a star — the Sun — and began to give out an enormous amount of energy.

ENRICHMENT *INFO*

Pluto

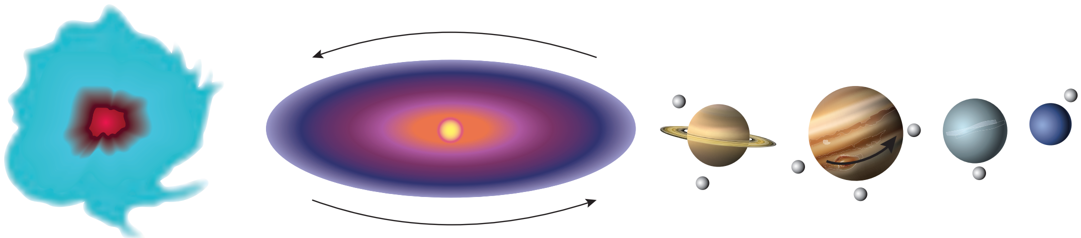
Pluto was discovered in 1930 and declared to be the ninth planet of the Solar System. After 1992, it was found to be less massive than previously thought, so it was reclassified as a dwarf planet.

LINK

Recall what you have learnt in Chapter 3 about gravity.

Recall what you have learnt in Chapter 6 about gravitational potential energy and kinetic energy.

The matter in the spinning disc also gradually clumped together to become the rest of the Solar System. The four rocky planets formed from heavier material that was pulled near the Sun by its force of gravity. Lighter gases collected further away, forming the four gas giants.



▲ A cloud of dust and gas, a **nebula**, is pulled inwards by the force of gravity.

▲ A protostar is formed at the centre with a disc of gas and dust swirling round it.

▲ The central mass becomes a star. Matter in the disc collects to form the planets, moons and asteroids.

Figure 21.7 *The stages in the birth of the Solar System.*

WORD ALERT

Nebula: singular of nebulae

What determines gravitational field strength?

Particles of gas and dust are small and have little mass. So their gravitational field strength is small and the force of attraction is weak. As they clump together, the mass and the gravitational field strength will increase. It will attract other particles with more force. The process is very slow at first but gradually speeds up. It takes millions of years for a cloud of dust and gas to form a Solar System.

The Sun contains 99% of the matter in the Solar System, so its gravitational field is very strong. This is why it pulls the planets into orbit around it and they do not fly off into space. The gravitational field strengths of the planets are much weaker in comparison because they have much less mass.

Gravitational fields around the Sun and the planets extend into space. The further away the distance from the Sun or the planets, the weaker the gravitational field becomes.

LINK

The speed of light is 3×10^8 m/s. At what speed do radio waves travel in space?

Recall what you have learnt in Chapter 13 about electromagnetic waves.

How big is the Solar System?

In 1977, the US space agency NASA launched two unmanned space craft from the Earth. In 1989, one of these, called Voyager 2, arrived close to Neptune, the furthest planet from the Sun (Figure 21.8). It sent pictures of Neptune back to Earth using radio signals. Radio signals are carried by radio waves that are electromagnetic waves and travel at the fastest speed possible. How long do you think it took the signals to get back to Earth? See Worked Example 21B.

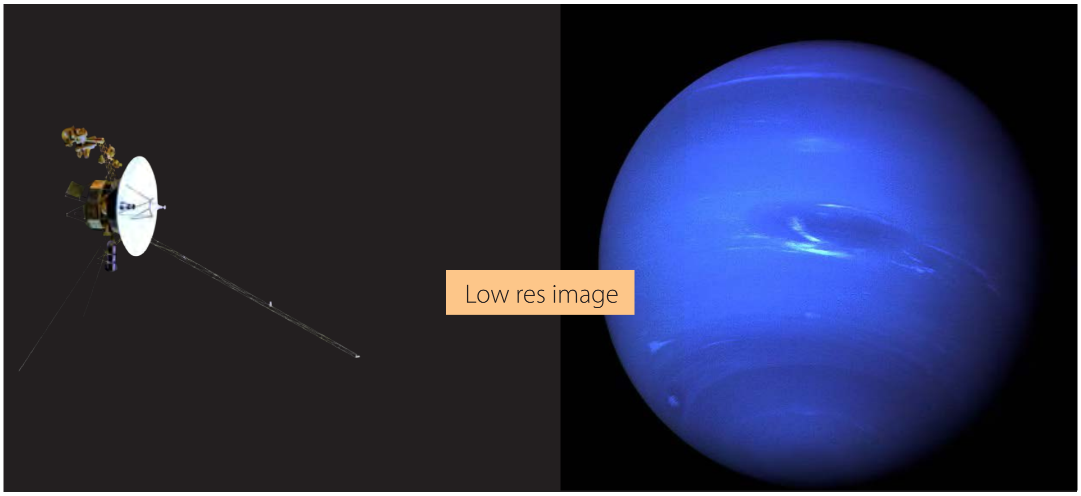


Figure 21.8 *Voyager 2's encounter with Neptune*

Worked Example 21B

When Voyager 2 was close to Neptune, it was about 4.5×10^9 km from the Earth. It sent radio signals back to Earth. Calculate how long it took the signals to reach the Earth.

Solution

First, we must rearrange the equation for speed: $v = \frac{s}{t}$

$t = \frac{s}{v}$

Distance = 4.5×10^9 km = 4.5×10^{12} m

Speed = 3×10^8 m/s

$\therefore$ Time $t = \frac{4.5 \times 10^{12}\ \text{m}}{3 \times 10^8\ \text{m/s}} = 15\ 000$ s = 4.2 h

What are the shapes of orbits?

Long ago, astronomers thought that all orbits were perfect circles. Detailed observations and measurements showed that objects in the Solar System move in an **elliptical orbit**. Remember that the Moon's orbit round the Earth is slightly elliptical — like a squashed circle. The eight planets also have slightly elliptical orbits with the Sun near the centre. Some minor planets and moons have orbits that are more elliptical. Figure 21.9 shows how the shape of an ellipse is obtained using two foci.

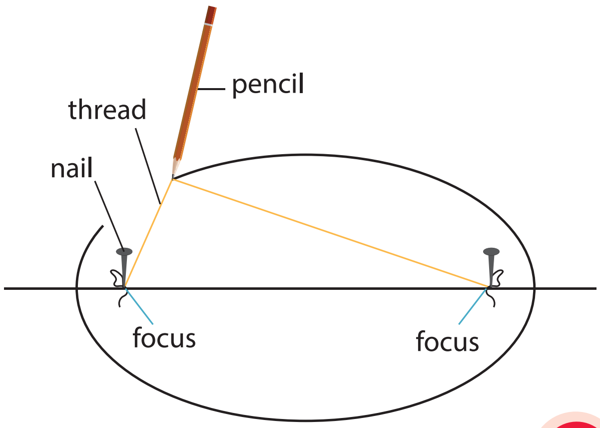


Figure 21.9 *Ellipse showing the two foci*

Comets have very elliptical orbits. The Sun is not at the centre of the ellipse but at one focus. Comets are lumps of frozen gases and dust left over from the birth of the Solar System. They come from either the Kuiper belt or the Oort cloud, and they orbit the Sun.

When a comet is furthest from the Sun, it travels very slowly (Figure 20.10). Here, its kinetic energy is the lowest. The Sun's gravitational field pulls the comet towards it, so the comet speeds up. The gravitational force is greatest nearest the Sun. Here, the comet moves the fastest and its kinetic energy is the greatest. It starts to slow down as it moves away from the Sun again.

By the principle of conservation of energy, kinetic energy changes into gravitational potential energy as the comet moves away from the Sun. Gravitational potential energy changes back to kinetic energy as it moves towards the Sun.

Also the increased heat energy near the Sun causes some of the comet's frozen gas to evaporate. This creates a long bright tail streaming away from the direction of the Sun, making the comet visible. The bright tail disappears as it moves away again.

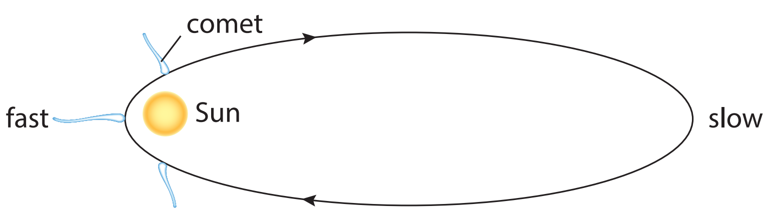


Figure 21.10 *Some stages in the path of a comet round the Sun*

WORD ALERT

Foci: centres, points, pivots

Focus: singular of foci

QUICK CHECK

A comet has the greatest gravitational potential energy when it is closest to the Sun. It has the least gravitational potential energy when it is furthest away from the Sun.

True or false?

Figure 21.11 Halley's comet

Perhaps the most famous comet is Halley's comet (Figure 21.11). It was first recorded by Chinese astronomers in 239 BC and is visible from the Earth for a short time every 79 years. Halley's comet orbits the Sun in the opposite direction to the planets.

What determines the orbital speed of the planets?

Table 21.2 shows some data from NASA about the eight planets.

Table 21.2 *Data about the eight planets of the Solar System from NASA*

	Average distance from the Sun/ millions of km	Approx. mass compared with the Earth	Approx. density/ kg/m³	Gravitational field strength compared with the Earth	Time to spin in Earth days	Time to orbit in Earth years	Approx. range of surface temps/°C
Mercury	58	0.05	5400	0.4	180	0.2	–170 to 450
Venus	110	0.8	5200	0.9	120	0.6	465
Earth	150	1	5500	1	1	1	–89 to 58
Mars	230	0.1	3300	0.4	1	2	–125 to 20
Jupiter	780	320	1300	2.4	0.4	12	–110
Saturn	1400	95	680	0.9	0.4	30	–140
Uranus	2900	15	1300	0.9	0.7	84	–195
Neptune	4500	17	1600	1.1	0.7	164	–200

S

Look at the columns of the distance from the Sun and the time to orbit. Can you see a pattern between them?

As the distance from the Sun increases, the time to orbit the Sun also increases. Nearer to the Sun, the gravitational field is stronger. The force on the inner planets pulls them into a tighter circle. They have a greater speed and have less distance to travel, so the time to orbit is much less.

ENRICHMENT
THINK

Would humans be able to survive on any other planet apart from the Earth. If no, why? If yes, what would they need from the Earth? What other information about the planets will you need to find out?

Let's Practise 21.2

1 **(a)** List the eight planets of our Solar System in order of increasing distance from the Sun.
  (b) What is the difference between the nature of the four planets nearest the Sun compared with the four furthest away?

2 State the energy conversions that take place when the material in a cloud of dust and gas clumps together.

3 Explain what is meant by the following terms:
  (a) moon **(b)** asteroid **(c)** protostar

4 The Sun is 150 million kilometres from the Earth. Work out how long it takes the light from the Sun to reach the Earth. (The speed of light in a vacuum is 3×10^8 m/s.)

5 S Use Table 21.2 to answer the following questions.
  (a) What is unusual about the temperature on Venus?
  (b) Which planet has a gravitational field strength similar to the Earth's?
  (c) Which planet is the most massive?
  (d) Which planet takes the longest to spin on its axis?
  (e) The asteroid belt lies between Mars and Jupiter. Estimate the time in Earth years for an asteroid in this belt to orbit the Sun.

6 **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

LINK TWB

Exercises 21B–21C, pp. XX–XX

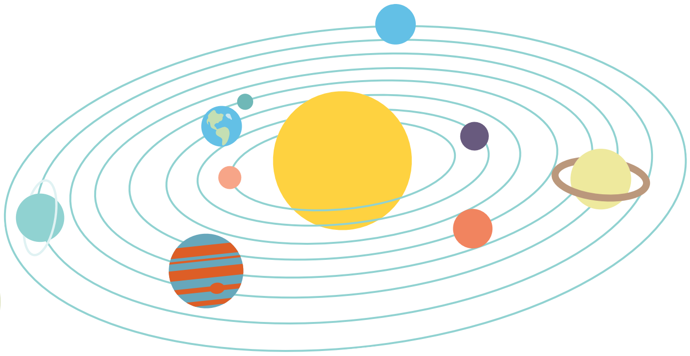
Exercise 21D Let's Reflect, p. XXX

Let's Map It

Cloud of dust and gas
- Mainly hydrogen and helium plus assorted heavier elements

the force of gravity causes matter to collect together—accretion—to form

SOLAR SYSTEM



Ⓢ Gravitational field strength
- Increases with mass
- Decreases with distance from planet

consists of

Main planets
- Mercury
- Venus
- Earth
- Mars

(rocky and small)

- Jupiter
- Saturn
- Uranus
- Neptune

(gaseous and large)

The Sun
- A star
- Massive size produces strong gravitational field
- Gives out energy

- Dwarf planets
- Moons
- Asteroids
- Comets

The Earth
- Spins once every 24 hours to give **night and day**
- Orbits the Sun every year (~365 days) on its tilted axis to give **seasons**

The Moon
- Earth's natural satellite
- Orbits the Earth every 27 days
- Appearance changes with position in orbit **(Moon phases)**

Orbits
- Kept in orbit by the Sun's gravitational attraction
- Ⓢ Elliptical orbit with the Sun at one focus
- Ⓢ Orbital speed $v = \frac{2\pi r}{T}$
- Time to orbit increases as distance from the Sun increases

Let's Review

Section A: Multiple-choice Questions

1 Which statement is incorrect?
  A The Moon is a natural satellite of the Earth.
  B The Earth spins on its axis once a year.
  C The Sun is the star at the centre of the Solar System.
  D The Solar System was produced from a cloud of dust and gas.

2 **S** An astronaut goes to Mars where the gravitational field strength is 40% of that of the Earth. Which statement correctly describes his mass and weight on Mars compared with the Earth?
  A Same mass and same weight
  B Smaller mass and same weight
  C Same mass and smaller weight
  D Smaller mass and smaller weight

Section B: Short-answer and Structured Questions

1 Explain why half of the Earth has 12 hours of night-time followed by 12 hours of daytime.

2 Choose the correct word to complete the sentences below which describe the seasons.
In December, the South Pole of the Earth is tilted ______________ (*towards/away from*) the Sun. The temperate countries in the ______________ (*Northern/ Southern*) Hemisphere will have long days and short nights. The ________________ (*Arctic/Antarctic*) Circle will have 24 hours of daytime. In the Northern Hemisphere, it is _________________ (*summer/winter*).

3 **(a)** Draw a diagram to show how the Sun, Earth and Moon are positioned when a full Moon is seen.
(b) Assuming that the Moon takes exactly 28 days to orbit the Earth. Describe the appearance of the Moon
  (i) 7 days;
  (ii) 14 days;
  (iii) 21 days
  after the full Moon.

4 **S** Figure 21.12 shows three stages in the formation of our Solar System. Explain what is happening in each stage.

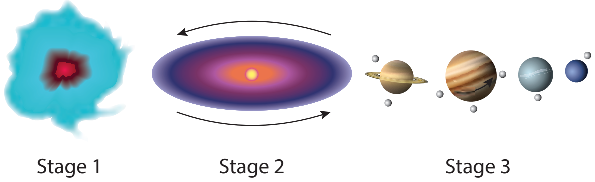


Figure 21.12

5 **S** Figure 21.13 shows the orbit of a comet around the Sun.

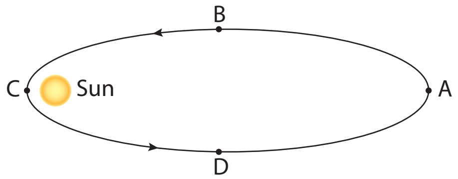


Figure 21.13

(a) Explain what a comet is.
(b) Give the name of this shape of orbit.
(c) At which point in the orbit is the comet travelling slowest?
(d) At which point in the orbit does the comet have the most kinetic energy. Explain your answer.
(e) At which point in the orbit is the comet's energy changing from kinetic energy to gravitational potential energy.
(f) Halley's comet orbits the Sun every 79 years. Give **two** reasons why it is only visible from the Earth for a few days each orbit.

6 **S** Geostationary satellites are used to transmit communication signals from one continent to another. They orbit above the same place on the equator.
(a) Explain why their orbit time must be 24 hours.
(b) These satellites orbit at a height of 36 000 km above the surface of the Earth. Work out their average orbital speed.
(Take the radius of the Earth to be 6 400 km.)

CHAPTER

22 Stars and the Universe

Credit: NASA, ESA, and T. Brown (STScI), W. Clarkson (University of Michigan-Dearborn), and A. Calamida and K. Sahu (STScI)

PHYSICS WATCH

Scan this page to watch a clip about the Hubble telescope and its contribution to astronomy.

Nancy Roman was interested in astronomy from an early age. Her mother used to take her out at night and teach her the constellations. When she became NASA's first chief of astronomy, she campaigned for a telescope to be launched into space in order to see the Universe more clearly. The Hubble space telescope was launched in 1990. Roman is called the 'mother of Hubble.'

The photo shows clusters of stars captured by the Hubble space telescope using its wide field camera. China, one of the Asian space powers, is planning to launch its own space telescope. It will have a much wider field of view than the Hubble telescope and will enable us to see more spectacular images of stars that we have never seen before.

QUESTIONS

- Why should the Hubble space telescope see space more clearly than a telescope on Earth?
- What differences can you observe in the appearance of the stars?
- How does this image compare with the stars that you can see at night from where you live?

22.1 The Sun as a Star

In this section, you will learn the following:

- Know that the Sun is a medium-sized star, consisting mostly of hydrogen and helium.
- Know that the Sun radiates most of its energy in the infrared, visible and ultraviolet regions of the electromagnetic spectrum.
- S Know that stars are powered by nuclear reactions that release energy.
- S Know that in stable stars the nuclear reactions involve the fusion of hydrogen into helium.

HELPFUL NOTES

The volume of the Sun is big enough for over a million Earths to fit inside!

How big is the Sun?

The Sun is a massive ball of mainly hydrogen and helium gases. It is the biggest object in the Solar System. The next biggest object is Jupiter — ten Jupiters would fit across the width of the Sun.

The Sun is massive enough for nuclear reactions to take place at its centre. These nuclear reactions produce enormous amounts of energy. The Sun radiates the energy in the form of electromagnetic radiation — mostly infrared, visible light and ultraviolet. Without this energy, life would not be possible on the Earth.

The Sun is one of many, many stars in the Universe. Compared with these stars, the Sun is an average yellow star. Some stars are bigger, hotter and bluer than the Sun, and some are smaller, cooler and redder.

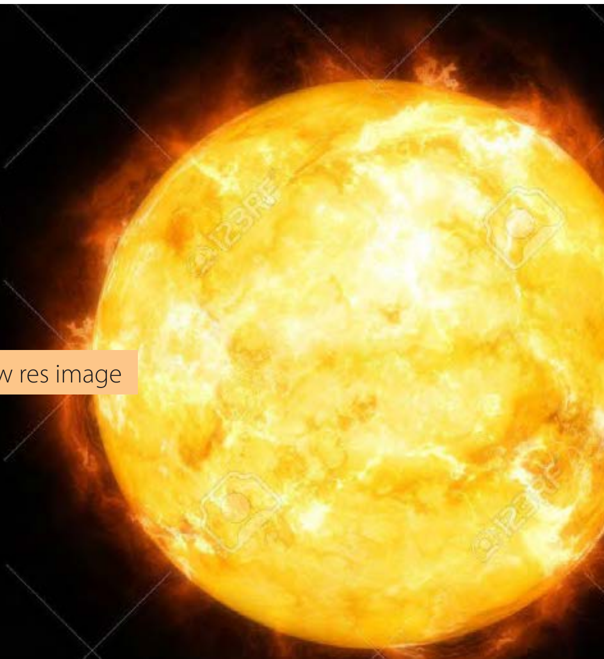


Figure 22.1 *The Sun in our Solar System*

LINK

Recall what you have learnt in Chapter 13 about electromagnetic radiation.

QUICK CHECK

The Sun is the biggest object in the Universe.

True or False?

S How do stars produce energy?

Stars are so massive that the density and temperature at the centre are high enough for nuclear reactions to occur. Positively charged hydrogen nuclei are able to overcome their electrostatic repulsion and combine or fuse together to become helium nuclei. When this nuclear fusion happens, a lot of energy is released. In this part of its life, the star is stable.

The Sun is a stable star. It has been shining for about 5000 million years. Although it consumes about 600 million tonnes of hydrogen each second, there is enough for nuclear fusion to continue for another 5000 million years.

Let's Practise 22.1

1 State whether each statement is true or false.
  - **(a)** The Sun is made of gases.
  - **(b)** The Sun is nearly at the end of its life.
  - **(c)** S Nuclear fission occurs in the centre of the Sun.
  - **(d)** S Smaller nuclei combine to make larger ones in the core of the Sun.

2 **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

LINK TWB

Exercise 22A, pp. XX–XX

22.2 Stars

In this section, you will learn the following:

- State that galaxies are each made up of many billions of stars.
- State that the Sun is a star in the galaxy known as the Milky Way.
- State that other stars that make up the Milky Way are much further away from Earth than the Sun is from the Earth.
- State that astronomical distances can be measured in light-years.
- S Know that one light-year is equal to 9.5×10^{15} m.
- S Describe the life cycle of a star.

What is the Milky Way?

On a really clear night and far away from bright city lights, you might be able to see a faint band of light stretching across the sky (Figure 22.2). This is the **Milky Way**. It is a group of many billions of stars or a **galaxy** to which our Sun belongs.

The Milky Way is a flattish spiral galaxy with a bulge at the centre. Our Solar System is in one of the spiral arms. If we could see it from above, it would look like the artist's impression in Figure 22.3.

A-Z WORD ALERT

Billion: a thousand million or 1 000 000 000

Figure 22.2 The Milky Way seen from the Earth

Figure 22.3 Artist's impression of the Milky Way galaxy viewed from above

QUICK CHECK

The bright star Sirius is 8.6 ly away from the Earth. It has taken the light from Sirius 8.6 years to reach the Earth.

True or False?

ENRICHMENT INFO

You can see the value for the distance of the light-year in metres by rearranging the equation for speed: $v = \frac{s}{t}$

to give $s = vt$.

The speed of light $v = 3 \times 10^8$ m/s

The time $t = 1$ year

$= 365 \times 24 \times 60 \times 60$ s

$= 3.15 \times 10^7$ s

The distance s

$= 3 \times 10^8 \times 3.15 \times 10^7$

$= 9.5 \times 10^{15}$ m or

9 500 000 000 000 000 m

QUICK CHECK

It will be 5000 million years before the Sun becomes a red giant.

True or False?

The closest star to the Sun in the Milky Way galaxy is called Proxima Centauri. It is about 38 million billion metres away. Distances in the Milky Way are so big that it is more convenient to use a larger unit of distance.

Light travels at the fastest speed possible and it takes light from Proxima Centauri about four years to reach the Earth. We call the distance that light travels in one year *a light-year*. So Proxima Centauri is about four light-years (4 ly) from the Earth.

S **1 light-year** is the distance that light travels in one year in the vacuum of space. It is equal to **9.5×10^{15} m**.

How do stars die?

You have learnt in Chapter 21 that a star is formed from a nebula, which is a cloud of dust and mainly hydrogen gas in space. Gravitational attraction causes the cloud to collapse. A hot spinning mass called a protostar forms at the centre of the cloud. Eventually, the protostar becomes dense and hot enough for nuclear fusion to occur at its centre. It has become a star.

Nuclear fusion causes hydrogen nuclei to fuse together forming helium nuclei. This process releases an enormous amount of energy in the form of electromagnetic radiation. The star is pulled inwards by gravitational attraction. This is balanced by the outward force due to the high temperature in the centre of the star (Figure 22.4). Thus, the star becomes stable.

Eventually, all stars will convert the hydrogen in their centre into helium. What happens next depends on their size. See Figure 22.5.

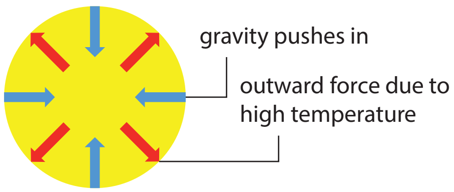


Figure 22.4 *Diagram to show the forces acting inside a stable star*

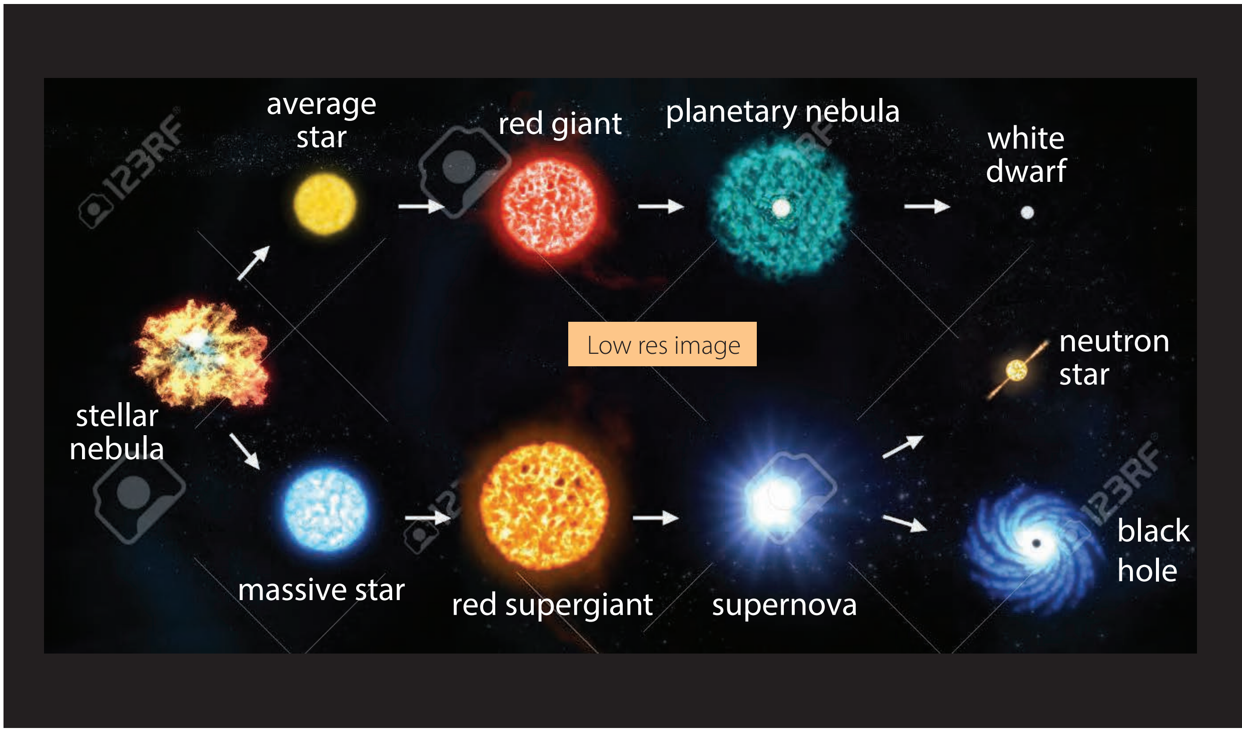


Figure 22.5 *Diagram to show the life of an average star (top row) and a massive star (bottom row)*

Average stars

Most stars are similar to the Sun and remain stable for billions of years. When they run out of hydrogen, nuclear fusion stops. There is no radiation pressure pushing out, so gravity causes the core to collapse and heat up. The collapsing core may be hot enough for some helium nuclei to fuse into carbon and oxygen nuclei. The outer layers expand and cool, turning the star into a **red giant**. Our Sun will probably swell enough to reach the orbit of the Earth.

Eventually, the outer layers are pushed away from the star to become a **planetary nebula**. The central core remains as a **white dwarf** which gradually cools.

Massive stars

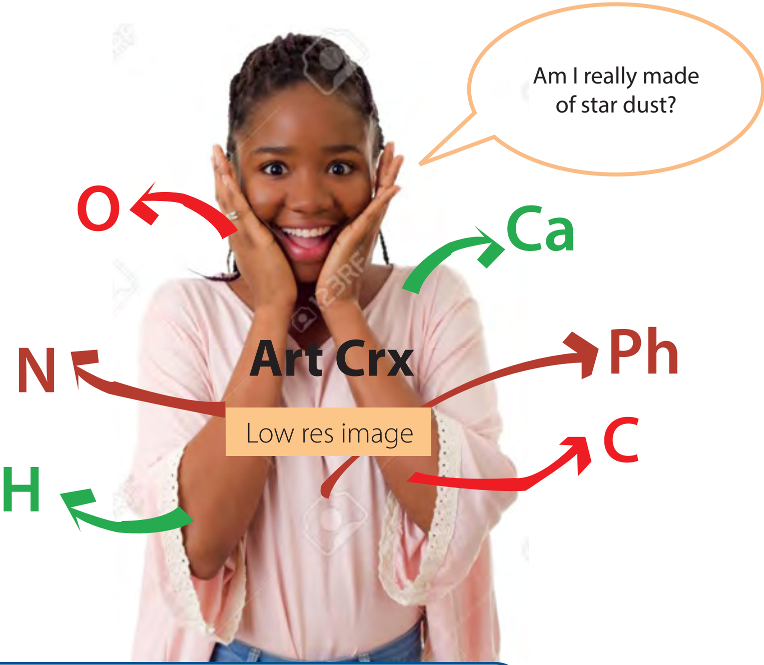
Blue **supergiants** are massive stars that are at least eight times the mass of the Sun. They are hotter and do not live as long as less massive stars. Supergiants live for millions not billions of years.

As with average stars, when the hydrogen is used up, the core shrinks and becomes hotter. The outer layers expand and turn the star into a **red supergiant**. In the core helium, nuclei fuse into more massive nuclei, such as carbon, neon, oxygen and silicon. This releases more energy.

Nuclear fusion stops when nuclei of iron are formed. The star quickly collapses then explodes violently. The explosion is called a **supernova**. There is enough energy in a supernova to produce nuclei more massive than iron. A nebula containing the remaining hydrogen and the new elements expands into space. The nebula may eventually form new stars and planets.

The core of the supernova can be a very dense **neutron star**, which is made of tightly packed neutrons. If it is very massive, it can also be a **black hole**, which is so dense that light cannot escape from it.

What elements are you made of? Almost 99% of the mass of the human body is made up of six elements: oxygen, carbon, hydrogen, nitrogen, calcium, and phosphorus. You have seen how the elements heavier than hydrogen were made inside stars. You really are made of stardust!



HELPFUL NOTES

The term 'planetary' nebula is misleading. It has nothing to do with planets. Astronomers thought they were looking at giant planets. But it is just the glowing shell of gas blown away from the remains of a star.

Let's Practise 22.2

1 Explain what the following terms mean:
   (a) billion **(b)** Milky Way **(c)** nuclear fusion **(d)** light-year
2 S What names are given to the following descriptions?
   (a) An average star that has used up its hydrogen, expanded and cooled
   (b) The cloud of gas that has blown away from a dying star
   (c) An exploding massive star
   (d) The cooling remains of an average star
3 S Put this list in order to describe the stages in the life cycle of a massive star.
   black hole, massive star, nebula, protostar, red supergiant, supernova
4 S What is the length of a light-year in metres?
5 S What happens to the forces inside a star when the hydrogen in its core is used up? What will happen to the star?
6 **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

TWB LINK

Exercise 22B, pp. XX–XX

22.3 The Universe

In this section, you will learn the following:

- Know the Milky Way as one of many billions of galaxies in the Universe and that it has an approximate diameter of 100 000 light years.
- Describe what is meant by *redshift*.
- Know that the light emitted from stars in distant galaxies appears redshifted compared to light emitted on the Earth.
- Know that redshift is evidence that the Universe is expanding and supports the Big Bang Theory.
- S Know what cosmic microwave background radiation (CMBR) is.
- S Explain that the CMBR was produced shortly after the Universe was formed and that this radiation has been expanded into the microwave region of the electromagnetic spectrum as the Universe expanded.
- S Know how the speed v at which a galaxy is moving away from the Earth can be found.
- S Know how the distance d of a far galaxy can be determined.
- S Define the *Hubble constant* H_0; recall and use the equation $H_0 = \frac{v}{d}$.
- S Know that the current estimate for H_0 is 2.2×10^{-18} per second.
- S Know what the equation $\frac{d}{v} = \frac{1}{H_0}$ represents.

What does the Universe consist of?

In the early 1900s, astronomers believed that the Milky Way was the whole Universe. They saw that it contained fuzzy spirals and thought that these were nebulae.

In 1919, an American astronomer, Edwin Hubble, used a powerful telescope to look at one of these nebulae. He saw that it contained bright stars just like the Milky Way. The fuzzy spirals were actually galaxies more distant than the Milky Way. The diameter of the Milky Way is approximately 100 000 light-years. The *nearest* galaxy to the Milky Way is over 25 000 light-years away from it.

Just as a galaxy contains billions of stars, the Universe contains billions of galaxies. The Universe was much, much larger than anyone had imagined!

ENRICHMENT THINK

1 The Andromeda galaxy is 2.2 million ly from the Earth. How long does it take light from this galaxy to reach the Earth?

2 Explain why looking at the night sky is looking back in time.

What is redshift?

You are probably aware of the Doppler effect (Figure 22.6). When an ambulance approaches, its siren sounds higher and when it moves away it sounds lower.

PHYSICS WATCH

Scan this page to watch a clip of an ambulance demonstrating the Doppler effect.

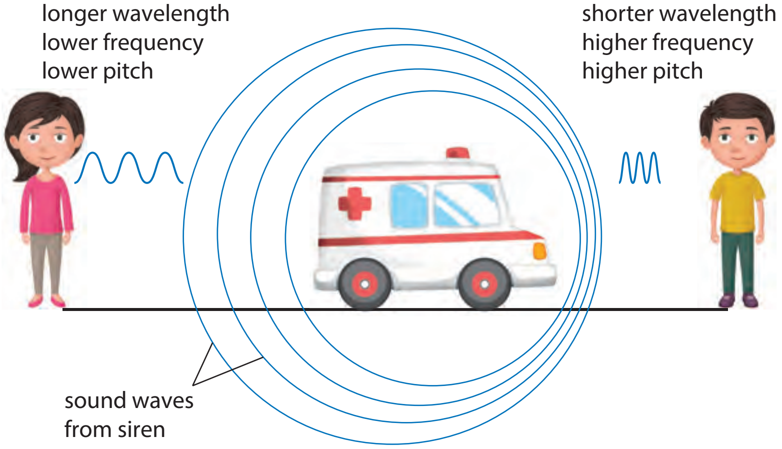


Figure 22.6 *The Doppler effect for sound waves*

This happens because the wavefronts of the sound become closer together when the sound is travelling in the same direction as the ambulance. A shorter wavelength means a higher frequency. When the ambulance moves away, the wavelength is longer so the frequency is lower.

The same thing happens with light sources. When a light source moves towards an observer, the light has a higher frequency. When it moves away, the light has a lower frequency. A higher frequency light would be bluer. It is said to be **blueshifted**. A lower frequency light is redder or **redshifted**.

In Figure 22.7, the top coloured band shows the spectrum of colours from the Sun's light. The black lines show colours that have been absorbed by gases around the Sun.

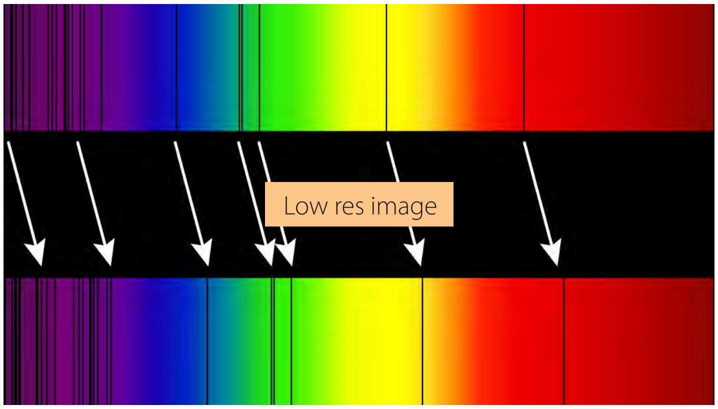


Figure 22.7 *Redshift of spectral lines in light from a distant galaxy*

The bottom coloured band shows the spectrum of colours from a distant galaxy. The white arrows show how the same pattern of black absorption lines have been shifted towards the red end of the spectrum.

What does this tell you about the movement of the distant galaxy? A redshift means the frequency is lower, so the distant galaxy is moving away from Earth.

Redshift is the increase in the observed wavelength of electromagnetic radiation emitted from stars and galaxies which are moving away from the Earth.

Astronomers found that the distant galaxies they can see in the Universe are moving away from the Milky Way galaxy in a similar way. It seems that the whole Universe is expanding.

But what if we imagined time going backwards? Then the galaxies would be moving closer and closer together to a single point. At some moment in the past, all of the matter in the Universe must have exploded outwards from this point and it is still expanding. This is known as the **Big Bang Theory** of the Universe.

ENRICHMENT *ACTIVITY*

You can make a two-dimensional model with a round balloon to show the effect of expansion.

Draw some galaxies on sticky paper and attach them to the balloon. Mark one of them with a cross to be the Milky Way.

Figure 22.8 *Demonstration of expansion of the Universe*

Blow up the balloon. What happens to the distances between the Milky Way and the other galaxies?

What happens to the distances between all the other galaxies?

You will see that the space between all of the galaxies is increasing and they are all moving apart from each other.

Is there more evidence for the Big Bang Theory?

After the Big Bang, the Universe would have been very hot and filled with short wavelength gamma radiation. Expansion of the Universe would cause the wavelength of this radiation to stretch into longer wavelength microwaves.

If the Big Bang theory is correct, the Universe should now be filled with microwaves. These microwaves are called the **cosmic microwave background radiation** or **CMBR**. A race began where scientists competed to build a microwave detector to see if CMBR existed.

A few years later, the CMBR was discovered by accident. Two scientists were testing a microwave receiver they had built for their own research. They found that it always picked up an unwanted background signal of microwaves of wavelength 2 mm. The two scientists thought that it was faulty. Eventually, they learnt about CMBR from a colleague. This led them to realise that what their receiver had found was CMBR.

ENRICHMENT *INFO*

Discovery of CMBR

Penzias and Wilson were the two scientists who were testing the microwave detector. They first thought that the unwanted signal was from pigeons that were nesting in the antenna. They removed the pigeons and their nest, but the signal was still there. They later realised that their detector had found the microwave radiation left behind from the Big Bang.

How old is the Universe?

Edwin Hubble used a powerful telescope (Figure 22.9) to measure the distance of galaxies from the Earth by using their brightness.

By measuring the redshift of starlight from the galaxies, the speed of the galaxy can be calculated.

Hubble found that the more distant galaxies had greater redshifts than the ones that were closer to the Earth. What does this mean?

Light from more distant galaxies has a greater redshift because they are moving away faster. He plotted a graph of the speed against their distance from the Earth and got results similar to the graph shown in Figure 22.10.

The graph in Figure 22.10 shows that the speed v is proportional to the distance d, i.e. $v \propto d$. This is known as *Hubble's law*. The constant of proportionality is known as the *Hubble constant*, H_0.

The **Hubble constant H_0** is defined as the ratio of the speed at which the galaxy is moving away from the Earth to its distance from the Earth.

$$H_0 = \frac{v}{d}$$

where H_0 = Hubble constant

v = speed of movement away from the Earth

d = distance from the Earth

Figure 22.9 *This is the telescope used by Edwin Hubble to measure the distance of galaxies from the Earth.*

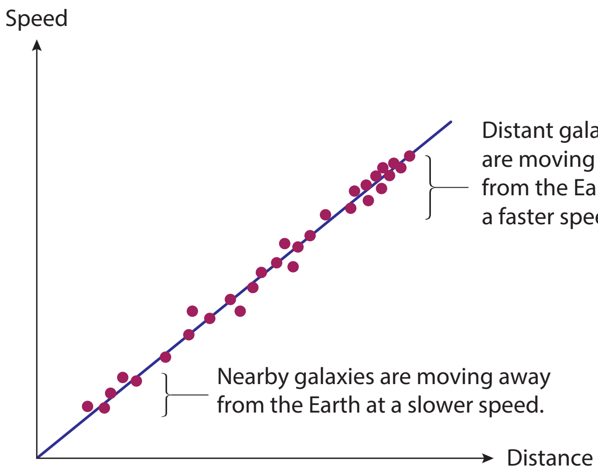


Figure 22.10 *A graph of Hubble's results*

ENRICHMENT *INFO*

To recede means to move away from. The velocity with which the galaxies are moving apart is called their *recessional velocity*.

Astronomers have repeated Hubble's measurements to get a more accurate measurement of the Hubble constant. They have been able to use the space telescope named after him to do this (Figure 22.11).

Figure 22.11 *Hubble space telescope orbiting above the Earth*

For very distant galaxies, astronomers have to look for exploding white dwarf stars. These supernovae produce enough energy to be seen from the Earth. They are thought to give out a known amount of light. The faint light that arrives on the Earth can then be used to estimate their distance away.

The current estimate of H_0 is **2.2×10^{-18} per second**.

A reason for getting an accurate value of the Hubble constant is that it can tell us how old the Universe is.

Since average speed v is given by the equation: $v = \frac{\text{distance travelled}}{\text{time}}$

Rearranging this gives: time $t = \frac{\text{distance travelled}}{\text{average speed}} = \frac{d}{v}$

From Hubble's graph, $H_0 = \frac{v}{d}$

$\therefore\ t = \frac{d}{v} = \frac{1}{H_0}$

So $\frac{1}{H_0}$ gives an estimate of the time from the Big Bang or the age of the Universe.

Using the current estimate, this gives:

$t = \frac{1}{2.2} \times 10^{-18}\ \text{s} = 4.5 \times 10^{17}\ \text{s}$ or 14 billion years

WORD ALERT

Supernovae: plural of *supernova*

Let's Practise 22.3

1 Explain why astronomers were shocked to find out that the fuzzy 'nebulae' in the Milky Way were in fact distant galaxies.

2 Which of the following is **correct**?

A The Universe consists of billions of stars.

B The Universe consists of millions of stars.

C The Universe consists of billions of galaxies.

D The Universe consists of millions of galaxies.

3 Explain what is meant by

(a) the Doppler effect;

(b) redshift.

4 **(a)** S What is meant by the *Big Bang Theory*?

(b) What two pieces of evidence support the Big Bang Theory?

5 S Explain what *Hubble's constant* is.

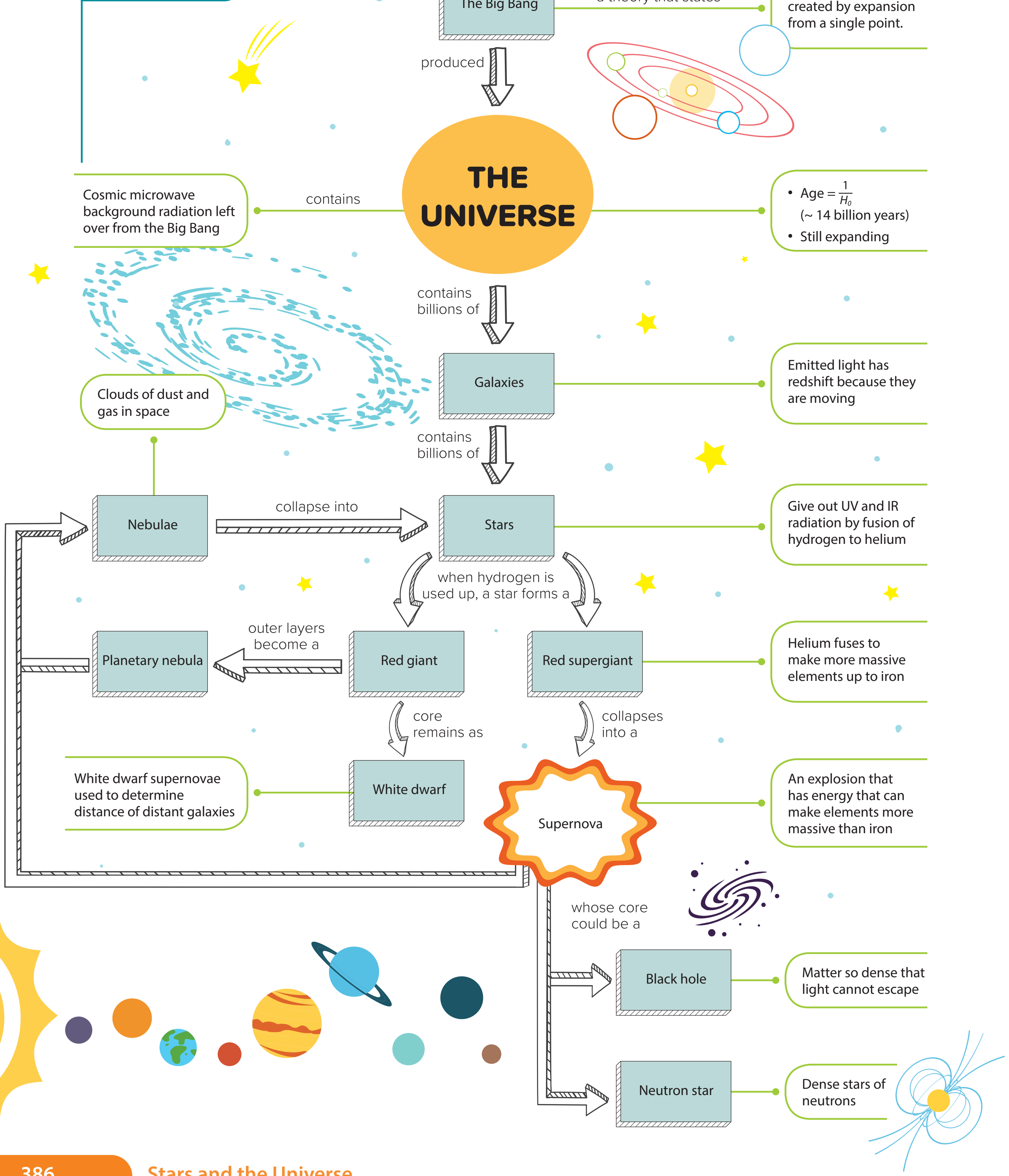
6 **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

LINK

Exercise 22C–D, pp. XX–XX

Exercise 22E Let's Reflect, p. X

Let's Map It



The Big Bang
a theory that states
The Universe was created by expansion from a single point.
produced
THE UNIVERSE
contains
Cosmic microwave background radiation left over from the Big Bang
• Age = $\frac{1}{H_0}$ (~ 14 billion years)
• Still expanding
contains billions of
Galaxies
Emitted light has redshift because they are moving
contains billions of
Clouds of dust and gas in space
Nebulae
collapse into
Stars
Give out UV and IR radiation by fusion of hydrogen to helium
when hydrogen is used up, a star forms a
Red giant
Red supergiant
outer layers become a
Planetary nebula
Helium fuses to make more massive elements up to iron
core remains as
White dwarf
collapses into a
Supernova
White dwarf supernovae used to determine distance of distant galaxies
An explosion that has energy that can make elements more massive than iron
whose core could be a
Black hole
Matter so dense that light cannot escape
Neutron star
Dense stars of neutrons

Let's Review

Section A: Multiple-choice Questions

1 Which statement is **correct**?

A A galaxy is a group of millions of stars.
B Large stars live longer than small stars.
C Elements heavier than iron are formed in supernovae.
D A light-year is a unit for measuring time.

2 Which of the following gives the **correct** order of size from largest to smallest?

A Milky Way, Universe, Sun, Jupiter
B Sun, Universe, Jupiter, Milky Way
C Jupiter, Sun, Milky Way, Universe
D Universe, Milky Way, Sun, Jupiter

Section B: Short-answer and Structured Questions

1 S Describe **three** similarities and **three** differences between the life cycle of an average star like the Sun and the life cycle of a massive star.

2 S The astronomer Hubble plotted a graph of the speed with which galaxies were moving away from the Earth against the distance of the galaxies from the Earth.

(a) Explain how he could measure the speed.
(b) Use the axes in Figure 22.12 and sketch the graph he obtained from his results.

Figure 22.12

(c) Explain how the age of the Universe can be estimated from the graph.

3 Figure 22.13 shows Andromeda, a spiral galaxy outside the Milky Way.

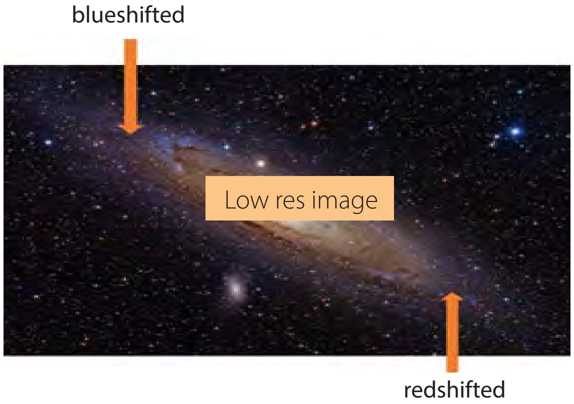


Figure 22.13

When the light from the galaxy was observed on the Earth, light from the left hand side was found to be blueshifted while light from the right hand side was found to be redshifted.

(a) What does this tell you about the movement of each end of the galaxy?
(b) Suggest a reason for this.