6 Radioactivity: a two-edged sword

Why learn this?

When most people hear the word 'radioactivity', they immediately conjure up mental images of scientists in lead suits holding ticking Geiger counters out in front of them, or of the horrible burns or cancers suffered by survivors of atomic bombs or the Chernobyl disaster. But destruction is not all that there is to radioactivity. It can also be a valuable lifesaver and scientific tool.

In this chapter, students will:

6.1 understand that our knowledge of radioactivity is the result of the work of many scientists building on each other's discoveries

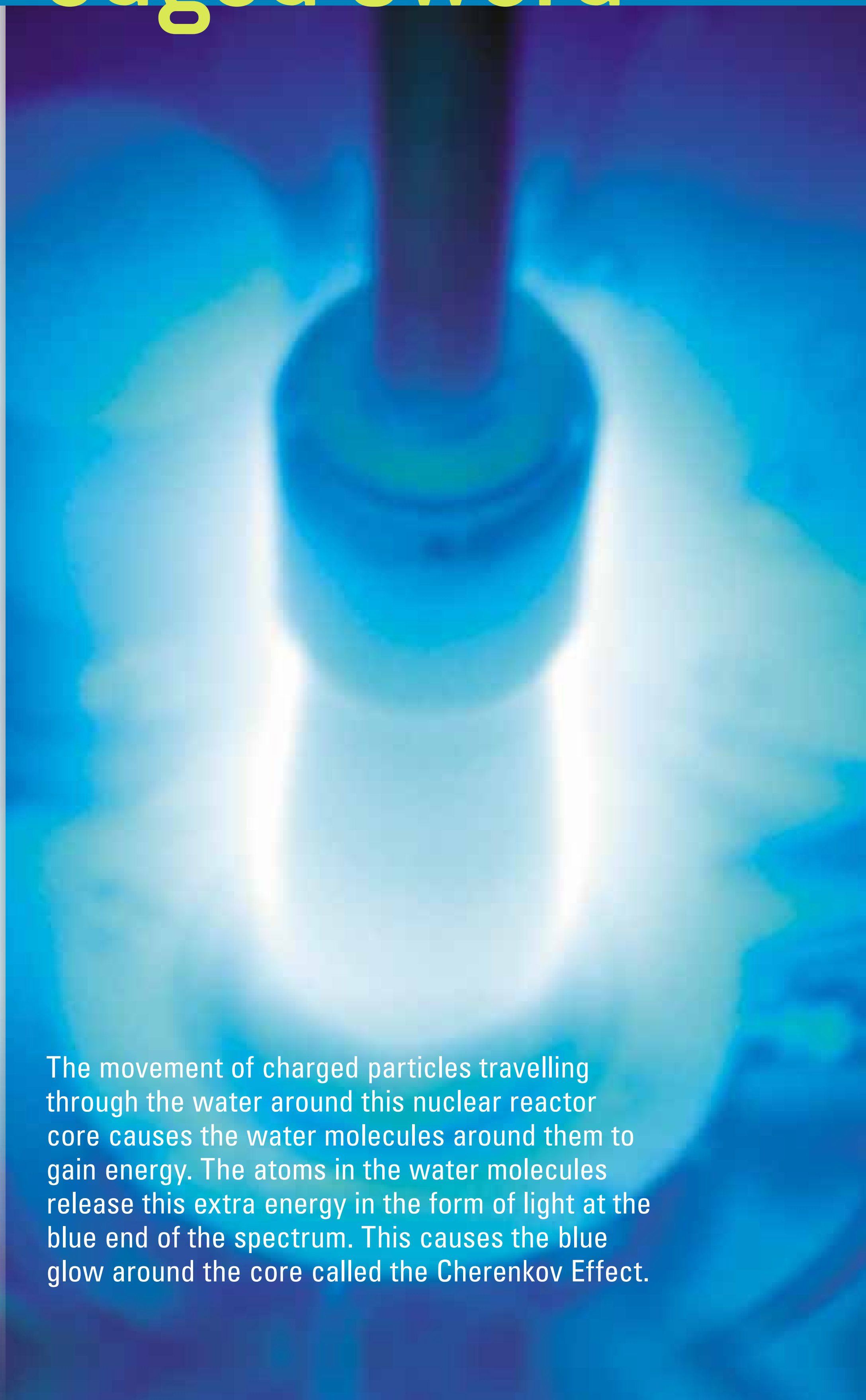
6.2 describe the properties that make some isotopes stable while others decay, producing radioactivity

6.3 explore the types, properties and effects of nuclear radiation

6.4 consider the many ways in which radiation is used as a tool for society's benefit

6.5 understand the different types of nuclear reaction that can produce energy and learn how this energy is harnessed in nuclear reactors

6.6 describe the detrimental short-term and long-term effects that reactor accidents and nuclear weapons can have on a population and an environment.



The movement of charged particles travelling through the water around this nuclear reactor core causes the water molecules around them to gain energy. The atoms in the water molecules release this extra energy in the form of light at the blue end of the spectrum. This causes the blue glow around the core called the Cherenkov Effect.

1. Superpowers for everybody?

If the comics, TV and movies are to be believed, being hit with radiation can give you superpowers!
(a) List as many superheroes that you can who owed their powers to radiation or radioactivity. What powers did they have?
(b) Can radioactivity exposure actually cause mutation? Explain using examples.
(c) What is radiation sickness? What are its symptoms?
(d) How much radiation can a human be exposed to before they get radiation sickness?

2. The element of surprise!
Complete the table below, but be careful — you may need a periodic table and some thought!

Element	Number of protons	Number of neutrons	Atomic mass
Carbon	6		12
		8	14
	7		14
	17	20	
	92		235
	92		238
	18		40
	1	2	
		2	3

3. Cloud of doom?
Consider the image below.
(a) What name is given to clouds like this?
(b) What causes them to form?
(c) How high into the sky do you think the top of the cloud reaches?
(d) What is the cloud made of?

4. Who's who?
Find out who each of the following elements were named for and what their contribution was to our understanding of radioactivity: meitnerium; curium; rutherfordium; fermium; einsteinium; roentgenium; bohrium.

6.1

Pioneers of radiation

While nuclear power stations and MRI machines are all very much inventions of the twentieth century, the foundations of nuclear physics actually lie in the late nineteenth century. Without the pioneering work of scientists such as Wilhelm Roentgen, Henri Becquerel and the Curies, chances are that many of the technologies that we now take for granted would not have been developed.

Wilhelm Roentgen (German scientist, 1845–1923)

In November 1895, the German scientist Wilhelm Roentgen was using a Crookes tube (see opposite page) in a series of experiments. He found that, even when the tube was completely covered in thick black cardboard to prevent visible light escaping, a nearby screen coated in barium platinocyanide glowed when the Crookes tube was turned on and the voltage was high. Roentgen quickly determined that this glow was not caused by cathode rays and reasoned that the Crookes tube was producing some other sort of invisible rays which were able to travel through the cardboard to the screen. He named these mysterious rays **X-rays**. Later experiments showed him that the X-rays could travel through low density substances such as cardboard and human flesh, but were blocked by denser substances such as metals and bone.

Wilhelm Roentgen

The first X-ray

Less than a month after his first discovery of X-rays, Roentgen demonstrated their usefulness for medical diagnosis by producing an X-ray image of his wife's hand which clearly showed the bones inside as well as the ring that she wore, yet not the skin, sinews, muscles or veins.

How it works — the Crookes tube

Invented by English scientist William Crookes in the 1870s, a Crookes tube is made up of a glass tube with most of the air removed from inside it to form a vacuum. It contains two plates — the anode and the cathode. When the plates are connected to a voltage source, the end of the tube glows **(fluoresces)**. Scientists of Crookes' time believed that this glow was caused by rays travelling from the cathode and overshooting the anode. Later, J. J. Thomson realised that these 'cathode rays' were actually negatively charged parts of atoms which he eventually named electrons.

The first X-ray

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The mystery of radium

Watch a video from *The story of science* about the Curies and radioactivity.

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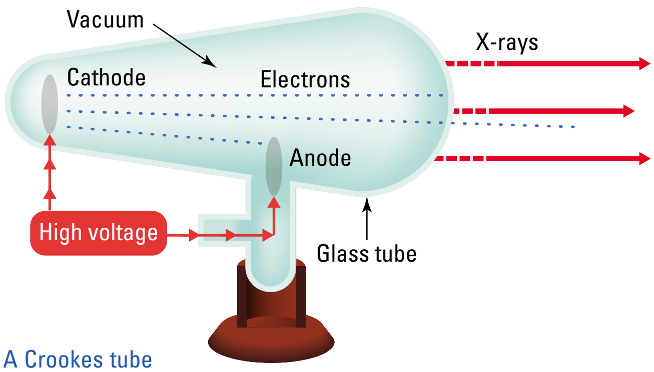


A Crookes tube

Henri Becquerel (French scientist, 1852–1908)

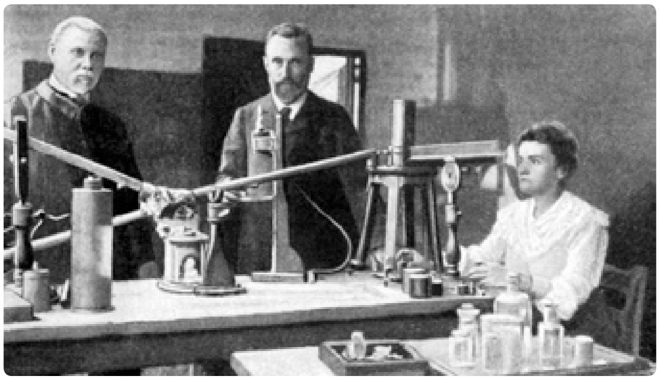
Becquerel was excited by Roentgen's discovery of X-rays as it gave new insights into his own studies at the time into the phenomenon of fluorescence. He found that some substances would glow if they were exposed to an energy source such as X-rays or even sunlight. When the energy source was removed, the substance stopped glowing. One day in 1896, Becquerel discovered that some covered photographic plates had been exposed when kept in a dark drawer with uranium ore samples in it. As there were no energy sources in the drawer, Becquerel reasoned that the uranium must have been producing some sort of invisible rays that had exposed the plates.

Marie Sklodowska-Curie (Polish/French scientist, 1867–1934) and Pierre Curie (French scientist, 1859–1906)

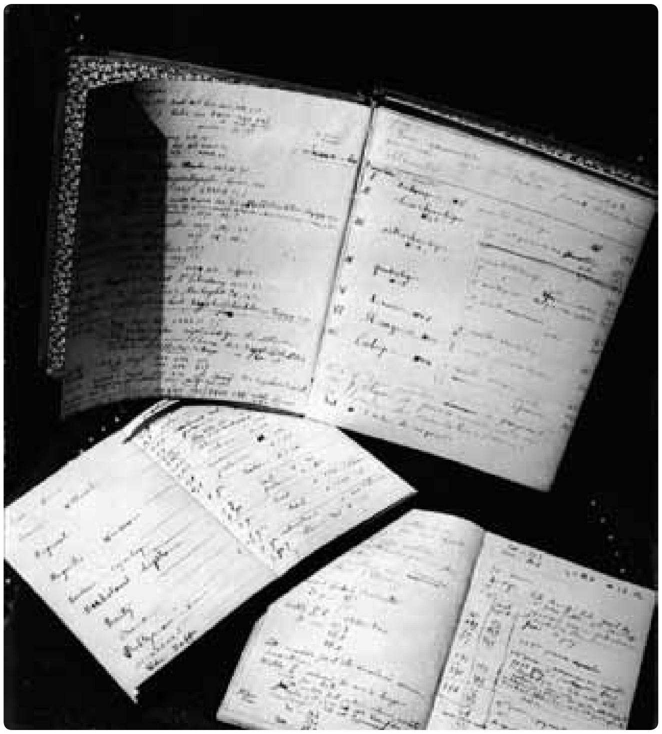
The Curies came to work with Becquerel, investigating the invisible rays that his uranium samples had produced. They found that the rays produced by uranium ores caused the air particles around them to become ionised. They referred to the rate at which the ionisation occurred as **activity** and the substances that produced this activity as being **radioactive**.

While experimenting with a uranium-containing mineral called **pitchblende**, they found that material remaining from the ore was much more radioactive than the pure uranium that had been removed from it. They reasoned that there was another element in the mineral that they named **polonium** after Marie's country of birth. After many years, the Curies found another element, which they called **radium**, which had similar properties to polonium. It took four years of processing tons of pitchblende to get enough of each of these new elements to determine their chemical properties!

Marie and Pierre Curie and Henri Becquerel were jointly awarded the 1903 Nobel Prize for Physics for their discovery of radioactivity.



(From left) Henri Becquerel, Pierre Curie and Marie Sklodowska-Curie

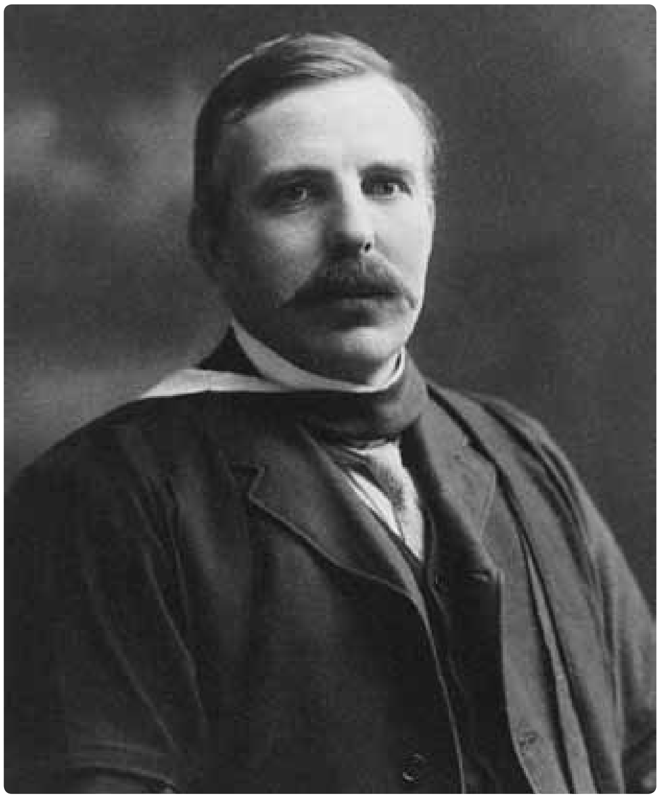


Marie Curie's laboratory notebooks, today stored at the Bibliotheque Nationale in Paris, can be viewed from behind thick glass but are still so radioactive that they cannot be touched or handled without wearing proper protection.

HOW ABOUT THAT!

Marie Curie was the first woman to win a Nobel Prize. After Pierre's death, Marie continued her studies into radioactivity and was awarded the 1911 Nobel Prize for Chemistry for her discovery of the elements polonium and radium, and for her work in unravelling the properties of radioactive elements. She was the first person to win two Nobel prizes in the award's history yet, because of the attitudes of the scientific community towards women at the time, the French Academy of Sciences refused to allow her to become a member.

Ernest Rutherford (New Zealand scientist, 1871–1937)



Ernest Rutherford

Interested by the findings of Becquerel, Ernest Rutherford began to investigate the radiation produced by uranium ore. Like Becquerel, he originally assumed that these rays were similar to cathode rays. However, his experiments led him to conclude that at least two different types of rays were being produced which had different penetrating power. He named the rays that were easily blocked or absorbed **alpha (α)** and the more penetrating rays were referred to as **beta (β)**. By 1901, he determined that the alpha and beta rays were in fact made up of streams of charged particles which became known as alpha and beta particles. Rutherford further determined that alpha particles were positively charged helium nuclei while beta particles were negatively charged electrons. When passed through a magnetic field, the charge on the particles interacted with the magnetic field in such a way that the paths of alpha particles entering the field would curve in one direction while those of beta particles would curve in the other. It was this distinguishing feature that allowed Paul Villard to make the next big discovery.

Paul Villard (French scientist, 1860–1934)

Paul Villard

At the same time that Rutherford was investigating the nature of the radiation produced by uranium, Paul Villard studied the radiation produced by the element radium, which had been newly isolated by the Curies. He passed the radium radiation through a thin layer of lead which had been shown by Rutherford to stop alpha rays. Rutherford had also earlier found that, in a magnetic field, the path of alpha rays would curve in one direction while beta 'rays' curved in the other.

In Villard's experiments the radiation passing through the lead was sent through a magnetic field where he found that, while some of the rays (later found to be beta rays) did indeed curve, the rest of the radiation continued travelling in a straight line, unaffected by the magnetic field.

Rutherford suggested that Villard's rays should be named gamma (γ) rays when it was found that they were far more penetrating than the alpha rays and beta rays which he had discovered. Villard found that the gamma rays were similar in nature to Roentgen's X-rays. In 1913, it was confirmed that gamma rays and X-rays were both forms of electromagnetic radiation.

ACTIVITIES

REMEMBER

1 **Explain** how X-ray images are formed.
2 What does radioactive mean?
3 Name the radioactive elements discovered by the Curies.
4 **Describe** at least two applications for X-rays.
5 What is fluorescence?
6 How did the Curies know that there was another radioactive substance in pitchblende apart from uranium?
7 In what ways are gamma, beta and alpha radiation different?

THINK

8 In the first X-ray image produced by Roentgen, the ring on his wife's hand can be clearly seen but the skin on her hand is invisible. Why is this?

INVESTIGATE

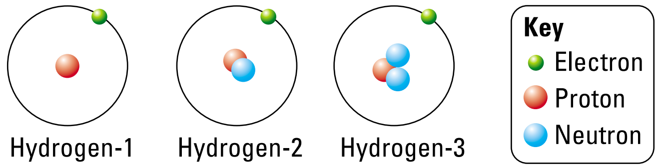
9 Find out how fluorescence is different from phosphorescence. Which of these is demonstrated by glow-in-the-dark stickers?
10 Marie and Pierre Curie's daughter Irene also won a Nobel prize. Find out (a) who she shared it with, (b) what it was won for and (c) in what year it was awarded.

Radioactive isotopes

This suit protects its wearer against something that can't be seen, touched or heard.

Isotopes

As you may remember from chapter 5, all atoms of the same element have the same number of protons — in other words, they have the same atomic number. However, while the atoms of a particular element have the same number of protons, they may not always have the same number of neutrons in their nuclei. For example, the normal version of hydrogen has a single proton in its nucleus but another version of hydrogen (called hydrogen-2 or **deuterium**) has a proton and a neutron in its nucleus, and yet another version (called hydrogen-3 or **tritium**) has a proton and 2 neutrons.



The three isotopes of hydrogen. Hydrogen-2 and hydrogen-3 are also known as deuterium and tritium respectively.

Atoms that have the same number of protons but which differ in how many neutrons they have are called **isotopes**. Most elements have 2 or 3 different isotope forms. The isotopes of an element have the same chemical properties — they just differ in mass number. Remember, the mass number of an atom is equal to the number of protons and neutrons in its nucleus.

As you will remember from chapter 5, the symbol for an isotope is written as $^{A}_{Z}E$ where

A = mass number = number of protons + number of neutrons
Z = atomic number = number of protons
E is the chemical symbol for the element.

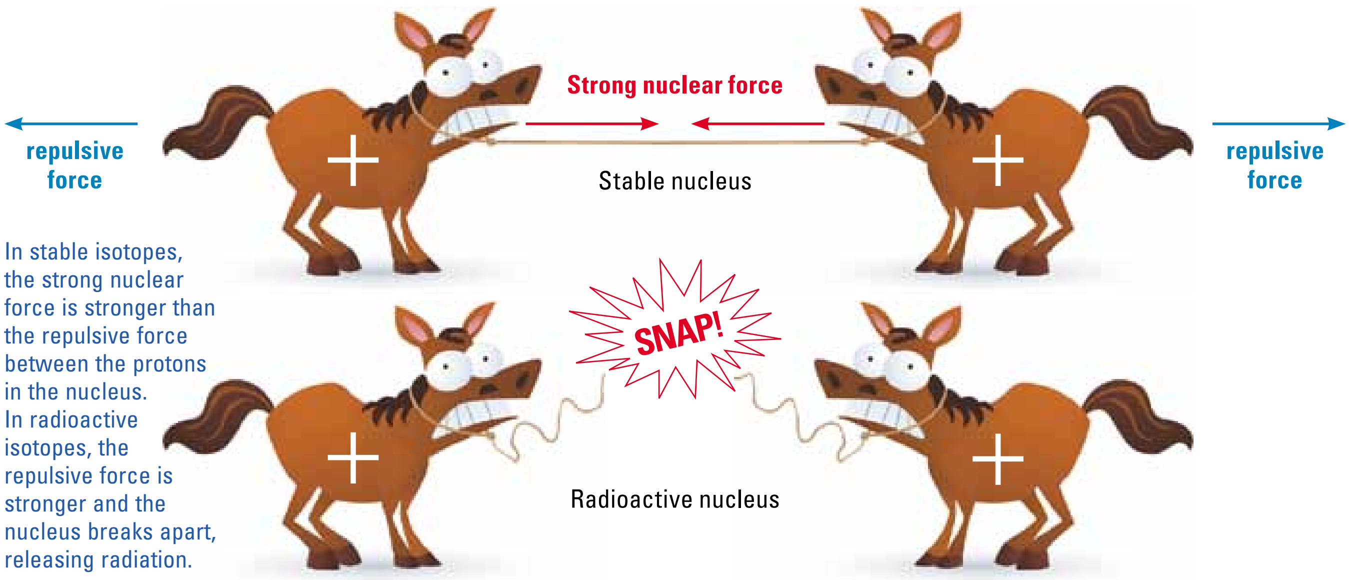
So, while the most common isotope of carbon (which has 6 protons and 6 neutrons) is written as $^{12}_{6}C$, the isotope carbon-14 (which has 6 protons but 8 neutrons) is written as $^{14}_{6}C$.

Radioactive isotopes

The protons and neutrons of the nucleus are held tightly together by something called the **strong nuclear force**. Without the strong nuclear force, the repulsive force between the positively charged protons would tear the nucleus apart. In most isotopes, the repulsive force and the strong nuclear force balance out and the nucleus remains intact, or **stable**.

In some isotopes, however, the extra neutrons in the nucleus make it much harder for the strong nuclear force to keep the nucleus together and the nucleus breaks apart or **decays**. When an unstable nucleus breaks up, energy in the form of **radiation** is released and smaller, more stable elements are formed. As a result, isotopes whose nuclei have a tendency to decay are said to be radioactive.

Element	Symbol	Number of protons	Number of neutrons	Stable or radioactive?
Carbon-12	$^{12}_{6}C$	6	6	Stable
Carbon-14	$^{14}_{6}C$	6	8	Radioactive
Uranium-235	$^{235}_{92}U$	92	143	Radioactive
Uranium-238	$^{238}_{92}U$	92	146	Stable



In stable isotopes, the strong nuclear force is stronger than the repulsive force between the protons in the nucleus. In radioactive isotopes, the repulsive force is stronger and the nucleus breaks apart, releasing radiation.

The half-life

When an atom of a radioactive isotope decays, it releases radiation and forms a different, usually lighter nucleus. The rate at which these isotopes decay is described by its **half-life** — the time you would need to wait for half of the amount of the radioactive material to decay. For example, carbon-14 has a half-life of 5700 years. If you had a 1 kg lump of carbon-14, after 5700 years had elapsed, only 500 g would still be carbon-14. The other 500 g would have decayed to form the stable isotope nitrogen-14 (we say that nitrogen-14 is the **daughter isotope** of carbon-14). After 11 400 years, you would have only 250 g of carbon-14 and after 16 100 years only 125 g of the carbon-14 would be left. The following table shows the decay of carbon-14.

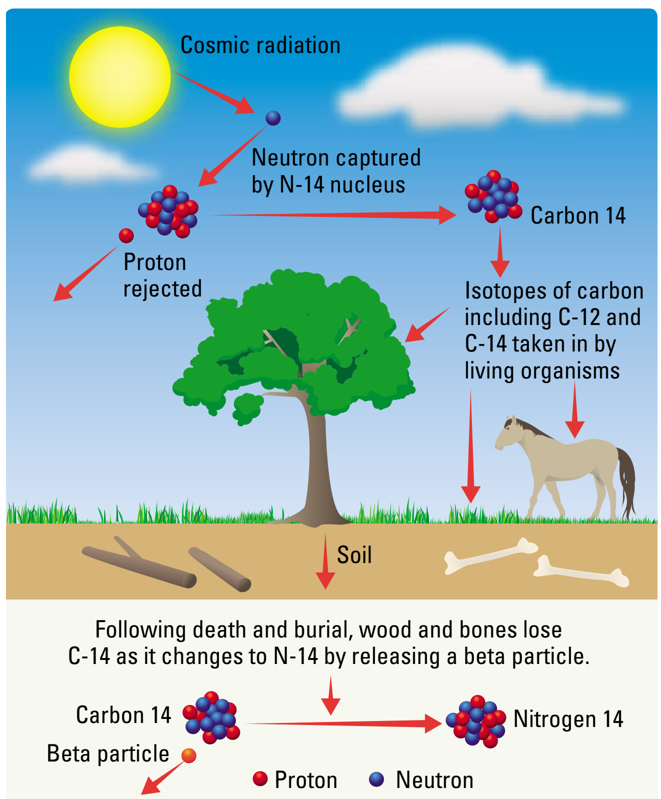
Time elapsed (years)	Amount of carbon-14 present (g)	Fraction of starting amount remaining
0	1000	1
5 700	500	½
11 400	250	¼
16 100	125	1/8
21 800	62.5	1/16

Some radioactive materials decay at faster rates than others. Many of the substances used in cancer treatments have half-lives of only a few hours, while uranium-238 has a half-life of 4.5 billion years!

Radiocarbon dating

The decay of carbon-14 is a particularly useful tool for archaeologists and anthropologists who wish to determine how old an organic relic is. This is done by considering how much carbon-14 is in the relic.

Carbon-14 is produced in the Earth's atmosphere when cosmic rays strike nitrogen-14 atoms. All living things take in carbon including radioactive carbon-14 throughout their lives. New carbon-14 is taken in to replace the carbon-14 that decays, so the total amount of carbon-14 in an organism stays constant while it is alive. When an organism dies, however, no new carbon-14 is taken in so the amount of carbon-14 in the organism's remains decreases over time.



Radioactive carbon-14 is absorbed by all living things. When the organism dies, the carbon-14 in the organism decays over time.

INVESTIGATION 6.1

Simulating radioactive decay

AIM **To model radioactive decay**

You will need:
100 M&Ms
clean sheet of white paper
large plastic container
plastic gloves or very well-scrubbed hands

- First make a copy of the table below in your notebook.

Turn	Number of M&Ms in container at start of turn	Number of M&Ms that 'decayed' this turn	Total number of M&Ms 'decayed' since the start	% of M&Ms that have decayed since the start	% of M&Ms remaining from the start
1	100				
2					
3					
4					
5					
6					

- Lay out all the M&Ms on the sheet of paper with the 'M' side down. This represents all of the atoms in the parent isotope before radioactive decay occurs.
- Place all of the M&Ms into the plastic container and shake them thoroughly. The M&Ms should be able to move around freely in the container. Pour the M&Ms onto the paper again and spread them out *without changing which side up each one has landed.*
- Separate out the M&Ms that have landed with the 'M' facing upwards. These represent the atoms that have decayed into a new isotope. Count how many of these there are and enter the amount in the table. Place these to one side.
- Collect the remaining M&Ms (the ones that landed 'M' side down) and return them to the container. Shake the container, pour out the M&Ms and repeat the previous step.
- Continue in this way until all of the M&Ms have been removed. You may need more rows in your data table than have been shown.

DISCUSSION

1. **Plot your results as a line graph with the turn number on the horizontal axis and the percentage of 'undecayed' M&Ms remaining at the end of the turn on the vertical axis.**
2. **Compare your group's results with the other groups in your class. Did you all get similar results? Explain why there would be some variation.**
3. **Your teacher will combine the class results. Plot these results on a line graph using the same axes as you used in question 1. Compare this graph shape to the one that you drew earlier.**
4. **Looking at your combined results, describe the general relationship between the turn number and the percentage of undecayed M&Ms left at the end of the turn.**

When scientists find the preserved organism, they measure the amounts of carbon-12 and carbon-14 in a sample of the organism. The ratio of carbon-14 to carbon-12 is fairly standard in a living organism (about one carbon-14 atom for every trillion carbon-12 atoms). As the amount of carbon-12 in the sample remains nearly constant over time, it is then possible to work backwards and estimate the original amount of carbon-14 that the sample would have originally had. This original amount is then compared to the amount of carbon-14 remaining in the organism's preserved body. This allows the scientists to work out how many half-lives of carbon-14 have elapsed since the creature died and, as the half-life is known, an approximate time of death for the organism can be determined. For example, if the organism has only half the amount of carbon-14 in it than would be expected, it has been dead for 1 half-life; i.e. about 5700 years. Carbon-14 dating can be unreliable, however, if the specimen is contaminated with other organic matter.

Sample being removed from bone for carbon dating using accelerator mass spectrometry (AMS). The bone is a human femur that is thought to date to the Middle Ages.

Dating rocks

Radiocarbon dating can only be done on things that were once part of living organisms. As a result, you can't use it to work out how old a rock is. Instead, the decay of other isotopes can be used to date rocks. One of the most widely used systems looks at the decay of uranium isotopes in zircon, which is a mineral common to many rocks.

Uranium-235 has a half-life of 704 million years and it decays to form an isotope of lead ($^{207}_{82}Pb$). By comparing the amounts of lead-207 and uranium-235 a rock sample containing zircon has in it, the age of the rock can be estimated.

ACTIVITIES

REMEMBER

1 In the symbol $^{A}_{Z}E$, what is represented by (a) the letter A (b) the letter Z?

2 **Calculate** the number of (a) protons (b) electrons (c) neutrons in:
(a) $^{235}_{92}U$
(b) carbon-13
(c) hydrogen-2.

3 How do isotopes of the same element differ from each other?

4 **Explain** why the isotopes of some elements are radioactive.

5 What do the terms (a) half-life (b) daughter isotope (c) radiocarbon mean?

6 Why can't radiocarbon dating be used to determine the age of a rock?

THINK

7 The half-life for a radioactive isotope X is 2 hours.
(a) If you had 500 g of isotope X, how much would remain after (i) 2 hours (ii) 8 hours?
(b) How long will it take until only 125 g of isotope X is left?

8 The Earth is estimated to be about 4.5 billion years old. How much uranium-235 would there have been when the Earth was formed compared to how much there presently is?

9 About 0.01 per cent of the potassium in your body is the radioisotope $^{40}_{19}K$.
(a) How many protons and neutrons are in each atom of this radioisotope?
(b) The stable nuclei of potassium atoms have one less neutron than the nuclei of potassium's unstable radioisotope. Write down the complete symbol for the stable isotope of potassium.

10 Are the atoms $^{230}_{93}X$ and $^{230}_{94}Y$ isotopes of the same element? **Explain**.

11 The half-life of tritium is 4500 days. How many days will it take an amount of tritium to fall to a quarter of its initial mass?

12 Parts of the skeleton of a large animal are found buried in sand dunes. The amount of radioactive carbon-14 in the bones is about one-eighth of that found in the skeletons of living animals. How long ago did the animal probably die (to the nearest thousand years)?

13 Approximately what percentage of the original amount of radioactive carbon-14 would you expect to find in:
(i) an Aboriginal spear 11 000 years old?
(ii) a skull 23 000 years old, found in a cave?

USING DATA

14 Graph the decay of carbon-14 by using the data in the table on page 202. You will need to have the time in days on the horizontal axis and the amount of carbon-14 remaining in grams on the vertical axis. Use your graph to approximate:
(a) the amount of carbon-14 left after 8000 years
(b) how long it takes for there to be 300 g of carbon-14 remaining.

INVESTIGATE

15 Find out which radioactive gas in the atmosphere is responsible for most of the background radiation we are exposed to on Earth.

16 While radiocarbon dating is very useful for determining the age of relics that have organic material in them, it can be used only for relics of particular ages. Find out what the age limitations on radiocarbon dating are and the cause of these limitations.

Radiation

Types of radiation

When radioactive substances decay to form more stable nuclei, their nuclei release energy in the form of **nuclear radiation**. As Rutherford and his contemporaries found early in the twentieth century, there are three types of nuclear radiation: alpha (α), beta (β) and gamma (γ).

Background radiation

Every day, we are all exposed to low levels of radiation from a variety of natural and artificial sources. These sources include the radiation released by the decay of isotopes in the Earth's crust, the cosmic radiation that reaches us from the sun and even radiation from buildings which are made from naturally radioactive materials in clay bricks or granite. This constant low-level radiation that surrounds us is called **background radiation** and is harmless to us.

Ionising radiation

Alpha, beta and gamma radiation are all forms of ionising radiation because of their ability to pull electrons from nearby atoms and molecules, turning them into ions. Exposure to ionising radiation can cause damage to living body tissue. Long-term exposure to low amounts or 'doses' can cause DNA damage, cancer and tumour growth, while high doses in a short period of time can cause burns, nausea, destruction of bone marrow and blood cells, and death.

The effect that ionising radiation has on the human body depends upon a number of different things including:

- the mass of the person
- amount/period of exposure to the radiation
- type of radiation
- radioactivity of the material
- rate at which the radiation is received
- presence of shielding material that could absorb some of the radiation
- distance from the radiation source.

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DNA and Hiroshima

Watch a video from *The story of science* about DNA.

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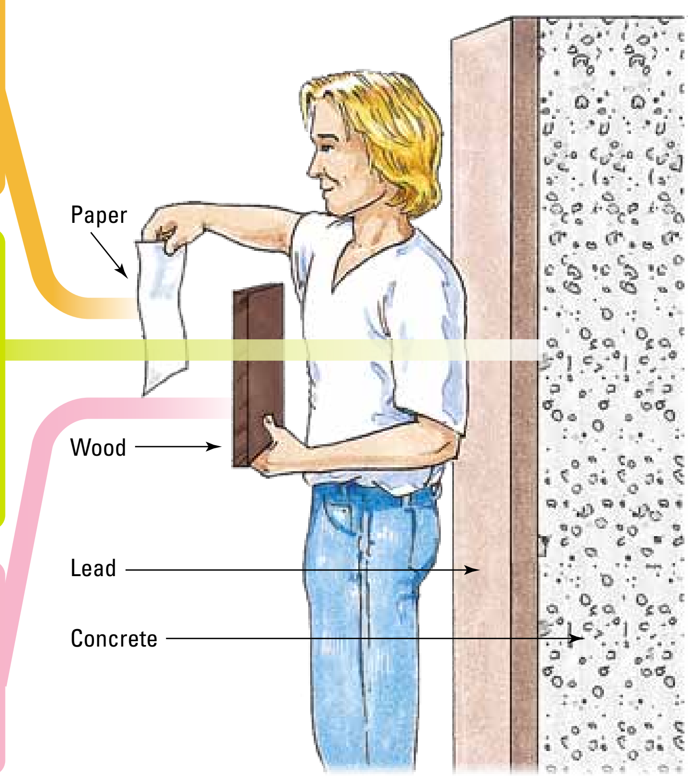
Alpha particles are streams of helium nuclei. These particles are the largest of the radiation particles and move relatively slowly. They cannot travel easily through materials and can be stopped by a few centimetres of air, a sheet of paper or human skin. They are of little danger to the outside of the body but they can cause serious damage if breathed in, eaten or injected. They are produced by the heavier radioactive elements.

Gamma rays are made up of electromagnetic waves (as are radio waves and microwaves) rather than particles. Gamma rays have no mass and travel at the speed of light. They have a lot more penetrating power than alpha or beta particles and can be stopped only by a thick shield of lead or concrete. As they pass through the body, they can cause serious and permanent damage to the living tissue and the DNA of the cells themselves. Gamma rays are produced along with alpha and beta particles.

Beta particles are fast-moving electrons. Smaller than the alpha particles, beta particles travel at 99 per cent of the speed of light. Beta particles can penetrate human skin and damage living tissue, but they can be absorbed by 100 cm of air and cannot penetrate thin layers of aluminium or centimetres-thick plastic or wood. They are produced by the lighter radioactive elements.



The different penetrating powers of alpha (α), beta (β) and gamma (γ) radiation

Measuring radiation doses

When a person is exposed to radiation, energy is deposited in the tissues of the body. The average amount of energy in Joules absorbed per kilogram of body mass is referred to as the **absorbed dose** (D). The unit of absorbed dose is the **Sievert (Sv)**:

$$D = \text{energy absorbed/mass}$$

For example, if a 100 kg person absorbs 0.01 J of radiation energy:

$$D = 0.01/100 = 0.0001 \text{ Sv} = 0.1 \text{ mSv}$$

However, some radiation is more damaging than others. In order to assess how much damage the radiation does to the body, the absorbed dose is multiplied by the **quality factor (Q)** to provide a measurement called the **human dose equivalent (H)**. Like the absorbed dose, the human equivalent dose is measured in Sieverts. The more damage that the radiation can do, the higher the quality factor and, so, the higher the human dose equivalent. The following table shows the quality factors of radiation.

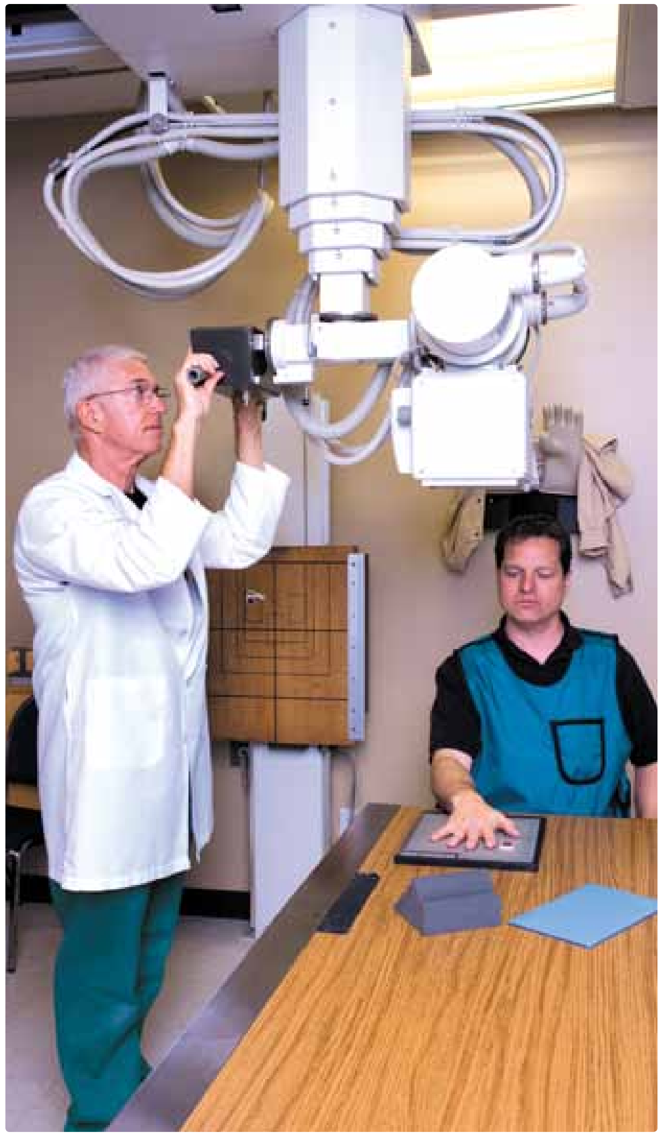
Type of radiation	Quality factor
X-rays, gamma radiation, beta radiation	1
Neutrons (depending on energy)	2–20
High-energy protons, alpha radiation, heavy nuclei	20

$$H = Q \times D$$

A 100 kg person who absorbs 0.1 mSv of energy from beta radiation will get a human equivalent dose of 0.1 mSv. However, if the energy came from alpha radiation, the human equivalent dose would be $0.1 \times 10 = 1$ mSv.

The following table gives the typical H values for a number of different radioactive sources.

Human equivalent dose, H (mSv)	Source
0.005	1 hour in an aircraft on an international flight
0.06	one chest X-ray
0.7	one mammogram
1	living 1 year in a house with granite tile flooring
1.5	background radiation experienced by the average Australian in a year
2.4	world average background radiation in a year
2.5	total experienced by the average radiography technician in a year
2.6	one head CT scan



A radiographer positions a patient's hand for an X-ray. Notice that the patient is wearing a protective apron. This apron is lined with lead to protect the rest of the patient's body from the X-rays. When the X-ray is ready to be taken, the radiographer will retreat behind a radiation shield in order to limit his own exposure to radiation.

How much is too much?

The amount of radiation that a person can experience before they suffer damage to their health depends upon the size of the dose received as well as the length of time over which they received it. High radiation doses tend to kill body cells while low doses damage the structure of the DNA within the cell, leading to cancer and leukaemia. The reproductive cells are particularly at risk.

In fact, high doses of radiation can kill so many cells that entire organs are destroyed. The higher the dose, the sooner the effects of radiation poisoning will appear and the higher the probability that the exposure will be fatal. **Acute radiation syndrome** is caused when a person is exposed to a high dose of radiation over a short period of time — minutes or hours. This can result in extreme nausea, diarrhoea, internal bleeding, bone marrow depletion and organ failure. The effects of acute radiation doses are shown in the next table.

Radiation dose (Sv)	Effects
0.75	Causes vomiting in 10 per cent of people
1	Short-term effects such as nausea and diarrhoea. Development of cancer after many years in around 5 per cent of people.
3–5	Damage to bone marrow which results in infection and haemorrhage. Can lead to death in about 50 per cent of people within two months if medical treatment is not available.
> 10	Death within 10 days due to fluid and electrolyte imbalance, bone marrow and gastrointestinal damage and infection
> 40	Death within 48 hours due to damage to the vascular systems resulting in an accumulation of fluid in the brain

Radiation burns on the back and arm of a victim of the Hiroshima nuclear explosion. Darker areas of clothing produced more heat and led to burning of the skin in the shape of the fabric pattern.

HOW ABOUT THAT!

French physicist Henri Becquerel accidentally discovered radioactivity while investigating the fluorescence of uranium salts in 1896. When he developed a photographic plate that had been in a drawer near his bench top, he found that it had been fogged up by radiation from the uranium salts.

This effect of radioactivity is now used in a protective device worn by people who work with radioactive materials. The 'fogging' of the film in this device measures the amount of radioactivity they have been exposed to.

Becquerel was the first scientist to report the effects of radioactivity on living tissue. He suffered from burns on his skin as a result of carrying a small quantity of the element radium in his pocket.

Most people will generally experience less than 0.1 Sv over the course of their life. Obviously, those who work with nuclear sources for a living such as radiographers, uranium miners and nuclear engineers would receive more than this. However, industry standards are applied to these occupations to minimise their risk to prolonged exposure effects. For example, people who work with radiation sources (radiographers, nuclear engineers, nuclear power plant workers) are limited to an exposure of 0.1 Sv over a 5 year period (0.02 Sv/year average) while uranium workers are not permitted to be exposed to more than 0.013 Sv in a year.

Radium Girls

In the 1920s, the United States Radium Corporation employed hundreds of women at their factory in Orange, New Jersey, to paint their trademark 'glow in the dark' paint onto the dials of watches. To paint the tiny numbers and indicator hands of the watches, the women would use fine-tipped brushes and they would often lick the tips of the brushes to keep the points of the brushes sharp. Many years later, these same women started to develop serious bone-related problems, particularly in the jaw. Many of the women died of cancer before the company revealed that the paint was made from a radium salt that was a million times more radioactive than uranium. Hundreds of these 'Radium Girls', as they were called in the newspapers of the day, died as a result of repeated exposure to the radiation.

The Radium Girls of the 1920s suffered radiation poisoning from the radium that they used to paint the dials of the first 'glow in the dark' watch faces.

ACTIVITIES

REMEMBER

1 What type of nuclear radiation is described by the following statements:
(a) a radioactive particle that has the same size and mass as an electron
(b) a radioactive particle that is made up of two protons and two neutrons
(c) the type of radiation that can penetrate the human body and can be stopped only by a thick shield of lead or concrete
(d) a radioactive particle that can travel almost at the speed of light
(e) a radioactive particle that carries the highest amount of charge
(f) radiation which has the smallest penetrating power
(g) radiation that travels as a wave rather than a particle.

2 Why are alpha, beta and gamma radiation referred to as ionising radiation?

3 What is background radiation caused by?

4 **Describe** factors that affect how much radiation you absorb from a radioactive source.

5 What electric charge is carried by an alpha particle?

6 How are we protected from cosmic radiation from outer space?

THINK

7 Why does alpha radiation have a higher quality factor than gamma and beta radiation even though it is less penetrating?

8 During nuclear tests in the 1950s, US soldiers were told that they were safe from alpha radiation as long as they didn't open their mouths. Why do you think they were told this?

9 Radiographers perform hundreds of X-rays, CT scans and mammograms every week, yet their yearly radiation exposure from their job is only 2.5 mSv — just under the amount you would experience in a single head CT scan. How is this possible?

10 The crews of passenger jets are exposed to more radiation than most people. Where does this extra radiation come from?

USING DATA

11 A scientist wished to determine the type of radiation emitted by a radioisotope. She had three materials (paper, plastic and lead) and an instrument called a Geiger counter, which detects nuclear radiation. She covered the radioisotope with each of the three materials and measured the radiation that passed through each material. The results of her experiment are shown in the table below.

Results of radioactivity experiment

Material	Effect on Geiger counter readings
Paper	No effect on readings
Plastic	Readings fell by two-thirds
Lead	Large fall in readings

What type of nuclear radiation does this radioisotope emit? **Explain** your answer.

INVESTIGATE

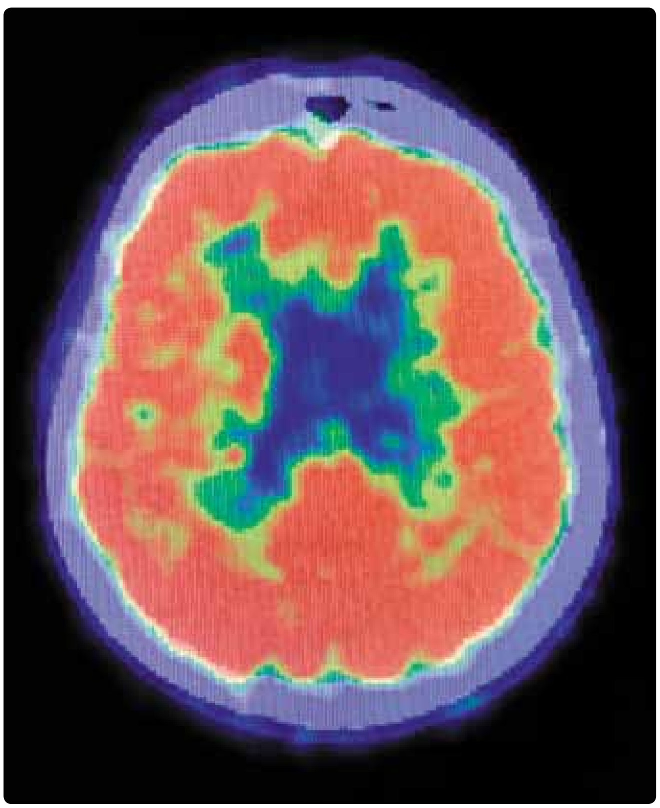
12 Most of the background radiation we experience comes from a radioactive element called radon. Find out (a) where this radon comes from and (b) why people in countries where their houses have cellars are worried about radon.

Helpful radiation

Medical uses of radiation

Diagnosing disease

Nuclear medicine imaging techniques use radioisotopes with short half-lives to find tumours, blockages in blood vessels and problems with the body's organs. The radioisotopes are given to the patient in the form of either an injection or as part of a thick liquid that the patient drinks. The type of radioisotope used depends upon what tissues or organs are being investigated and the type of diagnostic tool being used. One of the most commonly used is **positron emission topography (PET)**. During a PET scan, the radioisotope absorbed by the tumour or tissue cells produces gamma rays. These pass through the patient's body and are detected by the scanner moving around the patient to form a 2-D image 'slice'. By moving the patient slowly through the scanner, hundreds of these slice images are taken and the slices are then reassembled by computer into a 3-D image of the tissue or tumour.



A PET image of the human brain

Many nuclear instruments are used to treat and diagnose disease. Here a PET (positron emission tomography) scan is being carried out on a patient.

Some of the radioisotopes used in the treatment and diagnosis of disease

Radioisotope	Use	Half-life
Phosphorus-32	Treatment of leukaemia	14.3 days
Cobalt-60	Used in radiotherapy for treating cancer	5 years
Barium-137	Diagnosis of digestive illnesses	2.6 minutes
Iodine-123	Monitoring of thyroid and adrenal glands, and assessment of damage caused by strokes	13 hours
Iodine-131	Diagnosis and treatment of thyroid problems	8 days
Iron-59	Measurement of blood flow and volume	46 days
Thallium-201	Detection of damaged heart muscles	3 days

Radiotherapy

Radiotherapy is the use of radiation such as X-ray or the radiation produced by decaying isotopes to kill cancer cells or prevent them from spreading. It is often used along with other treatments such as surgery or chemotherapy. Unlike chemotherapy, radiotherapy can be targeted precisely so that damage to healthy tissue surrounding the cancer is minimised.

There are two main methods by which radiotherapy can be administered. In **external radiotherapy**, radiation is directed at the cancer by a machine (like the one shown below) which moves around the patient. Each beam sent by the machine strikes the tumour from a slightly different direction with the result that the tumour is blasted with large amounts of radiation while the healthy cells between the machine and the tumour receive much less radiation.

External radiotherapy

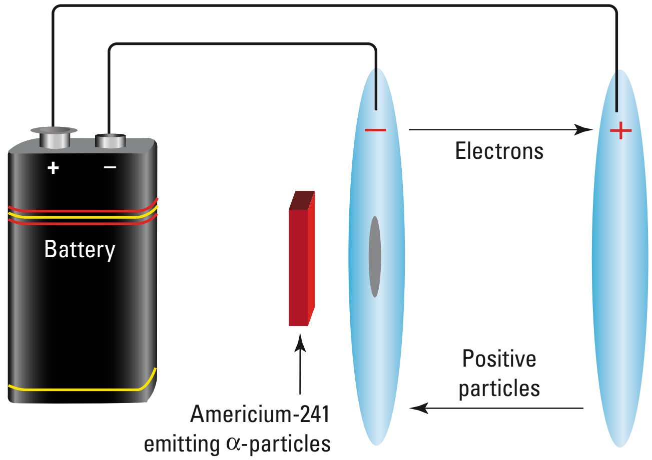
The other method, known as **internal radiotherapy** or **brachytherapy**, involves placing radioisotopes inside the body at or near the site of the cancer. In some cases both external and internal radiotherapy are used. The type of treatment depends on the type of cancer, its size and location, as well as the general health of the patient.

Smoke alarms

Inside a smoke alarm in the ionisation chamber are two plates that are oppositely charged. There is also a tiny amount of americium-241, which has a half-life of 432 years. Americium-241 atoms emit alpha radiation and change into neptunium-237 atoms. The alpha particles knock electrons off the nitrogen and oxygen molecules in the air. This creates positive particles and free electrons. The positive particles are attracted to the negative plate, and the electrons are attracted to the positive plate. A small current is set up.

When smoke particles are drawn into the smoke alarm, they attach themselves to the positive ions, make them neutral and disrupt the current. This change is sensed by the detector and the siren sounds.

Smoke alarms are cheap and save lives.

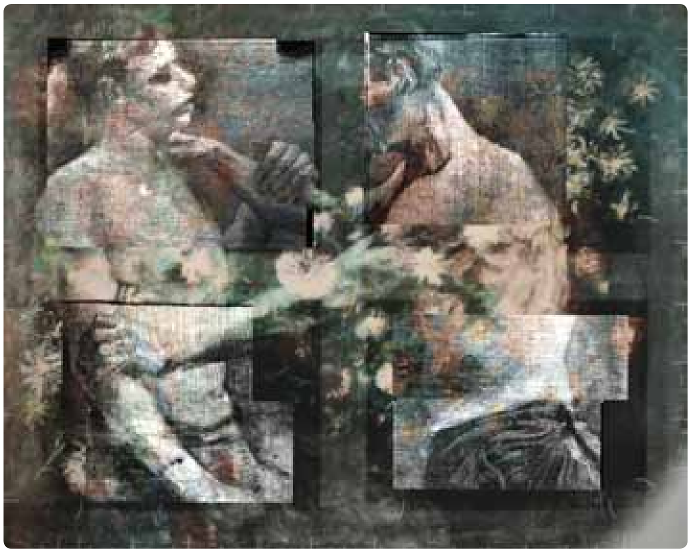


What happens in the ionisation chamber?

HOW ABOUT THAT!

No butts

Some smoke detectors can detect different types of smoke, including cigarette and cigar smoke. Different particle sizes absorb differing amounts of radiation. These smoke alarms are used in places where smoking is discouraged such as airplane toilets and non-smoking areas in restaurants. Some can even be programmed with a voice message warning smokers that it is about to sound the alarm!



This painting of a vase of flowers was credited to an anonymous artist. However, X-ray imaging of the canvas revealed a scene of two wrestlers painted beneath. This helped historians to identify this canvas as the work of Vincent Van Gogh.

X rays — not just for medicine!

Today X-rays are used not only for medical purposes, but also to detect flawed welds in engineered structures, to study under-painting in famous art works like the Mona Lisa and even to observe distant objects beyond the edges of our galaxy.

Irradiating food

Food irradiation is a commonly used process in which food is exposed to a source of ionising radiation, usually gamma rays from cobalt-60. It has a number of different purposes. It can be used to kill pests on fruit and vegetables instead of using chemical treatments. It is particularly important for controlling unwanted pests that can be imported along with the produce from other countries. Food irradiation is used by food processors to kill harmful bacteria such as salmonella and campylobacter that may be found in meat, poultry and eggs. These bacteria can cause serious illness if consumed.

Irradiation also helps to keep food from spoiling as quickly by destroying moulds and yeasts and by slowing the action of enzymes within the food.

However, food irradiation has a downside as the process also destroys some of the food's vitamins. While B vitamins such as riboflavin and niacin, and vitamin D are not particularly affected, levels of radiation sensitive vitamins A, B1 (thiamine), C, E and K can be reduced by as much as 20 per cent.

Engineer studying an X-ray of an aircraft part. Aeroplanes undergo regular inspections to check for any defects that could cause parts, or the entire aircraft, to fail.

ACTIVITIES

REMEMBER

1 What is radiotherapy?

2 How does external radiotherapy differ from internal radiotherapy?

3 **Explain** how a smoke alarm works.

4 **Describe** how a PET scan produces an image of the body.

5 Which isotopes are used in nuclear medicine for the diagnosis or treatment of (a) digestive problems (b) thyroid tumours (c) leukaemia?

6 **Explain** how radioisotopes used in food preservation stop food from spoiling.

THINK

7 (a) Is iodine-131 a more stable radioisotope than barium-137? **Explain**.
(b) The use of barium-137 in the diagnosis of digestive illnesses involves the patient drinking it in a syrup. What property of barium-137 makes its use quite safe?

8 Is cobalt-60, used in the treatment of cancer, more likely to be used in external radiotherapy or internal radiotherapy? Use the information in the table to **explain** your answer.

9 Why is it important that imaging is done within a short period of time after the patient has been given the appropriate radioactive isotope?

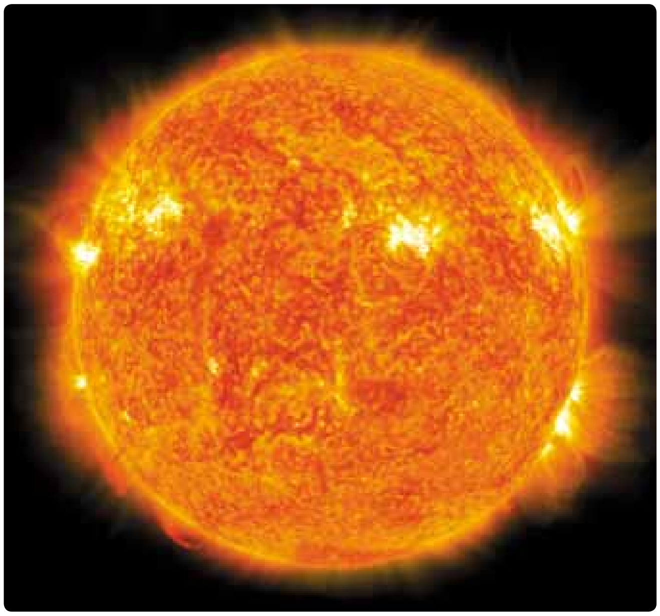
10 Why do the radioisotopes used for diagnosis not cause radiation sickness in the patient?

INVESTIGATE

11 Find out what the following isotopes are used for: (a) cadmium-109 (b) californium-252 (c) krypton-85 (d) copper-67 (e) radium 226 (f) uranium-234.

12 Radiotherapy is an effective method of treating cancer. However, it has a number of side effects. Research what the side effects are.

Energy from the atom



The largest nuclear reactor near us is the sun. Every second, 500 million tons of hydrogen is fused into larger elements producing energy, including light and heat.

The sun is a powerhouse of energy. It provides radiation in many different forms; not just as gamma and cosmic rays, but also as light and heat that allows life on Earth to flourish. All of this energy comes from special types of reactions that are occurring deep within the sun's core. While we will look at plenty of chemical reactions which involve the electrons in the outside of atoms in a later chapter, for now we will look at reactions that involve the nuclei of atoms. These are called, unsurprisingly, nuclear reactions and they occur only under certain conditions. By harnessing the power of these reactions, we can produce vast amounts of energy.

Nuclear reactions

When one substance reacts with another in a chemical reaction, bonds involving their electrons are broken and formed between the atoms of the substances to form new chemical products. In these reactions, the atoms present in the reacting substances are the same ones that are present in the products of the reaction.

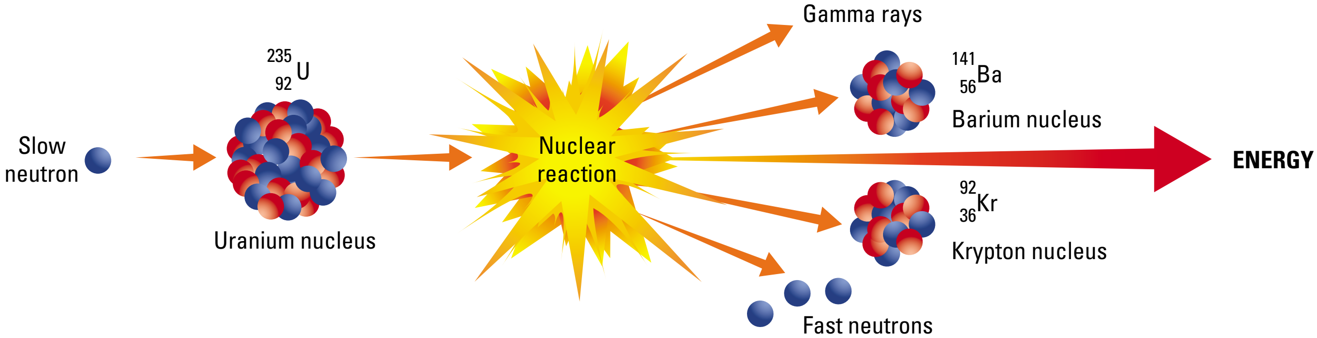
Nuclear reactions are those that take place when the nucleus of an atom interacts with either another nucleus or a nucleus particle. As a result of these reactions, new atoms are formed and energy is released. The two most important types of nuclear reaction that provide energy are nuclear fission and nuclear fusion.

Nuclear fission

Nuclear fission occurs when the nuclei of large atoms such as uranium or plutonium split to form the nuclei of smaller atoms, releasing energy in the form of radiation and heat. In some nuclear reactors, the fission of uranium-235 is caused when a neutron is absorbed by the nucleus. The nucleus splits to form two smaller nuclei (which are called **fission products**) as well as releasing more neutrons, gamma rays and heat energy.

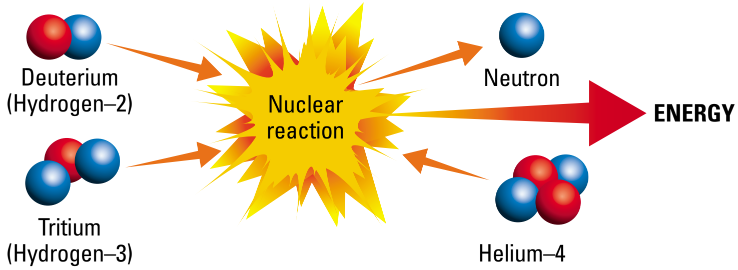
If the neutrons released in this process then go on to cause the splitting of other uranium-235 nuclei, a **chain reaction** occurs. The rate at which energy is produced can be controlled by limiting the number of neutrons that can react with other uranium nuclei. This is what happens in a nuclear reactor. The destructive power of nuclear weapons, on the other hand, is caused by an uncontrolled chain reaction.

Nuclear equation: $^{235}_{92}U + ^{1}_{0}n \longrightarrow ^{141}_{56}Ba + ^{92}_{36}Kr + 3\,^{1}_{0}n$



Nuclear fusion

In **nuclear fusion**, two small nuclei combine to form larger nuclei releasing energy. In the sun, the nuclei of the hydrogen isotopes deuterium (hydrogen-2) and tritium (hydrogen-3) fuse together to form helium nuclei releasing neutrons and massive amounts of heat and radiation. Nuclear fusion has so far been reliably produced only at very high temperatures of millions of degrees. However, the quest to perfect fusion at low temperatures — called **cold fusion** — continues. If cold fusion were to be achieved, huge amounts of energy could be produced from just the hydrogen in water!



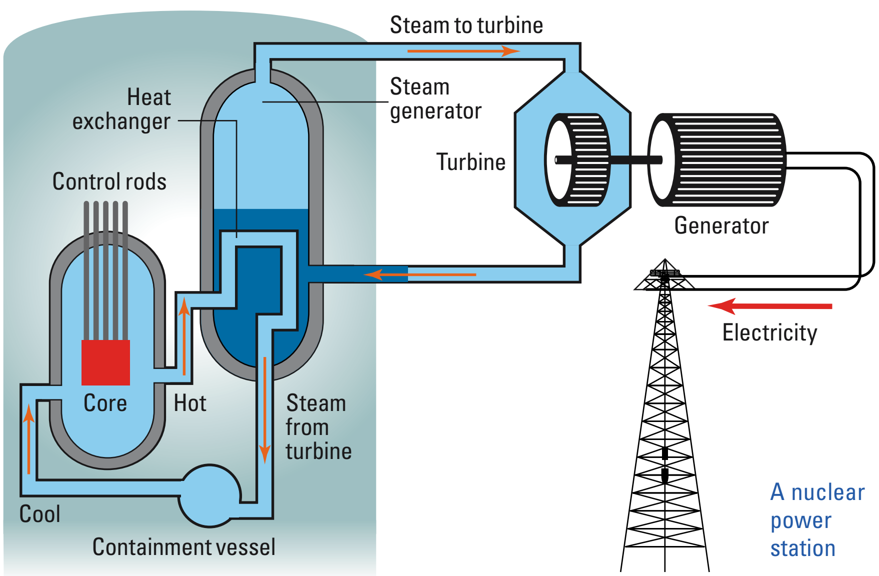
An example of a nuclear fusion reaction

Nuclear power stations

Nuclear energy is used for electricity generation in some countries, for up to 75 per cent of their energy needs. Nuclear fuels produce radiation; however, this is not electricity. So, how do these power stations produce power?

The fuel for a nuclear power station is natural uranium, slightly enriched with uranium-235. This is because, besides decaying, uranium-235 will spontaneously split (fission) if hit by a neutron, starting a chain reaction. The **control rods** are used to slow or increase the rate of the reaction by absorbing spare neutrons. They are lowered or raised as needed.

When uranium-235 splits, an incredible amount of energy is produced as heat and gamma radiation. One gram of uranium produces a million and a half times more energy than the burning of one gram of methane. This amount of **thermal energy** heats water that turns into steam and is then channelled through pipes out of the containment vessel. This steam is used to spin a turbine that is connected to an electrical generator, turning the kinetic energy of the moving steam into electrical energy. This is the same process of using steam to generate electricity in coal- or gas-fired power stations.



A nuclear power station

The nuclear energy issue

At present, Australia has only one nuclear reactor and it is used for research purposes and to produce radioisotopes for medical and industrial purposes. While many countries use nuclear energy to provide their electricity, Australia has yet to do so. It is not an easy decision to make and there are many arguments in favour of and against the use of nuclear energy.

The arguments for nuclear energy

Ready access to fuel

As Australia has 30 per cent of the world's uranium supply, we are able to supply our own nuclear fuel for any reactors built here. Presently, we export nearly all of the 7000 tonnes of uranium ore that comes from mines in the Northern Territory (Ranger and Nabarlek) and South Australia (Roxby Downs).

No greenhouse gases

Coal-fired power stations pump enormous amounts of greenhouse gases into the Earth's atmosphere, gases which are believed to contribute to global warming, acid rain and climate instability. The average coal-fired power station produces about seven million tonnes of carbon dioxide each year, as well as around 200 000 tonnes of sulfur dioxide (a major source of atmospheric pollution) and about the same amount again of other waste products that contain toxic metals such as arsenic, cadmium and mercury. Nuclear power stations, on the other hand, release only water vapour into the air.

Efficiency

One of nuclear power's biggest advantages is that it is extremely efficient in terms of the amount of energy that you get from a small amount of uranium fuel. One tonne of uranium produces more energy than is produced by several million tonnes of coal or several million barrels of oil. The following table shows the typical heat values of various fuels.

Fuel source	Energy produced from 1 kg of fuel (MJ)
Brown coal	9.7
Firewood	16
Black coal	30
Natural gas	39
Crude oil	46
Uranium (light water reactor)	500 000

Note 1 MJ = 1 million Joules

The arguments against nuclear energy

Cost

While nuclear fuel and its efficiency make it more competitively priced than fossil fuels, the costs of building a nuclear reactor are much higher than those involved in coal burning power stations, especially as the safety measures that must be incorporated into their design make them more expensive.

Safety concerns

Undoubtedly, the biggest concern of most people is with regard to the safety of nuclear reactors. This concern is difficult to dismiss in light of the widely reported mishaps at Three Mile Island in 1979, Chernobyl in 1986 and Fukushima in 2011. Accidents at nuclear facilities releasing deadly radiation into the atmosphere can affect whole regions. The background radiation levels in Europe, Africa and Asia were all increased by the radiation released from Chernobyl.

The hazards of uranium

Radioactive material makes its way into air, water, soil, food, animals and human tissue. Uranium releases radioactive radon gas into the atmosphere when it is mined and milled. This radioactive gas returns to Earth as rain, contaminating soil and water. The solid radioactive wastes from mining, called **tailings**, can infiltrate through the soil and into the ground water or are dispersed into the environment by wind.

Nuclear waste management

The average nuclear reactor produces around 25 tonnes or so of this spent fuel each year it is in operation. This waste is highly radioactive and gives off a great deal of heat. While most of this waste can be reprocessed for reuse, it must be stored until this can be done. Many methods of storing or disposing of this waste have been used including storage in steel or concrete containers that are then buried in deep disused mineshafts or in isolated areas, and **vitrification**, where liquid radioactive waste is mixed with glass and poured into steel drums. The steel drums are then dug deep into the ground or under the sea floor. However, none of these has yet proved satisfactory due to the risk of leakage and subsequent damage to the environment.

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eLesson

Australia's nuclear future

Watch a video from the ABC's *Catalyst* program about the future of nuclear energy in Australia.

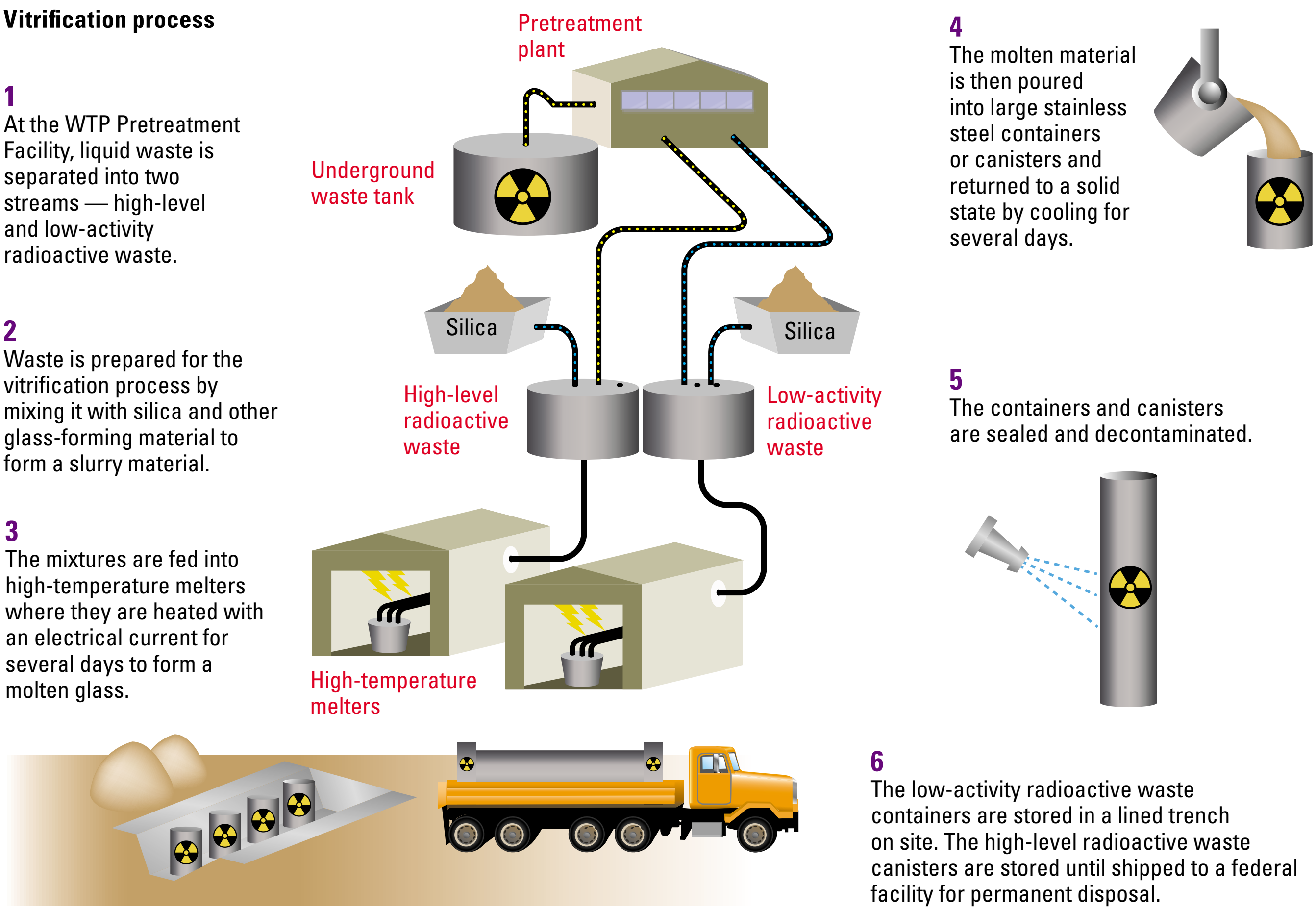
eles-1075

HOW ABOUT THAT!

Yummy — nuclear waste!

The strange green things in this photo are *Geobacter metallireducens*, a species of anaerobic bacteria that use metals to produce energy in the same way that humans use oxygen. These bacteria are hardy enough to survive in radioactive environments and they are able to convert soluble uranium waste, which can leach out of storage containers and contaminate water supplies, into a solid form which is easier to dispose of safely. Other helpful species of *Geobacter* being studied can remove petroleum contamination from polluted water and convert waste organic matter to electricity.

Vitrification process



ACTIVITIES

REMEMBER

1 Write down two advantages and two disadvantages of nuclear power stations.

2 **Explain** the difference between nuclear fission and nuclear fusion.

3 What type of reaction is happening in the sun?

4 How are nuclear reactions different from chemical reactions?

5 **Explain** briefly how a nuclear power station generates electricity.

6 **Describe** the nature of nuclear waste.

7 **Explain** how radioactive waste can affect people via its effect on the environment.

8 **Describe** some technological solutions to the disposal of nuclear wastes.

THINK

9 Some people have suggested sending all of the nuclear waste into the sun by rocket to get rid of it. Is this a good idea? **Explain** your answer.

10 Nuclear submarines have two big advantages over conventional diesel submarines. What are they?

INVESTIGATE

11 Research the following types of nuclear reactors and find out: (a) what they are built from (b) what fuel rods and control rods are (c) what type of nuclear reaction occurs in the reactor (d) how the reactor is kept cool (e) how electricity is generated (f) what kinds of safety features are used.
(i) RBMK
(ii) PWR
(iii) GCR
(iv) FBR

CREATE

12 Imagine that you have been asked to design a series of signs to be placed around a nuclear waste site somewhere in the desert warning of its danger. However, you've been asked to do this in the form of a picture rather than using words on the basis that the nature of the hazard needs to be understood by anyone — including those who can't read or who have no idea what nuclear waste is! Design a sign that fulfils these criteria.

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work sheet — 6.1 The sun and nuclear fusion

The dark side of radiation

While nuclear radiation has many uses that are beneficial to society as a whole, there is no doubt that it is very much a two-edged sword. For every person whose life has been saved by radiotherapy or a smoke detector, there is someone who remembers the toll taken by Chernobyl, Fukushima, Hiroshima and Nagasaki.

When reactors go wrong

Like any other piece of complex technology, a nuclear reactor can work safely only if its many individual systems are functioning smoothly and efficiently. They must be well-maintained and well-managed by highly trained personnel. Unfortunately, in many cases the flaws of a nuclear reactor's design are not spotted until it is too late.

Chernobyl 1986

Reactor 4 was an old design that used graphite moderators, used water as a coolant and had no radiation containment shields around the reactor cores. On 25 April 1986, Reactor 4 at Chernobyl was scheduled to be shut down for routine maintenance. Due to a series of operational errors, nearly all of the control rods were withdrawn from the core to compensate for a power loss. This caused the reactor to become rapidly unstable and fission started to occur too quickly. While an attempt was made to fully insert all of the control rods (absorbing all of the neutrons in the core and stopping the fission reaction), a reaction with the graphite tips of the control rods suddenly caused an uncontrollable power surge in the reactor. In 4 seconds, the power rocketed up to 100 times its normal value and the reactor core reached 5000 °C (about the same temperature as the surface of the sun), causing some of the fuel rods to rupture. The hot fuel particles hit the cooler water and caused a steam explosion that destroyed the reactor core. The graphite core caught fire and, because it had no containment shield, some of the vaporised radioactive fuel went into the atmosphere.

While only two people were killed in the original explosion, three others died during the night and fifty emergency workers died from acute radiation

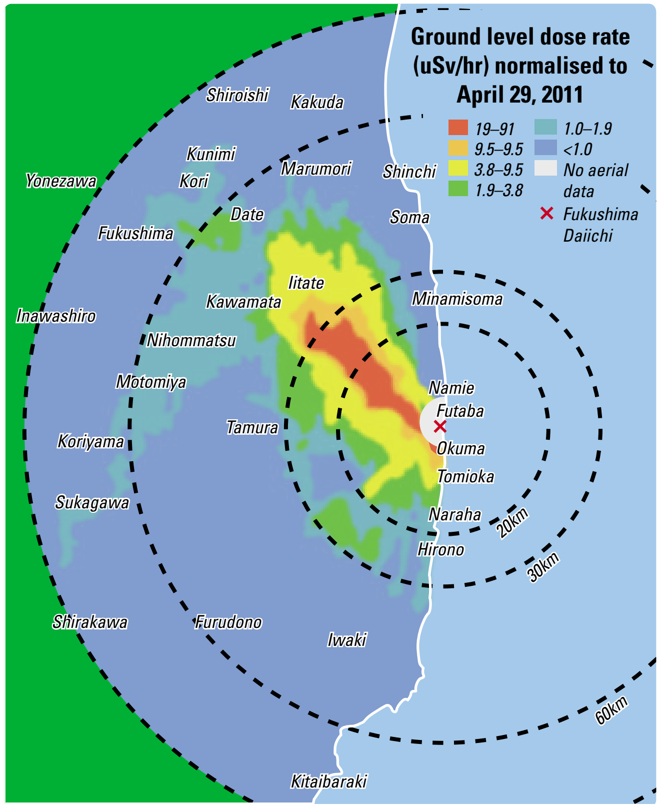
Pripyat in the Ukraine was home to 50 000 people, most of whom had jobs at Chernobyl. When reactor 4 of the Chernobyl nuclear power plant exploded, the town was abandoned. Now, nature is starting to reclaim it despite the remaining radiation.

The remains of Reactor 4 after the explosion

poisoning. Since the accident, the rate of thyroid cancer in children has been ten times higher in the region around Chernobyl and, of the 600 000 people contaminated by radiation, 4000 have died from long-term cancers.

Fukushima 2011

The Fukushima Daiichi nuclear disaster was caused by a series of unlucky events occurring one after another. On 11 March 2011 a massive earthquake occurred off the coast of Honshu (the main island of Japan) leaving the Fukushima nuclear reactor complex relatively unharmed but reliant on its back-up generators. Unfortunately, the earthquake caused a tsunami that struck the coast of Honshu less than an hour later, killing more than 19 000 people and destroying over 1 000 000 buildings. The reactors at Fukushima Daiichi were flooded by the 15 m high tsunami, disabling 12 of the 13 back-up generators as well as the heat exchangers that released waste heat into the sea. Without power, the circulation of water coolant around the reactor cores ceased, causing them to become so hot that much of the coolant water was boiled off. The heat became high enough to melt the fuel rods in reactors 1, 2 and 3 (this is referred to as a **melt-down**). A reaction between the cladding of the melted fuel rods and the remaining coolant water produced hydrogen gas that exploded when mixed with the air. This threw nuclear material up into the atmosphere. More than 160 000 people had to be evacuated from the area for fear of radiation. While three employees at the Daiichi plants were killed directly by the earthquake and tsunami, there were no fatalities from the nuclear accident.



Map showing the amount of radiation absorbed per hour at ground level around Fukushima six weeks after the melt-down

Nuclear weapons

There are at least 30 000 nuclear weapons in the world today, enough to destroy our planet many times over and effectively obliterate life from its face.

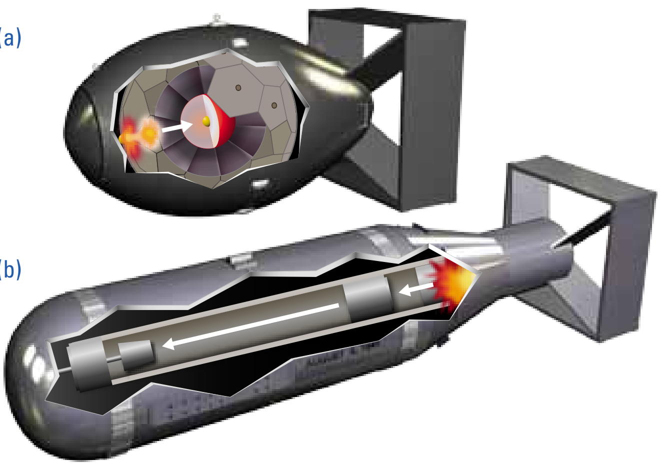
Fission bombs

As you'll recall from section 6.5, a chain reaction occurs when slow neutrons strike a uranium-235 nucleus, causing it to break into smaller nuclei, releasing energy, radiation and more neutrons which, in turn, strike more uranium nuclei and so on. Nuclear reactors utilise a controlled chain reaction where the number of neutrons available to fission the uranium nuclei is manipulated to ensure that energy is released at a steady rate. Fission bombs (also called

atom bombs or **A bombs**), on the other hand, rely on uncontrolled chain reactions in unstable radioactive materials. In an **uncontrolled chain reaction**, *all* of the released neutrons cause further reactions, releasing devastating amounts of energy (mainly in the form of heat and light) and radiation.

An uncontrolled chain reaction can occur only if the amount of radioactive material is over a certain mass — this is called the **critical mass**. The more fissionable the material, the smaller the critical mass will be. For example, the critical mass of enriched uranium ore in which 97 per cent of the uranium atoms are fissionable uranium-235 is about 15 kg. Uranium that is 15 per cent uranium-235 has a critical mass of 400 kg.

If you wanted to cause an uncontrolled chain reaction in naturally occurring uranium ore (which is made up of less than 1% of uranium-235) you would need more uranium than there is in the whole world!



(a) This implosion bomb uses plutonium-239 as its energy source. It is similar to the bomb code-named Fat Man that was dropped on Nagasaki on 9 August 1945. (b) This gun-style bomb uses enriched uranium-235 and is similar to the bomb code-named Little Boy that was dropped on Hiroshima on 6 August 1945.

Structure of a fission bomb

Fission bombs use lumps of fissionable material such as uranium or plutonium. Each lump is smaller than the critical mass. The fission bomb works by bringing two or three of these subcritical masses together, usually using an explosive charge. When the masses are combined, the mass exceeds the critical mass, causing a nuclear explosion.

Fusion bombs

Fusion bombs (also known as **hydrogen bombs** or **H bombs**) detonate in two stages. The first stage involves the explosion of a small fission bomb that creates the necessary high temperatures and the second stage occurs when the superheated hydrogen nuclei combine.

INVESTIGATION 6.2

Modelling critical mass

AIM To model how nuclear reactions can become critical

You will need:
40 marbles
a metre ruler
chalk

- Draw up a data table like the one shown here:

Circle radius (cm)	Number of collisions
50	
40	
30	
20	
10	

- Find a flat area where you can draw a chalk circle (outside on concrete is a good idea). Be careful that no-one slips on escaped marbles!
- Use the metre ruler and the chalk to draw a circle on the ground. The circle should have a radius of about 50 cm.
- Place 39 of the marbles evenly throughout the area of the circle.
- Place a single marble just outside the edge of the circle and shoot it into the marbles in the circle. Count the total number of marbles that were involved in one or more collisions. Enter this value into your data table.
- Repeat this procedure for circles that have radii of 40 cm, 30 cm, 20 cm and 10 cm.

DISCUSSION

1. **What circle radius gave the most collisions?**
2. **What relationship did you find between the circle radius and the number of marble collisions?**
3. **Each circle had the same number of marbles spread evenly over its area. In which circle were the marbles most densely packed (closest together)?**
4. **The total circle area represents the amount of uranium in a sample, while the areas covered by each marble represent the uranium-235 in the sample. In which circle did the marbles cover the biggest fraction of the total area? (This represents the richness of the sample.)**
5. **Each marble collision represents the fission of one of the uranium-235 nuclei. How did the richness of the sample circles affect the number of fission reactions/collisions?**
6. **Is it more likely for chain reactions to occur in samples with a high richness or a low richness? Explain.**

Effects of nuclear weapons

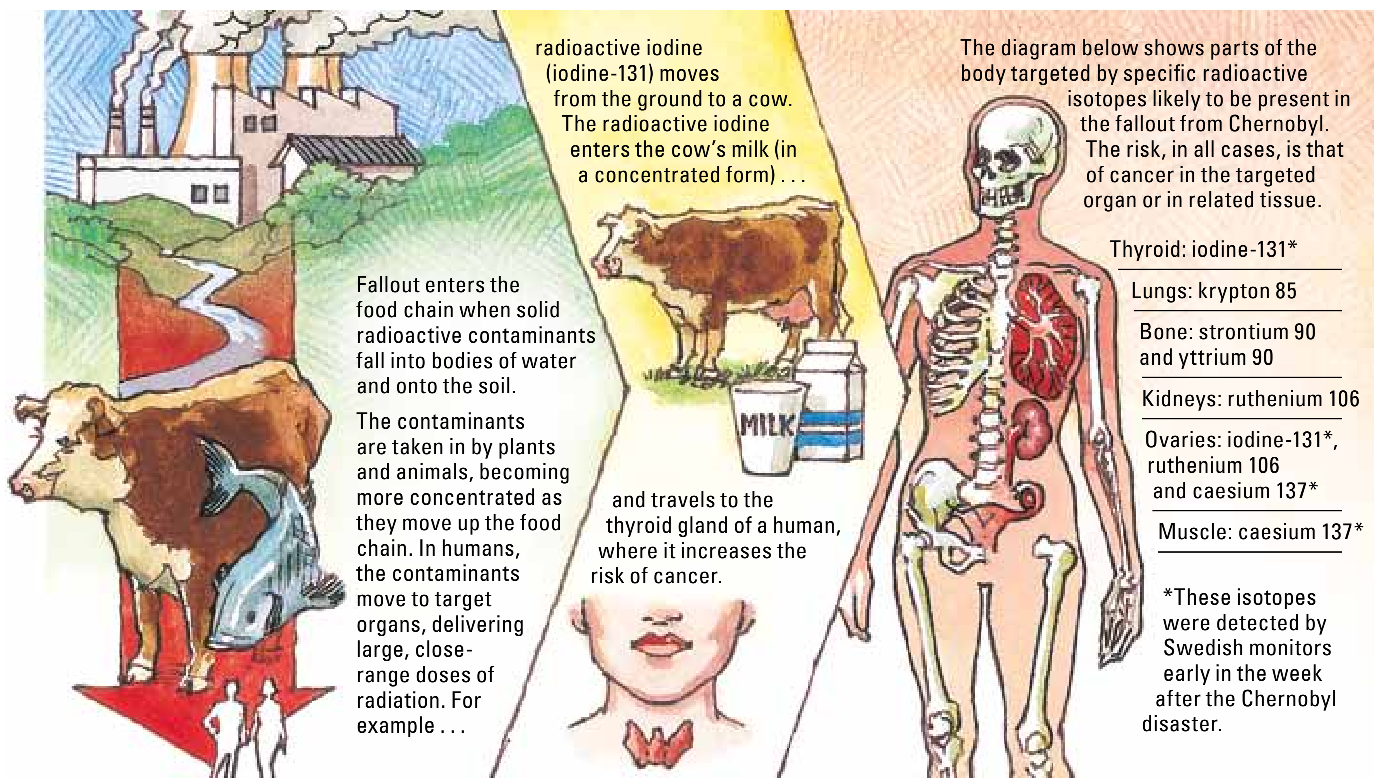
When nuclear weapons are detonated, enormous amounts of heat and radiation spread out from the centre of the blast (known as **ground zero**) in what is called a **thermal flash**. This radiation forms a fireball which generates the distinctive mushroom cloud associated with nuclear weapons. The fireball from the Hiroshima bomb formed a fireball 7 km across. At locations close to ground zero, most substances were melted or burned and organic matter (including people) was vaporised. People up to 50 km away received serious burns and those who looked directly at the flash were blinded.

Atomic bomb destruction, Hiroshima, Japan. Around 90 per cent of the buildings were destroyed, with only a few concrete-reinforced buildings surviving. Some 70 000 people died instantly, with tens of thousands more dying in the aftermath.

After the initial blast, the vaporisation of particles close to the blast causes an implosion of air from further out. When these inrushing air particles collide, they cause a high pressure shock wave to spread outwards at speeds of up to 3000 km/h. This shock wave causes the destruction of buildings, blowing them outwards from the centre of the blast.

The detonation of nuclear devices releases large amounts of radiation in the form of gamma rays which cause very strong electromagnetic fields to form and then collapse. These electromagnetic fields can burn out electrical and electronic systems including computer networks and power grids, and even disrupt the electrical systems that control cars, planes and weaponry. This burst of electromagnetic activity is called an **electromagnetic pulse**.

The most devastating effects for survivors are due to radiation exposure. As we saw earlier in



this chapter, large amounts of radiation, as would be experienced by those closest to the blast, would be fatal with the level of exposure reducing with increasing distance from ground zero. The DNA in a survivor's cells can be damaged, leading to cancer, leukaemia and immune system collapse later in life, while damaged DNA in the sex cells means that their children and even grandchildren may suffer mental or physical defects.

The radioactive nuclei formed during the nuclear reactions as well as tonnes of irradiated dust are blasted high into the atmosphere during detonation and the formation of the mushroom cloud. In the weeks following the nuclear explosion, these come back down to Earth as **nuclear fallout**. This radioactive fallout increases the background radiation for many years where it comes down, so people in the fallout zones are exposed to higher radiation levels with damaging effects.

ACTIVITIES

REMEMBER

1 What nuclear reaction is used in nuclear power stations?

2 **Describe** radioactive fallout.

3 **Explain** how the Chernobyl nuclear accident occurred.

4 **Define** the following terms: (a) melt-down (b) critical mass (c) electromagnetic pulse (d) ground zero

5 **Describe** the short-term and long-term effects of an atomic explosion.

THINK

6 Why did the incidence of leukaemia increase among young children rather than adults after Chernobyl?

7 After the Fukushima disaster, people who may have been in the area may have been exposed to radioactive iodine. Why would these people have a higher chance of developing thyroid cancer?

8 **Explain** why nuclear energy is described by some as 'a blessing and a curse'.

9 Why don't the uranium deposits in the Earth's crust undergo a chain reaction?

10 Is it possible for nuclear reactors to explode like atomic bombs? **Explain**.

11 One of the problems that led to the disaster at the Chernobyl nuclear reactor was due to the fact that the control rods could not be inserted into the reactor. Why would this have been a problem?

INVESTIGATE

12 Find out how a Geiger counter is able to measure the amount of radiation in a location.

13 Create a report on the accident at Chernobyl, Fukushima or Three Mile Island, explaining
(a) how the accident affected the workers at the power plant and the surrounding towns and villages
(b) the attempts made to reduce or control the damage caused by the radiation
(c) the long-term effects of the accident.

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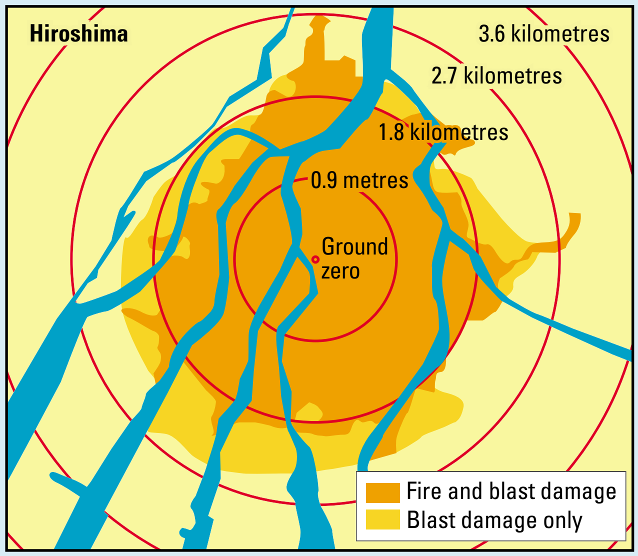
14 Suppose you have been asked to write a report to discuss the following proposal: The use of radioactive elements should be banned in Australia. Give both sides of the argument, but present a conclusion for or against the proposal. For more information, click on the **Uranium Information Centre** weblink in your eBookPLUS. You should also search the internet using keywords such as uranium, radiation, mining, nuclear and waste to find other useful sites.

USING DATA

15 The map and table shown here indicate the distribution of deaths and injuries caused by the Hiroshima bombing.



Distance from ground zero (km)	Killed	Injured	Population
0–1.0	26 700 (86%)	3 000 (10%)	31 200
1.0–2.5	39 600 (27%)	53 000 (37%)	144 800
2.5–5.0	1 700 (2%)	20 000 (25%)	80 300
Total	**68 000 (27%)**	**76 000 (30%)**	**256 300**

Atomic bomb damage of Hiroshima

(a) Use this information to determine:
(i) original population of Hiroshima before the bombing
(ii) number of people killed who were within 1 km of ground zero.
(b) As you would expect, the number of people killed gets smaller the further from ground zero that they were located. What explanations can you give that the percentage wounded doesn't follow the same pattern?

assess on

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FOCUS activity

Explain why nuclear energy is described by some as 'a blessing and a curse'.

Access more details about focus activities for this chapter in your eBookPLUS.

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1 What do the following terms mean: enrichment, radiation, chain reaction?

2 **Explain** the function of each of these components of a nuclear reactor:
(a) coolant
(b) control rods
(c) moderator.

3 Why is graphite rarely used as a moderator material in Western countries?

4 Uranium-235 has an atomic mass of 235 and an atomic number of 92.
(a) How many protons
(b) neutrons
(c) nucleons does it have?
(d) Why is uranium-235 more fissionable than uranium-238?

5 **Describe** the three main types of radiation and their penetrating power.

6 How do control rods allow the fission rate in a reactor to be manipulated?

7 **Explain** why a 2 kg lump of uranium-235 could not be made to explode like an atom bomb.

8 Determine how many X-rays you would need to have in a short period of time before you developed any acute symptoms of radiation poisoning.

9 It has been found that crews of international passenger jets develop cancers at a slightly higher rate than people in many other professions. Why do you think this is the case?

10 How does a controlled chain reaction differ from an uncontrolled chain reaction?

11 Imagine that it has been decided that a nuclear power station will be built in Queensland. Suggest possible locations for the site as well as a place to store the waste and justify your choices.

12 It has been suggested that a good way to dispose of nuclear waste would be to load it onto a rocket and send it into the sun. Do you think that this would work? **Explain** your answer.

13 The hydrogen atom exists as three different isotopes.
(a) How are the atoms of each isotope different from the others?
(b) **Identify** two features of the hydrogen atom that are the same for each of the three isotopes.

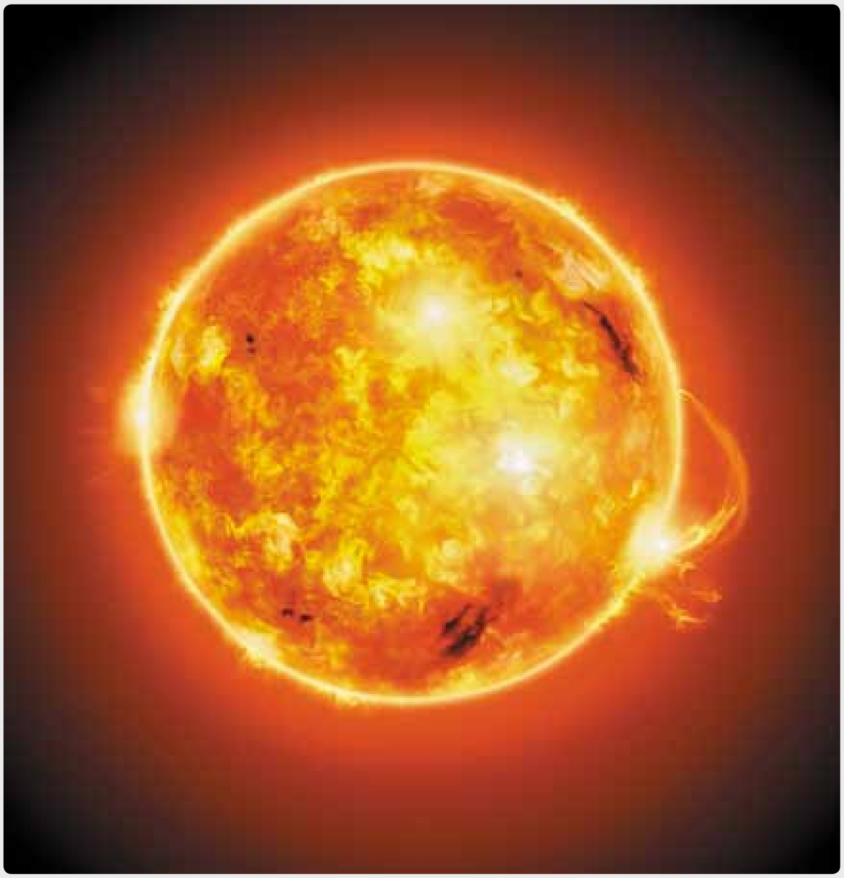
14 Alpha particles are helium nuclei containing two protons and two neutrons.
(a) What is the electric charge of an alpha particle?
(b) How does the mass and size of an alpha particle compare with the mass and size of a beta particle?
(c) Suggest why alpha particles are easily stopped by human skin while beta particles are not.
(d) Which type of radiation from the nucleus is more penetrating than either alpha or beta particles?

15 Why is radiation therapy able to be used in the treatment of cancerous tumours when radiation is able to *cause* cancer?

16 Which type of nuclear radiation travels at the speed of light?

17 Where does most of the natural background radiation that we experience every day come from?

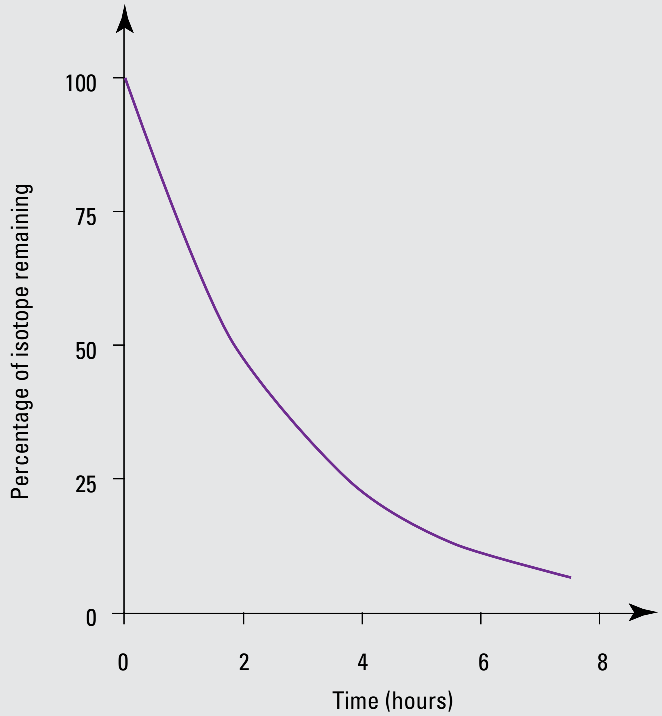
18 Radioisotopes have many uses.
(a) What property of radioisotopes makes them useful?
(b) **Describe** some of the beneficial uses of radioisotopes.
(c) Some radioisotopes are considered highly dangerous even after thousands of years. Why?



19 Two isotopes of the element carbon found naturally on Earth are carbon-12 and carbon-14.
(a) How is every atom of carbon-14 different from every atom of carbon-12?
(b) What features and properties do carbon-14 and carbon-12 have in common?
(c) Which of the two carbon isotopes is stable?

20 The half-life of strontium-90 is 28 years. If a 400 g sample of strontium-90 was left to decay, how many grams of the sample would be left after:
(a) 28 years
(b) 56 years
(c) 84 years?

21 Estimate the half-life of the isotope whose decay is shown in the graph below.



22 **Explain** how it is possible to use carbon-14 to determine the age of a dead plant found embedded in rock.

23 How did the Curies know that there was an unknown element apart from uranium in pitchblende?

24 The total number of protons and neutrons in the nucleus is known as the ___________ number.

25 Tritium is an isotope of ___________.

26 Nuclear power stations produce energy from the ___________ of uranium-238.

27 Smoke alarms contain a radioactive isotope that produces ___________ particles.

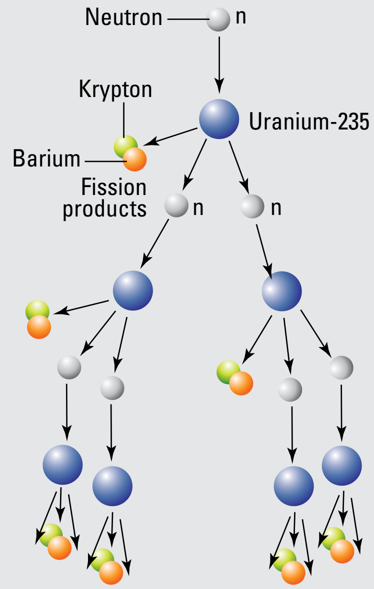
28 Of the three main types of radiation, ___________ radiation is the most dangerous.

29 Americium-241 has a ___________ of 432 years.

30 How many protons and neutrons does hydrogen-3, $^{3}_{1}H$ have?

31 What is the mass number of $^{12}_{6}C$?

32 **Explain** what is happening in the diagram below.



TEST YOURSELF

1 The half-life of an isotope is the
A mass of the isotope that will decay over a year.
B time taken for an isotope to cease being radioactive.
C period taken for half of its particles to decay.
D half the mass of an isotope in kilograms. (1 mark)

2 Which of the following isotopes is used in the diagnosis of thyroid tumours?
A Cobalt-60
B Iodine-131
C Barium-137
D Thallium-201 (1 mark)

3 Which of the following could be dated using Carbon-14?
A stone axe head
B dinosaur bone
C medieval manuscript
D early 20th century teacup (1 mark)

4 What is the purpose of the control rods in a nuclear reactor?
A To store used nuclear fuel.
B To absorb neutrons.
C To keep the core cool.
D To deflect neutrons back into the core. (1 mark)

5 Which of these isotopes is stable?
A Carbon-12
B Nitrogen-13
C Hydrogen-3
D Uranium-235 (1 mark)

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6.2 Radioactivity: puzzles
6.3 Radioactivity: summary

STUDY CHECKLIST

HISTORY OF RADIOACTIVITY

- ☐ **investigate** the contribution of scientists such as Henri Becquerel, Marie and Pierre Curie, and Lord Rutherford to the development of the model of the structure of the atom and radioactivity **6.1**
- ☐ **describe** the impact of the discovery of radioactivity and the subsequent development of nuclear technology on the course of history **6.1, 6.4**
- ☐ **explain** how radioisotopes are used in nuclear reactors, radiometric dating, the treatment of cancer, medical diagnosis and food preservation **6.2**
- ☐ **examine** the risks associated with radioactivity **6.6**

RADIOISOTOPES

- ☐ associate different isotopes of elements with the number of neutrons in the nucleus **6.2**
- ☐ **explain** why, in terms of the stability of the nucleus, some isotopes are radioactive while others are not **6.2**
- ☐ represent isotopes correctly in both symbols and words **6.2**

NUCLEAR RADIATION

- ☐ **describe** the characteristics of alpha, beta and gamma radiation, including penetrating power **6.3**
- ☐ **identify** the main sources of background radiation **6.3**
- ☐ **define** the half-life of radioisotopes **6.3**
- ☐ **explain** how the known half-life of some radioisotopes can be used to determine the age of rocks, fossils and ancient artefacts **6.4**
- ☐ **describe** the effects of radiation on survivors of Hiroshima and Nagasaki **6.3**

ENERGY FROM ATOMS

- ☐ **describe** the use of nuclear fission reactions in nuclear reactors **6.5**
- ☐ **explain** why not all radioactive elements are suitable for use in nuclear reactors **6.5**
- ☐ **describe** the events that led to the accidents at Chernobyl and Fukushima **6.6**
- ☐ **compare** and contrast fission and fusion reactions **6.6**
- ☐ **explain** how nuclear reactions differ from chemical reactions **6.6**
- ☐ **identify** the two methods used to create a critical mass in nuclear weapons. **6.6**

SUMMARY

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Digital documents

Individual pathways

Activity 6.1 Revising radioactivity doc-10651	**Activity 6.2** Investigating radioactivity doc-10652	**Activity 6.3** Investigating radioactivity further doc-10653

eLessons

The mystery of radium
Watch a video from *The story of science* about the Curies and radioactivity.
Searchlight ID: eles-1779

DNA and Hiroshima
Watch a video from *The story of science* about DNA.
Searchlight ID: eles-1781

Australia's nuclear future
Watch a video from the ABC's *Catalyst* program about the future of nuclear energy in Australia.
Searchlight ID: eles-1075