TOPIC 6
Inside the atom

6.1 Overview

What does a cake have to do with chemistry? This model depicts an early idea for the structure of an atom. This was called the plum pudding model and was devised by English chemist J. J. Thomson. It shows negatively charged electrons embedded in a positively charged sphere. We now have a much better understanding of atoms.

6.1.1 Think about atoms

• How did a plum pudding help scientists gain an understanding of atoms?
• How did Lord Rutherford find out that the atoms in solid gold are mostly empty space?
• What causes radioactivity?
• Does ‘radioactive’ always mean ‘dangerous’?
• How is uranium used in a nuclear reactor?
• What’s the connection between radioactivity and fossils?
• How is radioactivity used in the treatment of cancer?

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6.1.2 Do you have the inside information?

All substances are made up of tiny particles. You probably already know quite a lot about the particles inside substances. This knowledge is the first step in your quest to find out why substances behave the way they do.
Think

Answer the questions below to find out how much you already know about the inside story on substances.

1. The substances around you and inside you can be placed into three groups — elements, compounds and mixtures.
   (a) Which one of these groups contains substances that are made up of only one type of atom?
   (b) Which one of these groups is the least likely to be found naturally in the Earth’s crust?
   (c) What is the difference between a compound and a mixture?
   (d) Arrange the substances listed below into the three groups of substances to complete the affinity diagram below.

2. Elements, compounds and mixtures are made up of tiny particles called atoms and molecules.
   (a) How is a molecule different from an atom?
   (b) List two elements that can be made up of molecules.
   (c) List two compounds that are made up of molecules.
   (d) Name one compound that is not made up of molecules.

3. Name three particles found inside an atom.

4. Which of the diagrams below represents:
   (a) an atom of an element
   (b) a molecule of an element
   (c) a molecule of a compound?

(i)  

(ii) 

(iii) 

(iv)
6.2 Chemical building blocks

6.2.1 The mystery of matter

Most of our knowledge about the ‘building blocks’ of matter that we call atoms is less than 100 years old. But the idea that matter was made up of atoms was first suggested about 2500 years ago by the great philosopher and teacher Democritus. Since then, various theories and models of the atom have been accepted, rejected and modified. The flowchart below shows some of the important developments in our knowledge of the atom.

6.2.2 The current model

The model of the atom accepted today consists of a tiny, dense nucleus, made up of protons and neutrons, which is surrounded by electrons. It provides us with an explanation of many observable phenomena. However, it is likely that the model will continue to change or become more detailed as scientists continue with their research.
The nucleus, in the middle of the atom, is small and very dense. It is made up of protons and neutrons, which are held together by a very large nuclear force. The nucleus makes up almost all of the mass of an atom.

Protons have a positive electric charge.

Electrons orbit the nucleus, following paths commonly referred to as electron clouds. Electrons have a negative electric charge equal in size to the positive charge of a proton, and a tiny mass, about \( \frac{1}{1800} \) of the mass of a proton or neutron. The number of electrons in an atom is equal to the number of protons in its nucleus. This means that an atom is electrically neutral.

Neutrons have no electric charge and approximately the same mass as protons.

**HOW ABOUT THAT!**

Even the largest atoms are less than one billionth of a metre across. That's a millionth of a millimetre and about \( \frac{1}{20\,000} \) of the diameter of the finest of human hairs.

**HOW ABOUT THAT!**

Lord Rutherford's model of the atom was based on experiments in which he fired tiny positive alpha particles at very thin sheets of gold foil. Most of the particles went straight through the gold foil and very few were reflected back. He explained that the few particles that were reflected back were repelled by a very small, positively charged nucleus in the atoms of the gold. Most of the alpha particles, he said, continued through the foil because each gold atom consists mainly of empty space. Lord Rutherford said later that his observations were about as credible as if you had fired a 16-inch shell at a piece of tissue paper and it had come back and hit you!
INVESTIGATION 6.1
Locate the nucleus
AIM: To model Rutherford’s experiment

Materials:
a hardcover book of at least A4 size
5 plastic soft drink bottle lids
a 10 mm diameter ball bearing or 12 mm diameter marble

Method and results
• Support the book on a benchtop using a bottle lid under each corner.
• Have one member of your group lift the book, place the fifth bottle lid somewhere in the area surrounded by the other four lids and replace the book. The fifth lid represents the nucleus of the atom in this model.
• After the other members of your group turn around, they take turns to roll the ball bearing or marble under the book to find the location of the ‘nucleus’.

Discuss and explain
1. Record the number of times the ball bearing or marble is rolled before striking the ‘nucleus’ for the first time.
2. Comment on how difficult it is to locate the ‘nucleus’ in this model.
3. What is represented in this model of Rutherford’s experiment by:
   (a) the area under the book in the area surrounded by the four lids?
   (b) the ball bearing or marble?
4. Comment on the weaknesses of this model of Rutherford’s experiment.

6.2 Exercises: Understanding and inquiring
To answer questions online and to receive immediate feedback and sample responses for every question, go to your learnON title at www.jacplus.com.au. Note: Question numbers may vary slightly.

Remember
1. Describe the ‘plum pudding’ model of the atom proposed by J. J. Thomson.
2. Why did most of Rutherford’s alpha articles go through the thin sheets of gold foil?
3. What was the main weakness of the Rutherford model of the atom?
4. Describe, with the aid of a labelled diagram, the modern view of the structure of the atom.
5. Name the three important particles that make up an atom.
6. Where is most of the atom’s mass located?
7. How are protons different from neutrons? How are they similar?
8. Describe the differences between protons and electrons.

Think
9. What is the main difference between John Dalton’s model of the atom and the models of Thomson, Rutherford and Bohr?
10. Explain why it is not surprising that the neutron was discovered quite a long time after the electron and proton.
11. Is the current model of the atom a theory or a fact? Explain your answer.

Create
12. Make a 3D version of one of the models of the atom proposed since the time of Democritus.
6.3 Stability and change: Inside the nucleus

6.3.1 The core of the atom

At the centre of every atom is a tiny, solid core called the nucleus. Within the nucleus, protons and neutrons are usually held together by incredibly strong forces. Some of the mysteries of radioactivity can be unravelled by taking a closer look inside the nucleus.

6.3.2 Neutrons and isotopes

All atoms of a particular element have the same number of protons. However, often the number of neutrons in atoms of the same element is different. Such atoms have the same atomic numbers but different mass numbers. Atoms of the same element with different mass numbers are called isotopes. Most elements exist as two or more isotopes. These isotopes all have the same chemical properties, but slightly different masses.

Hydrogen, for example, has three isotopes. Each of the three isotopes has one proton. However, the different isotopes have 0, 1 or 2 neutrons respectively.

Naming isotopes

In symbols, isotopes are represented as $^A_E$, where:
- $A$ = the mass number; the sum of the number of neutrons and number of protons in the nucleus
- $Z$ = the atomic number; the number of protons in the nucleus
- $E$ = the symbol of the element.

In words, isotopes are described by using the element name and the mass number. For example, the isotope of hydrogen that has two neutrons has a mass number of 3 and an atomic number of 1. It is therefore represented as $^3_H$ or, in words, hydrogen-3.

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

In most atoms, the protons and neutrons found in the nucleus are held together very strongly. The nuclei of these atoms are said to be **stable**. However, in some atoms the neutrons and protons in the nucleus are not held together strongly. These nuclei are **unstable**. Consequently, some isotopes of elements are stable and some are unstable. Isotopes that are unstable decay to form other elements. These isotopes are said to be radioactive and are called radioactive isotopes, or **radioisotopes**. For example, two isotopes of carbon, carbon-12 and carbon-14, have identical chemical properties. However, the nucleus of carbon-14 is not stable and disintegrates naturally. Carbon-12 is a stable isotope while carbon-14 is a radioactive isotope.

<table>
<thead>
<tr>
<th><strong>Element</strong></th>
<th><strong>Symbol</strong></th>
<th><strong>Number of protons</strong></th>
<th><strong>Number of neutrons</strong></th>
<th><strong>Stable or radioactive?</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon-12</td>
<td>$^{12}\text{C}$</td>
<td>6</td>
<td>6</td>
<td>Stable</td>
</tr>
<tr>
<td>Carbon-14</td>
<td>$^{14}\text{C}$</td>
<td>6</td>
<td>8</td>
<td>Radioactive</td>
</tr>
<tr>
<td>Uranium-235</td>
<td>$^{235}\text{U}$</td>
<td>92</td>
<td>143</td>
<td>Radioactive</td>
</tr>
<tr>
<td>Uranium-238</td>
<td>$^{238}\text{U}$</td>
<td>92</td>
<td>146</td>
<td>Stable</td>
</tr>
</tbody>
</table>

6.3.3 Natural and artificial radioactivity

Natural radioactivity is radioactivity emitted from matter without energy being supplied to atoms. There are about 50 isotopes that emit radioactivity naturally. They exist in the air, in water, in living things and in the ground. Most radioactive isotopes (about 2000 in total) are made radioactive artificially by bombarding their atoms with sub-atomic particles like protons and neutrons.

6.3.4 Three of a kind

The energy emitted by radioactive substances is called **nuclear radiation** because it comes from the nucleus. Lord Rutherford showed that there were three different types of nuclear radiation: **alpha particles**, **beta particles** and **gamma rays**.

**Alpha particles**

Alpha particles are helium nuclei that contain two protons and two neutrons. Alpha particles are positively charged. They cannot travel easily through materials and can be stopped by a sheet of paper or human skin. They pose little hazard to the external body but can cause serious damage if breathed in, eaten or injected. The symbol for alpha particles is $\alpha$.

**Beta particles**

Beta particles are the same size and mass as electrons, can have a negative or positive electric charge and can travel at speeds as high as 99 per cent of the speed of light. Beta particles can penetrate human skin and damage living tissue, but they can not penetrate thin layers of plastic, wood or aluminium. The symbol for beta particles is $\beta$. 

**WHAT DOES IT MEAN?**

The word **isotope** is derived from the Greek words *isos*, meaning ‘equal’, and *topos*, meaning ‘place’. It came about because even though each isotope of the same element had different numbers of neutrons and therefore different weights, they occupied the same place on the periodic table of the elements.
**Gamma rays**

Gamma rays are not particles, but bursts of energy released after alpha or beta particles are emitted. Gamma rays travel at the speed of light and are highly penetrating. They can cause serious and permanent damage to living tissue and can be stopped only by a thick shield of lead or concrete. The symbol given to gamma rays is $\gamma$.

The different penetrating powers of alpha ($\alpha$), beta ($\beta$) and gamma ($\gamma$) radiation

6.3.5 The lives and half-lives of radioisotopes

The nuclei of different radioactive substances decay at different rates. Some radioisotopes decay in a few seconds, while others take thousands of years. The time taken for half of all the nuclei in a sample of a radioisotope to disintegrate or decay is known as its **half-life**.

There are three naturally occurring isotopes of uranium; uranium-238, uranium-235 and uranium-234. Each of the isotopes spontaneously disintegrates or decays, producing alpha particles and gamma rays. Each isotope has its own half-life; that is, the time taken for the concentration to fall to half its initial value. Half-lives can vary from microseconds to billions of years. The half-lives of each of the uranium isotopes are more than a billion years.
6.3.6 In the background

We are all exposed to background radioactivity every day. Fortunately it is quite safe. Most of it comes from naturally occurring radioactive elements in the Earth’s atmosphere and crust. A smaller amount comes from outer space in the form of cosmic radiation, mostly in the form of high energy protons emitted by stars, including the sun. The word cosmic comes from the Greek word kosmos, meaning ‘universe’. The Earth’s atmosphere protects us from the dangers of cosmic radiation. There are even small amounts of radioisotopes in the human body, including hydrogen-3 (tritium), carbon-14 and potassium-40.

### HOW ABOUT THAT!

Radioactivity was discovered by accident. French physicist Henri Becquerel discovered radioactivity while investigating the fluorescence of uranium salts in 1896. When he developed a photographic plate that had been left in a drawer near his benchtop, 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.

6.3.7 Smoke alarms

Inside a smoke alarm, in the ionisation chamber, there 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. The alpha particles knock electrons off the 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, making them neutral and disrupting the current. This change is sensed by the detector and the siren sounds.

### 6.3 Exercises: Understanding and inquiring

To answer questions online and to receive immediate feedback and sample responses for every question, go to your learnON title at www.jacplus.com.au. Note: Question numbers may vary slightly.

**Remember**

1. How are isotopes of the same element different from each other?
2. In the symbol $^{\text{2}}_{\text{Z}}\text{E}$, what is represented by
   (a) the letter $A$
   (b) the letter $Z$?
3. Why are the isotopes of some elements radioactive?

4. Write down the type of nuclear radiation 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

5. What electric charge is carried by an alpha particle?

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

Using data

7. 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.

<table>
<thead>
<tr>
<th>Material</th>
<th>Effect on Geiger counter readings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paper</td>
<td>No effect on readings</td>
</tr>
<tr>
<td>Plastic</td>
<td>Readings fell by two-thirds</td>
</tr>
<tr>
<td>Lead</td>
<td>Large fall in readings</td>
</tr>
</tbody>
</table>

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

Think

8. About 0.01 per cent of the potassium in your body is the radioisotope \(^{40}\text{K}\).
   (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.

9. Are the atoms \(^{36}\text{X}\) and \(^{32}\text{Y}\) isotopes of the same element? Explain.

10. An atom of uranium-238 (\(^{238}\text{U}\)) decays by emitting a single radioactive particle. The atom formed as a result of the decay is thorium-234 (\(^{234}\text{Th}\)). What type of radioactive particle is emitted? Explain how you got your answer.

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

Investigate

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

Analyse and evaluate

13. The graph at right shows the decay of a radioisotope over four minutes.
   (a) What is the half-life of this isotope?
   (b) How many radioactive particles would be left after five minutes?
   (c) When the decay takes place in a sealed container, helium gas is collected. Name one type of radiation produced in the decay.
6.4 Using radioactivity

6.4.1 Radioisotopes

In 1903, Marie Curie, her husband Pierre, and Henri Becquerel were awarded the Nobel Prize in Physics for their discovery of radioactivity and their work on uranium. Little did they know that their discoveries and investigations would change the course of history.

They could not have imagined that their work would lead to the development of nuclear weapons capable of killing millions of people, nuclear power plants that generate electricity, and radioactive isotopes that can be used to treat cancers and detect life-threatening illnesses.

Radioisotopes are used in industry and research, and also have medical applications. They can be used as radioactive ‘tracers’ to follow the movement of substances through liquids (for example, sediment movement in rivers and the movement of substances in the blood). Radioactive isotopes are also used in smoke detectors, soil analysis, pollution testing, measuring the thickness of objects and criminology.

6.4.2 Radiometric dating

Naturally occurring radioisotopes can be used to calculate the age of samples from archaeological sites. Geologists make use of radioisotopes to determine the age of rocks and fossils. The technique is called radiometric dating.

The isotope carbon-14 has a half-life of 5700 years. Radiometric dating with carbon is called radiocarbon dating. All living things contain the element carbon. A small amount of the carbon is radiocarbon. As long as organisms are alive, carbon (along with radiocarbon) is being replaced. Plants take in carbon dioxide, animals eat plants, and micro-organisms consume plant and animal matter or each other. All living things, therefore, contain a small amount of radiocarbon.

When living things die, the decaying radiocarbon is no longer being replaced. Since all fossils were once living, their age can be determined by measuring the amount of radiocarbon remaining. After 5700 years, only half of the usual amount of radiocarbon will be left. A graph can be used to estimate the age of a fossil. After about 50000 years, the amount of radiocarbon becomes too small to measure accurately.
All rocks contain small amounts of radioactive elements such as uranium and potassium. The age of older rocks, and the fossils within them, can be determined by using radioactive elements with longer half-lives.

6.4.3 Radioisotopes and nuclear power
The radioactive properties of uranium are used in the generation of electricity in nuclear reactors. Australia is one of several countries that have large high-grade deposits of uranium. Uranium is converted to uranium dioxide and then sealed in rods, called fuel rods. The uranium undergoes a fission reaction in the reactor when neutrons are fired at the radioactive uranium. This causes the uranium nuclei to split and form two new elements, releasing neutrons, radiation and heat in the process. This heat energy is used to heat water to produce steam, which is used to turn the turbines that generate the electricity.

Fast breeders
In some countries fast breeder reactors use the artificial radioisotope plutonium-239 as a fuel. Plutonium-239 is made by bombarding uranium-238 with fast moving neutrons (that’s why the term ‘fast breeder’ is used). The plutonium-239 produced is also used to produce nuclear weapons.

Nuclear waste
The used fuel rods in a nuclear reactor are radioactive and contain a mixture of radioisotopes. Some of the waste radioisotopes have half-lives of only minutes, while others have half-lives of thousands of years. These waste products are currently sealed in steel containers or glass blocks and stored in power stations or buried deep at sea or underground away from groundwater. There is, however, still no permanent solution to the problem of disposing of nuclear waste.

It has been suggested that nuclear waste should be sent by rocket to the sun or into outer space. However, the risk of a rocket carrying nuclear waste exploding before leaving the Earth’s atmosphere makes that solution very risky.

6.4.4 Radiotherapy in the treatment of cancer
Radiotherapy is the use of radioisotopes, or other radiation such as X-rays, to kill cancer cells or prevent them from multiplying. It can be targeted at a small area so that surrounding tissue is not damaged. Radiotherapy is often used along with other treatments such as surgery or chemotherapy.

Radiation can be directed at the cancer by a machine like the one at right. This method is known as 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 methods are used. The type of treatment depends on the type of cancer, its size and its location as well as the general health of the patient.

6.4.5 Radioisotopes in the diagnosis of disease
Radioactive substances may be inserted into the body to detect or identify the cause of disease. The radiation produced by the substance while it is in the part of the body under investigation is measured to diagnose the problem.

Some radioisotopes can be used to obtain images of parts of the body. The gamma rays emitted by these radioisotopes are used to produce the images. PET (positron emission tomography) scans use cameras surrounding the patient to detect gamma rays coming from radioisotopes injected into the body.
6.4.6 Preserving food

If you’ve ever suffered from food poisoning you will understand why it is necessary to keep food from spoiling. Food in sealed containers can be preserved by exposing it to gamma radiation. The radiation kills the micro-organisms in the food and keeps it from spoiling. However, there has been much controversy about the safety of food that has been treated in this way.
INVESTIGATION 6.2
Radioactive decay
AIM: To investigate the decay of a radioisotope

Materials:
graph paper

Method and results
1. The half-life of the radioisotope iodine-131 is 8 days. Calculate the amount of iodine-131 left after 8, 16, 24, 32, 40, 48, 56, 64, 72 and 80 days if 100 g is given to a patient to treat a thyroid problem. Present your information in a table.
2. Draw a graph showing how the radioisotope decays. Make the horizontal axis represent time and the vertical axis represent the amount of radioisotope left.

Discuss and explain
3. What fraction of the iodine-131 is left after:
   (a) 8 days
   (b) 16 days
   (c) 24 days
   (d) 80 days?

4. Why is it difficult to store radioisotopes with short half-lives?

6.4 Exercises: Understanding and inquiring
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Remember
1. What is the name of the nuclear reaction that takes place in nuclear power stations?
2. Describe three uses of radioactive elements.
3. What is radiotherapy and how does it prevent the spread of cancer through the body?
4. How is internal radiotherapy different from external radiotherapy?
5. How do radioisotopes used in food preservation stop food from spoiling?

Think
7. 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?

Imagine
8. It was Marie Curie who invented the word ‘radioactivity’ to describe the disintegration of the nucleus. What would Marie Curie think if she were still alive today and could see both the good and bad effects of radioactivity? Would she be proud? Would she be disappointed? Would she be angry? Imagine that you are Curie and write a letter explaining your feelings.

Investigate
9. Research the topic ‘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.
10. Radiotherapy is an effective method of treating cancer. However, it has a number of side effects. Find out what the side effects are.
6.5 The dark side of radiation

6.5.1 The dark side of radioactivity

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.

Nuclear radiation can have a devastating effect on living things. Exposure to large doses of radiation can cause immediate effects such as nausea, headaches, vomiting and diarrhoea. Nuclear radiation damages living cells, and too much exposure can lead to diseases such as leukaemia, cancer and immune system collapse later in life. It can also damage the reproductive mechanisms in cells, including DNA, leading to birth defects in the offspring of exposed organisms. It is a sad irony that Marie Curie herself died of leukaemia at the age of 67. Her illness was almost certainly caused by her constant exposure to radioactivity.

6.5.2 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 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

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

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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.

6.5.3 Nuclear weapons

There are approximately 20 000 nuclear weapons in the world today, enough to destroy our planet many times over and effectively obliterate life from its face.

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.

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 blast also releases large amounts of radiation in the form of gamma rays which 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 energy is called an electromagnetic pulse. The most devastating effects for survivors are due to radiation exposure.

 Fallout enters the food chain when solid radioactive contaminants fall into bodies of water and onto the soil. The contaminants are taken in by plants and animals, becoming more concentrated as they move up the food chain. In humans, the contaminants move to target organs, delivering large, close-range doses of radiation. For example...

![Diagram showing parts of the body targeted by specific radioactive isotopes likely to be present in the fallout from Chernobyl. The risk, in all cases, is that of cancer in the targeted organ or in related tissue.]

- Thyroid: iodine-131*
- Lungs: krypton 85
- Bone: strontium 90 and yttrium 90
- Kidneys: ruthenium 106
- Ovaries: iodine-131*, ruthenium 106 and caesium 137*
- Muscle: caesium 137*

*These isotopes were detected by Swedish monitors early in the week after the Chernobyl disaster.
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.

6.5 Exercises: Understanding and inquiring

To answer questions online and to receive immediate feedback and sample responses for every question, go to your learnON title at www.jacplus.com.au. Note: Question numbers may vary slightly.

Remember
1. List the effects of exposure to large doses of nuclear radiation to humans.
2. Describe radioactive fallout.
3. Explain how the Chernobyl nuclear accident occurred.
4. What caused the meltdown in reactors 1, 2 and 3 at the power station in Fukushima?
5. Define the following terms: (a) melt-down (b) thermal flush (c) electromagnetic pulse (d) ground zero
6. Describe the short-term and long-term effects of an atomic explosion.

Think
7. Why did the incidence of leukaemia increase among young children rather than adults after Chernobyl?
8. Explain why nuclear energy is described by some as ‘a blessing and a curse’.
9. 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
10. Find out how a Geiger counter is able to measure the amount of radiation in a location.
11. 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
12. 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 Resources section. You should also search the internet using keywords such as uranium, radiation, mining, nuclear and waste to find other useful sites.

Using data
13. The map and table shown here indicate the distribution of deaths and injuries caused by the Hiroshima bombing in 1945.
   (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?

<table>
<thead>
<tr>
<th>Distance from ground zero (km)</th>
<th>Killed</th>
<th>Injured</th>
<th>Population</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–1.0</td>
<td>26 700 (86%)</td>
<td>3 000 (10%)</td>
<td>31 200</td>
</tr>
<tr>
<td>1.0–2.5</td>
<td>39 600 (27%)</td>
<td>53 000 (37%)</td>
<td>144 800</td>
</tr>
<tr>
<td>2.5–5.0</td>
<td>1 700 (2%)</td>
<td>20 000 (25%)</td>
<td>80 300</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>68 000 (27%)</strong></td>
<td><strong>76 000 (30%)</strong></td>
<td><strong>256 300</strong></td>
</tr>
</tbody>
</table>
6.6 Concept maps and plus, minus, interesting charts

6.6.1 Concept maps and plus, minus, interesting charts

1. On small pieces of paper, write down all the ideas you can think of about a particular topic.
2. Select the most important ideas and arrange them under your topic. Link these main ideas to your topic and write the relationship along the link.
3. Choose ideas related to your main ideas and arrange them in order of importance under your main ideas, adding links and relationships.
4. When you have placed all of your ideas, try to find links between the branches and write in the relationships.

To show what you understand about a particular topic

Why use?

Knowledge map; concept web

Also called

How can I explain this topic to someone else?
What do I understand about this particular topic?

How to ...?

Concept map

Topic

Main idea

Link

Main idea

Link

Link

Main idea

Link

First-level idea

Link

First-level idea

Link

First-level idea

Link

Second-level idea

Link

Second-level idea

Link

Second-level idea

Link

Third-level idea

PMI chart

Topic/theme/idea

Plus

Minus

Interesting

Similarity

Comparision

Difference

PMI charts help you consider the pros and cons of a decision; concept maps help you to see the relationships between ideas or concepts.

Concept maps show the links between ideas; PMI charts group ideas into various perspectives.

Explore more with this weblink: Uranium Information Centre
6.5 Exercises: Understanding and inquiring

To answer questions online and to receive immediate feedback and sample responses for every question, go to your learnON title at www.jacplus.com.au. Note: Question numbers may vary slightly.

1. A concept map can be used to illustrate some of the important ideas associated with the atom and the links between the ideas.

(a) Copy the concept map above into your workbook and complete it by adding the links between the ideas.
(b) Construct your own concept map to show how ideas about what is inside substances are linked. Begin by working in a group to brainstorm the main ideas of the topic.

2. Construct a concept map of ideas associated with radioactivity.

3. Create a PMI chart on radioactivity, using the diagram below as a starting point.

Radioactive materials are classified as dangerous goods. The international symbol for radioactivity must be displayed wherever they are used.

4. A SWOT analysis, like a PMI chart, is a visual tool that helps you think about different viewpoints related to an issue or topic. Work in a small group to perform a SWOT analysis to represent the positive and negative aspects of one of the following issues.
   (a) Nuclear power for Australia
   (b) Exporting uranium to other countries
6.7 Review

6.7.1 Study checklist

Structure of the atom
• describe and model the main features of the currently accepted model of the atom
• identify the nucleus, protons, neutrons and electrons in a simple illustration of an atom
• compare the mass and charge of protons, neutrons and electrons

Radioactivity
• associate different isotopes of elements with the number of neutrons in the nucleus
• explain why, in terms of the stability of the nucleus, some isotopes are radioactive while others are not
• represent isotopes correctly in both symbols and words
• describe the characteristics of alpha, beta and gamma radiation, including penetrating power
• identify the main sources of background radiation
• define the half-life of radioisotopes
• explain how the known half-life of some radioisotopes can be used to determine the age of rocks, fossils and ancient artifacts
• describe the use of nuclear fission reactions in nuclear reactors

Science as a human endeavour
• investigate the historical development of models of the structure of the atom
• investigate the contribution of scientists such as Henri Becquerel, Marie and Pierre Curie, and Lord Rutherford to development of the model of the structure of the atom and radioactivity
• describe the impact of the discovery of radioactivity and the subsequent development of nuclear technology on the course of history
• explain how radioisotopes are used in nuclear reactors, radiometric dating, the treatment of cancer, medical diagnosis and food preservation
• examine the risks associated with radioactivity, nuclear power stations and nuclear weapons achievement.
6.7 Review 1: Looking back
To answer questions online and to receive immediate feedback and sample responses for every question, go to your learnON title at www.jacplus.com.au. Note: Question numbers may vary slightly.

Remember
1. The diagram at right represents a model of a neutral atom.
   (a) Which two types of particles make up the nucleus of the atom?
   (b) Which particles are shown orbiting the nucleus in the atom?
   (c) What features of atoms are not very well represented by this particular model?
   (d) To which element does this atom belong?
2. Which of the particles in the neutral atom has:
   (a) a negative electric charge
   (b) a positive electric charge
   (c) no electric charge
   (d) the smallest mass?
3. Describe the contributions of the following scientists to our understanding of the structure of the atom.
   (a) J. J. Thomson
   (b) Lord Rutherford
   (c) Niels Bohr
4. 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.
5. Alpha particles are helium nuclei containing two protons and two neutrons.
   (a) What is the electric charge of an alpha particle?
   (b) How do 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?
6. Which type of nuclear radiation travels at the speed of light?
7. Where does most of the natural background radiation that we experience every day come from?
8. 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?
9. 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?
10. The half-life of strontium-90 is 28 years. If a 400 gram 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?
11. Estimate the half-life of the isotope whose decay is shown in the graph at right.
12. Explain how it is possible to use carbon-14 to estimate the age of the remains of a dead plant embedded in a rock.
13. Imagine that a nuclear power station has been proposed 50 kilometres north of Melbourne’s city centre. Outline arguments for and against the proposal.
14. Use the Radioactive waste management weblink in your Resources section to investigate how and where waste is stored in Australia.

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100 75 50 25 0
0 2 4 6 8
Time (hours)
Percentage of isotope remaining