PEARSON

Science

STUDENT BOOK | VICTORIA

9

TOPIC 4

Atomic structure and radioactivity

Atoms are the tiny building blocks that make up everything around us. Elements are substances that only contain one type of atom, and each element can be represented using an atomic symbol, for example C for carbon and Ne for neon. There are 118 known elements in the universe.

Atoms are made up of even smaller subatomic particles called protons, neutrons and electrons. The protons and neutrons make up the middle of the atom, called the nucleus, while the electrons orbit the nucleus.

The nucleus in some atoms can be unstable. To become more stable, the atoms release energy or particles. This energy or particles is called nuclear radiation, and the atoms that do this are said to be radioactive. Radioactive atoms can be used to diagnose and treat diseases, but exposure to too much radiation can be very dangerous.

In this topic you will learn about the structure of atoms, and you will use this knowledge to explain and predict the behaviour of substances made up from atoms.

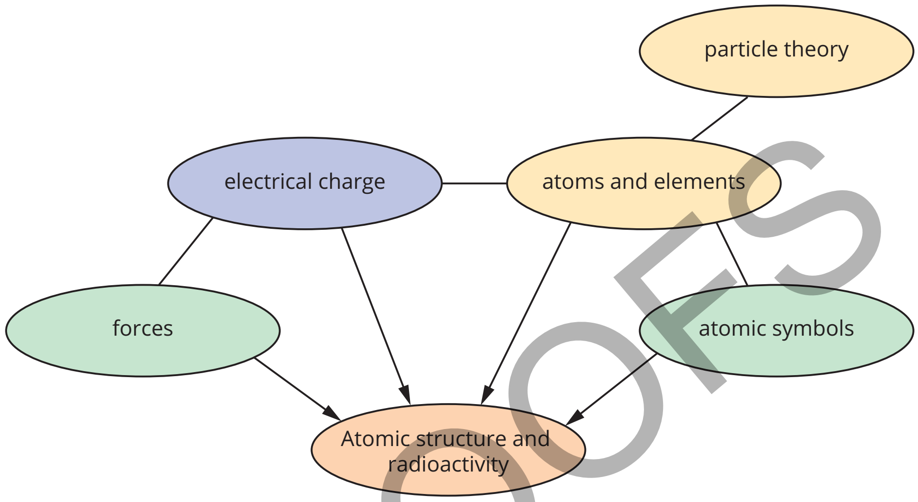
Learning intentions

- ☐ To understand the role that Marie Curie played in the modern understanding of atoms **xx**
- ☐ To be able to use a model to show how atoms are made up of subatomic particles **xx**
- ☐ To be able to describe discoveries that contributed to the knowledge of the structure of the atom **xx**
- ☐ To understand that different atoms have different numbers of subatomic particles **xx**
- ☐ To understand how different isotopes of atoms exist **xx**
- ☐ To understand that radioactivity is caused by the decay of atomic nuclei **xx**
- ☐ To understand the concept of radioactive half-life **xx**
- ☐ To be able to model radioactive decay **xx**
- ☐ To understand how radioactive decay and the concept of half-life is used in historical dating **xx**
- ☐ To be able to explain the use of radioactivity in medicine **xx**

Prior knowledge

4 Atomic structure and radioactivity

The key concepts that you will use in this topic:



The following prior knowledge questions will help to support your learning in the topic and can be attempted before the first lesson.

Chemical and physical changes

1 Identify the following processes as chemical or physical changes.

- **a** melting chocolate
- **b** photosynthesis
- **c** fermentation
- **d** dissolving salt into water

Exothermic and endothermic reactions

2 Describe the difference between an exothermic and endothermic reaction.

Chemical energy transformations

3 Select the correct answer: A lithium-ion battery is an example of chemical energy transformed into:

- **A** mechanical energy
- **B** sound energy
- **C** light energy
- **D** electrical energy

4 Define potential energy by using a chocolate bar as an example.

Elements, compounds and mixtures

5 Refer to the periodic table to list the elements in the $LiNiCoAlO_2$ battery.

Word and chemical equations

6 Identify the reactants and products in the following reaction:

calcium + hydrochloric acid → hydrogen + calcium chloride

$$Ca(s) + 2HCl(aq) \rightarrow H_2(g) + CaCl_2(aq)$$

4.1 Marie Curie and elements

Lesson overview

Maria Skłodowska was born in a time when women were not expected to be educated, much less attend university. She was not born into a wealthy family and therefore had to work to support herself while she studied. She had to travel from her homeland to study and consequently was not learning in her native language. Despite these difficulties, she was the first woman to receive a Nobel Prize, the first woman to teach at the Sorbonne (which was the most prestigious university in Paris) and the first and only person to receive two Nobel Prizes in different sciences.

When she married Pierre Curie, her name became Marie Curie. She is sometimes referred to as Marie Skłodowska-Curie.

In this lesson you will learn about this extraordinary woman and the contributions she made to science and society.

Learning intention

To understand the role that Marie Curie played in the modern understanding of atoms

Success criteria

SC 1: I can describe the challenges Marie Curie faced as a scientist.

SC 2: I can explain how Marie Curie improved knowledge of atoms and radioactivity.

SC 3: I can explain how Marie Curie's discoveries were accepted and recognised by the scientific community.

SC 1 I can describe the challenges Marie Curie faced as a scientist

Maria Skłodowska (married name: Marie Curie, Figure 4.1.1) faced many challenges as a scientist in late 1800s/early 1900s. A timeline of her life (Figure 4.1.2) demonstrates the difficulties of being born in Poland, studying and working as a woman in science, balancing motherhood with work, having her husband die of an accident and her own health declining due to radiation exposure.

FIGURE 4.1.1 Marie Curie with her husband, Pierre, and daughter, Irene; all three are Nobel Prize winners.

1867	Maria Skłodowska is born in Warsaw, Poland. Poland was under Russian rule. Times are hard. She cannot formally attend University in Poland.
1891	Maria Skłodowska travels to Paris and begins studying physics and mathematics at the Sorbonne. She is a top student in her studies.
1893–4	Maria Skłodowska obtains her Masters degree in Physics in 1893. She completes a second degree in chemistry. Marie meets Pierre Curie, marries, and her name changes to Marie Curie.
1896	In Paris, Henri Becquerel discovers invisible rays of high energy. Marie Curie names this phenomenon radioactivity and works to isolate the element creating the radioactivity.
1897	Marie Curie has her first child, Irene and is constantly juggling work with motherhood. There are no modern household conveniences like refrigerators or washing machines.
1898–1900	Marie Curie and Pierre Curie first identify the element polonium in 1898, and Marie Curie names it after her homeland, Poland. Radium is isolated later in 1898. Marie Curie becomes the head of the physics laboratory and begins teaching at a girls' school.
1903	Marie Curie achieves a doctorate in science and is the first woman to receive one from the Sorbonne. Henri Becquerel, Marie Curie and Pierre Curie are nominated for a Nobel Prize for their discoveries of radioactivity, polonium and radium. Initially, Marie's name is left off the acknowledgement, but Pierre refuses to accept it without her being recognised.
1904	Marie has her second child, Eve Curie.
1906	Pierre Curie dies in an accident. In the aftermath of Pierre Curie's death, Marie Curie begins teaching some of his physics classes while completing their research on her own. She is now a single mother of two little girls.
1911	Marie Curie works in Paris to produce a method to isolate radium from a uranium-rich mineral called pitchblende. She works with large quantities of pitchblende in an unventilated laboratory. The work earns her a nomination for a second Nobel Prize.
1914	Marie Curie is appointed the director of the Curie Laboratory at the University of Paris, gaining worldwide recognition. During World War I she creates mobile X-ray units and trains people (mostly women) to use them to treat casualties more quickly during the war.
1929	Marie Curie is invited to America on several occasions to receive accolades. In 1929 she receives a gift of $50,000 from the Americans which will be put towards research.
1934	The dangers of radioactivity were not known at the time. In July 1934, Marie Curie died from aplastic anaemia because of prolonged exposure to radiation from polonium and radium. Her body was so radioactive that she had to be interred in a coffin lined with lead.
1934 onwards	Marie Curie's first daughter, Irene Joliot-Curie, also studies physics and produces the first radioisotopes that will be used for medical purposes. Irene Joliot-Curie and her husband, Frederic Joliot, will also receive a Nobel Prize in 1935 for their work.

FIGURE 4.1.2 A timeline of the challenges Marie Curie faced as a scientist

SC 1 CHECK YOUR UNDERSTANDING

List the two elements Marie Curie discovered.

SC 2 I can explain how Marie Curie improved knowledge of atoms and radioactivity

Radioactivity

When Henri Becquerel first discovered **radioactivity**, he was unsure of what he had found. He knew it was ‘invisible radiation’, and he knew it was not **X-rays**. Like most scientific research, the truth is reached when many people group their knowledge together. It was the involvement of Marie Curie and Pierre Curie that expanded the understanding of this ‘invisible radiation’ (Figure 4.1.3).

Detecting radiation

Up until the late 1800s this ‘invisible radiation’ was not known about. Part of the problem was detection. If it is invisible, then how do you see it? In the case of radioactivity, photography was a new technology of the 1800s that allowed radiation to be seen. Henri Becquerel had found that photographic plates (Figure 4.1.4) were affected by nearby uranium salts, meaning the uranium salts were emitting **ionising radiation**.

KEY TERMS

radioactivity amount of radiation emitted from a nucleus undergoing nuclear decay

X-ray high-frequency electromagnetic radiation that can penetrate many materials

ionising radiation any form of radiation that can remove electrons from atoms and molecules

mineral naturally occurring solid substance with a known chemical composition

FIGURE 4.1.3 Henri Becquerel (left) with Pierre Curie and Marie Curie

FIGURE 4.1.4 Photographic plates from the time of Marie Curie

Energy from within atoms

Marie Curie and Pierre Curie took up this problem to find out what exactly in the uranium salts was producing the ionising radiation. They discovered the source of the ionising radiation came from two elements which they named: polonium and radium. Marie Curie realised that the ionising energy was not coming from the arrangement of the atoms but from within the atoms themselves.

Isolating radium

The next challenge was to try and isolate these elements. Marie Curie had no luck in isolating polonium, so she turned to radium. She had to create a chemical process to isolate the radium from the other elements in the **mineral** (Figure 4.1.5).

FIGURE 4.1.5 Small quantities of radium salts were extracted from highly radioactive pitchblende dissolved in concentrated acid.

KEY TERMS

ore rock containing valuable minerals
luminous an object that releases or emits light
half-life the time it takes for half of a radioactive sample to decay

FIGURE 4.1.6 Luminous hands on a watch

FIGURE 4.1.7 The gold coin presented to Nobel Prize winners

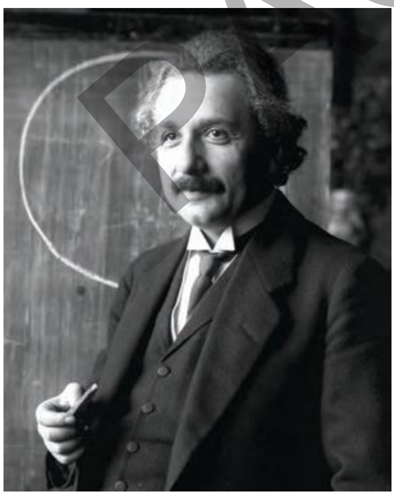


FIGURE 4.1.8 Albert Einstein

It was extremely hard work dissolving large quantities of the metal **ore** pitchblende in concentrated acids in a very small and poorly ventilated laboratory. She succeeded in isolating the radium salt, which paved the way for industry to use the method to produce larger quantities.

Radium uses and the half-life of radioactive materials

Radium salts were found to be **luminous**, and one of their major uses was on the dial and hands of men's wristwatches (Figure 4.1.6), which proved useful during trench warfare in World War I.

Marie Curie and Pierre Curie published their findings and presented them at the 1900 International Congress of Physics. However, it was not until 1907 when Ernest Rutherford formulated the idea of the **half-life** of radioactive materials that Marie Curie understood why she could not isolate polonium. Polonium has a half-life of only 138 days, meaning it decays relatively quickly into other atoms, making it difficult to isolate.

SC 2 CHECK YOUR UNDERSTANDING

Explain why Marie Curie was not able to isolate polonium.

SC 3 I can explain how Marie Curie's discoveries were accepted and recognised by the scientific community

The most significant recognition of Marie Curie's work by the scientific community was the two Nobel Prizes awarded to her. The founder of the Nobel Prize, Alfred Nobel, was a Swedish scientist and the inventor of dynamite. Worried that the legacy of his life would be the death of many, he established the Nobel Prize in 1901.

There were prizes for contributions to physics, chemistry, physiology, literature and for the promotion of world peace. A total of five prizes are awarded each year to recognise people who have made valuable contributions in these fields. There is both a medal (Figure 4.1.7) and a monetary gift attached to this prize.

You may be familiar with some recipients of the Nobel Prize, such as Albert Einstein (Figure 4.1.8), who won the Physics Prize in 1921 and Australia's Barry Marshall and Robin Warren, who won the Physiology Prize in 2005 for discovering the cause of stomach ulcers.

Winning this award is the highest recognition you can be given as a scientist, as it is a global award. Marie Curie was the first woman to win a Nobel Prize, sharing the Physics Prize with Pierre Curie and Henri Becquerel in 1903.

Apart from the Nobel Prizes, Marie Curie's scientific discoveries also led to the following awards and recognitions. Marie Curie:

- was the first woman to teach at the Sorbonne, an honour commensurate to her abilities
- became the first female professor of general physics
- received a second Nobel Prize, this time in chemistry for her work to isolate radium in 1911
- is the only person to have received two Nobel Prizes in two different scientific fields of physics and chemistry to this day
- developed portable X-ray machines, transported in cars called 'petites Curies', to be able to X-ray wounded soldiers at the battlefield hospitals
- became the director of the Curie Laboratory at the University of Paris in 1914
- was invited to America on several occasions in honour of her achievements and received gifts from the Americans
- has an element curium, discovered in 1944, named after her; curium is element number 96 on the periodic table
- was the first woman to be granted the honour of their remains being enshrined in the Panthéon in Paris; this is reserved for only the most revered people in France.

SC 3 CHECK YOUR UNDERSTANDING

Briefly describe the achievements that earnt Marie Curie two Nobel prizes.

Lesson review

Use these questions to check whether you have met the learning intention for this lesson.

1. Define radioactivity.
2. List one personal and one professional challenge Marie Curie had to overcome in her life.
3. Briefly describe the process Marie Curie used to isolate radium salts.
4. Apart from the Nobel Prizes, list three other ways the scientific community recognised Marie Curie's discoveries.

4.2 Modelling atomic structure

Learning intention

To be able to use a model to show how atoms are made up of subatomic particles

Success criteria

SC 1: I can create a representation of an atom that shows the relationships between the subatomic particles including protons, neutrons and electrons.

SC 2: I can describe the key features of each subatomic particle.

KEY TERMS

subatomic particle particle that atoms are made of—protons, neutrons and electrons
proton a subatomic particle with a positive electric charge located in the nucleus of an atom
neutron a subatomic particle with no electric charge located in the nucleus of an atom
electron negatively charged subatomic particle, located around the nucleus of an atom
electron cloud the region of negative charge surrounding the nucleus, containing the electrons

Introduction

What does an atom look like? Representations of atoms appear frequently in everyday life, often without being noticed. For example, in the television show *The Big Bang Theory*, atomic symbols are featured during scene transitions. While this model of atomic structure is widely recognised today, it has only been developed and understood in recent history.

In this practical investigation you will explore the structure of the atom and its subatomic particles through a practical process that should help you visualise what an atom looks like and the key features of the particles inside the atom.

Background

You cannot see atoms, so how do you know they exist and what they look like? Scientists conduct experiments and share their findings, allowing them to build a model that fits all observations. In this practical, you will explore this model to help visualise the structure of an atom.

Atoms contain three types of **subatomic particles**: **protons**, **neutrons**, and **electrons**. Protons and neutrons form the nucleus, while electrons move around it in random directions within the **electron cloud**. Protons and neutrons are much larger than electrons—if a proton has a mass of 1 and a neutron also has a mass of 1, an electron has almost no mass in comparison.

In terms of charge, protons are positive (+), neutrons are neutral (0), and electrons are negative (−).

Aim

To construct a model of an atom that shows the internal structure

Materials

- different colour modelling clay with the different colours used to represent the different subatomic particles
- large toothpicks or skewers
- A3 sheets of paper and colouring pens
- sticky labels

Method

Using the materials you have been provided with, write the steps to construct a model of an atom. You can choose which atom to build, or your teacher may assign you an atom. The numbers of protons, neutrons and electrons in the most common form of atoms of the first 10 elements are shown in Table 4.2.1.

TABLE 4.2.1 The first 10 elements and their numbers of protons, neutrons and electrons

Atom	Hydrogen	Helium	Lithium	Beryllium	Boron	Carbon	Nitrogen	Oxygen	Fluorine	Neon
Symbol	H	He	Li	Be	B	C	N	O	F	Ne
Protons	1	2	3	4	5	6	7	8	9	10
Neutrons	0	2	4	5	6	6	7	8	10	10
Electrons	1	2	3	4	5	6	7	8	9	10

You need to make the subatomic particles different colours and add labels to your model.

If you are not able to produce a 3D model, you can design a 2D representation.

Results

Present your model to other students and/or your teacher and request feedback.

Conclusion

1 What is the charge on the protons, neutrons and electrons? How did you represent this in your model?

2 What is the relative mass of the protons, neutrons and electrons? How did you represent this in your model?

3 The electrons in an atom move around the nucleus of the atom. How did you represent this in your model?

Evaluation

1 Based on feedback received and after viewing other models, explain one improvement that you could make to your model.

2 Describe how constructing a model helped you to improve your understanding of atomic structure.

Inquiry activity

4.3 Contributions to atomic theory

Learning intention

To be able to describe discoveries that contributed to the knowledge of the structure of the atom

Success criteria

SC 1: I can describe the main findings of historical experiments that investigated the structure of the atoms.

SC 2: I can describe how advances in technologies allowed the development of the understanding of atomic structure.

SC 3: I can compare the contributions of scientists to the development of the understanding of atomic structure.

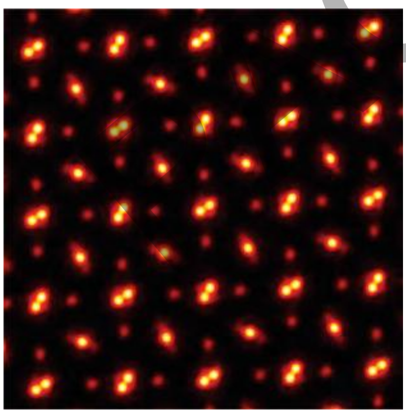


FIGURE 4.3.1 An image of the atoms in a crystal, zoomed in 100 million times

Introduction

The model of the atom has changed throughout the years, as different scientists develop new models to try to explain observed behaviour. Because the internal structure of the atom is not visible, even with the most powerful microscopes (Figure 4.3.1), these ideas involved abstract thought, backed up with indirect evidence obtained using a range of technologies. As with all scientific discoveries, the ideas have to be checked by the wider scientific community before they are accepted as a theory.

In this inquiry activity you will discover the work of some of the scientists who contributed to the modern understanding of atoms, how they use technology to obtain their evidence and how their ideas became accepted.

Background

Today's understanding of atoms is a result of several scientific discoveries. Each development builds on the previous one to improve the model of atomic structure to explain the properties of atoms and the substances made from atoms, which of course is all substances!

In recent years, research into atoms has progressed into the study of still smaller subatomic particles present in the nuclei of atoms, including particles such as quarks, bosons and neutrinos.

Aim

To conduct research to explain how the model of the atom developed over time and consider the contributions of scientists to these discoveries

Plan

As part of a team, each student should research the model of the atom proposed by one of the following scientists, including the evidence they used and how the idea was accepted.

1 John Dalton
2 J. J. Thomson
3 Ernest Rutherford
4 Niels Bohr

Keeping to this order, students should report key facts to the rest of the group. This can include an advantage and problem with each model.

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Summarise your findings of the four models by:

- presenting your findings with diagrams or 3D diagrams of the atomic models proposed by each scientist
- describing the technologies used to provide evidence for the models
- explaining how the model was accepted by the scientific community.

Go To
Toolkit section 4.2, Evaluation of secondary data

Conduct

Using the information from your team, create a timeline that summarises the four models of the atom. In the timeline, highlight key differences between each model.

Improve

After receiving constructive feedback on your timeline, suggest one improvement that you could make to your representation that would enhance how it communicates the development of the atomic model.

Evaluate

1 For one of the models, describe in detail how advances in technologies allowed the development of that model.

2 Neutrons were discovered by English scientist James Chadwick in 1932. Suggest why the neutron was the last of the three main subatomic particles to be discovered and compare the importance and impact of this discovery to the discovery one of the four models described in your timeline.

4.4 Elements and atoms

Learning intention

To understand that different atoms have different numbers of subatomic particles

Success criteria

SC 1: I can draw a two- or three-dimensional representation of a specific atom given the number of protons, electrons and neutrons present in the atom.

SC 2: I can calculate the mass number of atoms based on the number of protons and neutrons they contain.

SC 3: I can calculate the number of neutrons an atom contains from its mass number and atomic number.

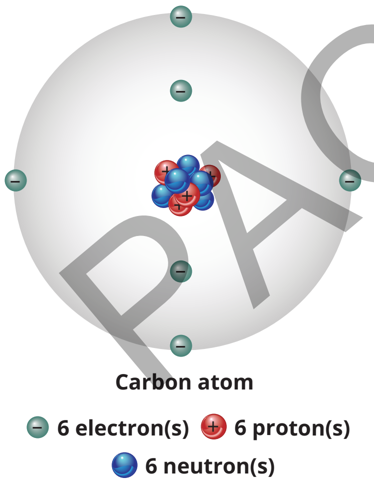


FIGURE 4.4.1 A representation of a hydrogen and a carbon atom

KEY TERM

atomic number the number of protons in the nucleus of an atom, indicated in the periodic table

Lesson overview

The writer Bill Bryson describes atoms in the following way: Protons give an atom their identity and electrons their personality. This is a great way to think about atoms, as the protons most certainly give an atom its identity. For example, all hydrogen atoms have one proton, and all carbon atoms have six protons (Figure 4.4.1). When you look at a picture of an atom, counting the number of protons will identify the type of atom it is.

In this lesson you will learn about the different numbers of subatomic particles in atoms.

SC 1 I can draw a two- or three-dimensional representation of a specific atom given the number of protons, electrons and neutrons present in the atom

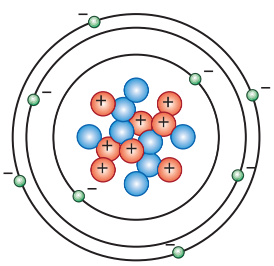
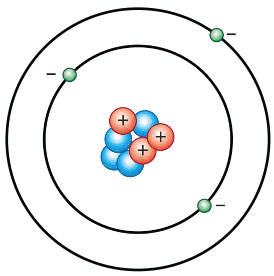
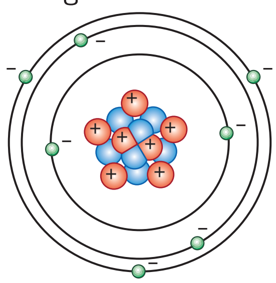
What's in an atom?

A periodic table provides lots of information about atoms of elements. It gives the name and symbol of an element and the number for that atom. This number is called the **atomic number** and is very important because it communicates the number of protons present in that atom. As you can see, each element has a unique atomic number. Periodic tables are written in a consistent format that groups elements based on their properties. You will learn more about the periodic table in Year 10.

All atoms will have the same number of electrons as protons. This makes all atoms neutral, which means the positive charge from the protons and the negative charge from the electrons cancel each other out. This means that an atom of carbon has 6 protons and 6 electrons. The number of neutrons can vary, and this will be considered later in the topic.

When you look at an illustration of an atom, count the number of protons and then use a periodic table to identify it. See Table 4.4.1 for some examples.

TABLE 4.4.1 Examples of atoms, the elements they represent and the number of protons, neutrons and electrons

oxygen	lithium	nitrogen
		
8 protons 8 neutrons 8 electrons	3 protons 4 neutrons 3 electrons	7 protons 7 neutrons 7 electrons

When drawing an atom, refer to the periodic table (Figure 4.4.2) and draw the correct number of protons in the nucleus. Then put the same number of electrons around the nucleus. (This is sometimes called the electron cloud.)

If you know the number of neutrons, these can be added to the protons.

Non-metal | Metal

13 Al aluminium

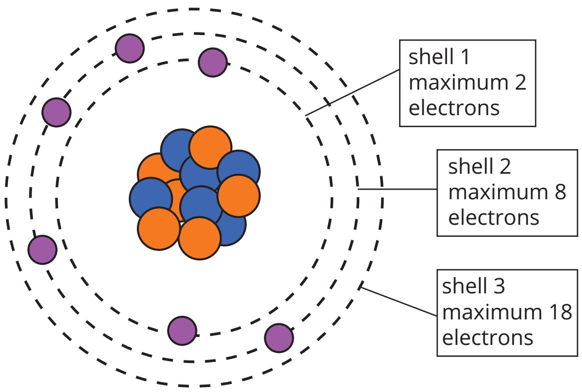
1 H hydrogen																	2 He helium
3 Li lithium	4 Be beryllium											5 B boron	6 C carbon	7 N nitrogen	8 O oxygen	9 F fluorine	10 Ne neon
11 Na sodium	12 Mg magnesium											13 Al aluminium	14 Si silicon	15 P phosphorus	16 S sulfur	17 Cl chlorine	18 Ar argon
19 K potassium	20 Ca calcium	21 Sc scandium	22 Ti titanium	23 V vanadium	24 Cr chromium	25 Mn manganese	26 Fe iron	27 Co cobalt	28 Ni nickel	29 Cu copper	30 Zn zinc	31 Ga gallium	32 Ge germanium	33 As arsenic	34 Se selenium	35 Br bromine	36 Kr krypton
37 Rb rubidium	38 Sr strontium	39 Y yttrium	40 Zr zirconium	41 Nb niobium	42 Mo molybdenum	43 Tc technetium	44 Ru ruthenium	45 Rh rhodium	46 Pd palladium	47 Ag silver	48 Cd cadmium	49 In indium	50 Sn tin	51 Sb antimony	52 Te tellurium	53 I iodine	54 Xe xenon
55 Cs caesium	56 Ba barium	57 La lanthanum	72 Hf hafnium	73 Ta tantalum	74 W tungsten	75 Re rhenium	76 Os osmium	77 Ir iridium	78 Pt platinum	79 Au gold	80 Hg mercury	81 Tl thallium	82 Pb lead	83 Bi bismuth	84 Po polonium	85 At astatine	86 Rn radon
87 Fr francium	88 Ra radium	89 Ac actinium	104 Rf rutherfordium	105 Db dubnium	106 Sg seaborgium	107 Bh bohrium	108 Hs hassium	109 Mt meitnerium	110 Ds darmstadtium	111 Rg roentgenium	112 Cn copernicium	113 Nh nihonium	114 Fl flerovium	115 Mc moscovium	116 Lv livermorium	117 Ts tennessine	118 Og oganesson
			58 Ce cerium	59 Pr praseodymium	60 Nd neodymium	61 Pm promethium	62 Sm samarium	63 Eu europium	64 Gd gadolinium	65 Tb terbium	66 Dy dysprosium	67 Ho holmium	68 Er erbium	69 Tm thulium	70 Yb ytterbium	71 Lu lutetium	
			90 Th thorium	91 Pa protactinium	92 U uranium	93 Np neptunium	94 Pu plutonium	95 Am americium	96 Cm curium	97 Bk berkelium	98 Cf californium	99 Es einsteinium	100 Fm fermium	101 Md mendelevium	102 No nobelium	103 Lr lawrencium	

FIGURE 4.4.2 The periodic table with elements discovered and named as of 2025.

Scifile

Where to draw your electrons?

Electrons are found outside the nucleus. However, when you are drawing your electrons on a 2D representation, you cannot place them in random locations. Each atom has energy levels, called shells where electrons are found. When you draw these shells, they look like large circles surrounding the nucleus, such as the illustration shown to the right.



Each shell can hold a maximum number of electrons. The innermost shell, (the one closest to the nucleus, shell 1) can hold a maximum of 2 electrons. Shell 2 can hold a maximum of 8 electrons and shell 3 can hold up to 18 electrons. Shell 4 can hold 32 electrons.

Start at shell 1 and fill the electrons out as follows.

- The first 2 electrons are placed in shell 1.
- The next 8 electrons are in shell 2.
- The next 18 electrons are in shell 3.

SC 1 CHECK YOUR UNDERSTANDING

Draw the 2D representation of helium, which has 2 protons, 2 neutrons and 2 electrons.

SC 2 I can calculate the mass number of atoms based on the number of protons and neutrons they contain

Calculating the mass number of atoms

In Figure 4.4.3, you can see the protons and neutrons are in the nucleus at the centre of the atom, and the electrons are surrounding it in the electron cloud. The electrons are much smaller than the protons and neutrons.

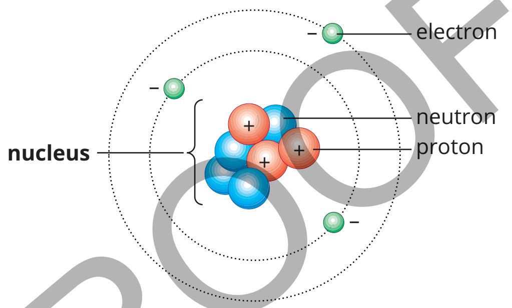


FIGURE 4.4.3 An atom of lithium showing the charges on the subatomic particles

Protons and neutrons are approximately the same size and mass and the electrons have only about 1/1840 the mass of a proton (Table 4.4.2).

So, if drawn to scale, the electrons would be impossible to see! For this reason, most of the mass of the atom is in the nucleus. The mass of an atoms can be represented by the mass number of the atom.

TABLE 4.4.2 Summary of the charge and the mass for the subatomic particles

Nuclear particle	Proton	Electron	Neutron
Location	nucleus	electron cloud surrounding nucleus	nucleus
Relative charge	+1	−1	0
Relative mass	1	$\frac{1}{1840}$	1

The atomic number for an atom is the number of protons in the nucleus. Atomic number can be represented by the letter *Z* and can always be found on the periodic table. The number of neutrons present does not affect the identity of an atom but will affect the mass of the atom. Mass number is determined by adding together the number of protons and neutrons in the atom and can be represented by the letter *A*.

- The mass number is always bigger than the atomic number (Figure 4.4.4).
- The mass number is **not** found in the periodic table (the periodic table shows the relative atomic masses).
- atomic number (*Z*) = number of protons
- mass number (*A*) = number of protons + number of neutrons

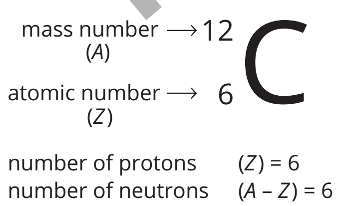


FIGURE 4.4.4 Carbon has 6 protons, so its atomic number is 6. In the illustration, carbon has 6 neutrons, so its mass number is 12.

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The number of electrons present does not affect the identity of an atom. The mass of the atom will also be unaffected by the different numbers of electrons as the mass of electrons is so small.

If electrons are lost or gained, positively or negatively charged atoms called ions are formed. You will learn more about ions in Year 10.

Examples of identifying and calculating atomic number and atomic mass are found in Table 4.4.3.

TABLE 4.4.3 Examples of elements, with the atomic number and mass number

Element	magnesium	chlorine	titanium
Symbol	$^{12}_{24}\mathrm{Mg}$	$^{17}_{35}\mathrm{Cl}$	$^{22}_{48}\mathrm{Ti}$
Atomic number	12	17	22
Mass number	24	35	48

SC 2 CHECK YOUR UNDERSTANDING

Calculate the mass number of a sodium atom with 11 protons and 12 neutrons.

SC 3 I can calculate the number of neutrons an atom contains from its mass number and atomic number

Numbers of neutrons in atoms

atomic number (Z) = number of protons

mass number (A) = number of protons + number of neutrons

Therefore:

number of neutrons = mass number – atomic number ($A - Z$)

This means that, if you know the mass number and atomic number, you can calculate the number of neutrons. Look at Table 4.4.4 for some examples.

TABLE 4.4.4 Examples of elements, with the atomic number and mass number and the number of neutrons

$^{56}_{26}\mathrm{Fe}$	iron	number of neutrons = mass number – atomic number 56 – 26 = 30
$^{64}_{29}\mathrm{Cu}$	copper	number of neutrons = mass number – atomic number 64 – 29 = 35
$^{133}_{55}\mathrm{Cs}$	caesium	number of neutrons = mass number – atomic number 133 – 55 = 78

SC 3 CHECK YOUR UNDERSTANDING

Calculate the number of neutrons in argon, $^{40}_{18}\mathrm{Ar}$.

Lesson review

Use these questions to check whether you have met the learning intention for this lesson.

1 Draw a two-dimensional representation of a beryllium atom, which has four protons, five neutrons, and four electrons.

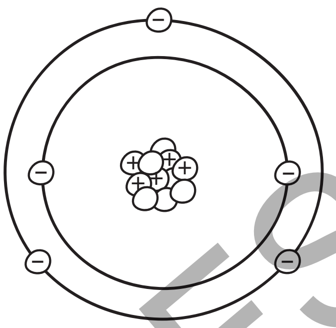
2 Calculate the mass number of a uranium atom, which has 92 protons and 146 neutrons.

3 Calculate the number of neutrons in an atom of phosphorus with the symbol: $^{31}_{15}P$

4 Name the following elements.

- **a** 17 protons, 18 neutrons and 17 electrons
- **b** 12 protons and a mass number of 24
- **c** 16 neutrons and a mass number of 31

5 Refer to the image to answer the following questions.



- **a** Determine the number of protons, neutrons and electrons.
- **b** Calculate the atomic number.
- **c** Calculate the mass number.
- **d** Referring to the periodic table in Figure 4.4.2, name the element.

6 Identify the mistake in each row of the following table.

Element	Number of protons	Number of neutrons	Atomic number	Mass number
Na	11	11	11	23
As	32	42	33	75
Ni	29	36	29	65
Ar	20	19	20	40

4.5 Isotopes

Lesson overview

Atoms contain the subatomic particles protons, neutrons and electrons. It is the number of protons that defines the atom. All carbon atoms contain 6 protons, all hydrogen atoms just the one. However, the number of neutrons in atoms of an element can vary. A carbon atom can have 6 neutrons, but some carbon atoms have 7 neutrons, and some have 8. It is not surprising that this can happen as most atoms have been formed in extreme conditions in stars at high pressure and incredibly high temperatures.

Atoms of the same element that have different numbers of neutrons are called isotopes, and there are lots of them!

In this lesson you will learn what an isotope is, see some common examples of isotopes and discover how the neutrons affect the properties of the atom, including its mass.

Learning intention

To understand how different isotopes of atoms exist

Success criteria

SC 1: I can describe, with examples, what an isotope is.

SC 2: I can identify isotopes of atoms based on the number of protons and neutrons they contain.

SC 3: I can explain, using an example, the different characteristics of isotopes of the same atom.

SC 1 I can describe, with examples, what an isotope is

Isotopes can be considered as different 'versions' of atoms. Atoms of the same element all contain the same number of protons. This number is called the atomic number. For example, neon (Figure 4.5.1) has the atomic number of 10 so every atom in the universe that has 10 protons is a neon atom.

However, in nature, if you had 10 000 neon atoms, around 9048 of them will contain 10 neutrons, around 27 of them would contain 11 neutrons and 925 of them would contain 12 neutrons.

These three different versions of neon are called **isotopes**. They are all neon and have the same chemical properties, but the mass of the three isotopes will be different.

To identify the different versions, numbers are used. The three isotopes of neon are called neon-20, neon-21 and neon-22.

KEY TERM

isotope group of atoms with the same number of protons but different numbers of neutrons

FIGURE 4.5.1 Neon is a gas commonly used for neon signs which are electrified tubes of neon gas.

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The masses of isotopes

Because the mass of atoms is made up almost entirely of the mass of the protons and neutrons, the masses of atoms can be compared by using the mass number.

Mass number is calculated by adding together the number of protons and neutrons in the atom.

mass number = number of protons + number of neutrons

For example, for a neon atom with 12 neutrons, the mass number is 10 plus 12 which equals 22. Therefore, this isotope of neon is called neon-22, or Ne-22.

Other examples of elements that have isotopes include carbon and hydrogen (Figure 4.5.2).

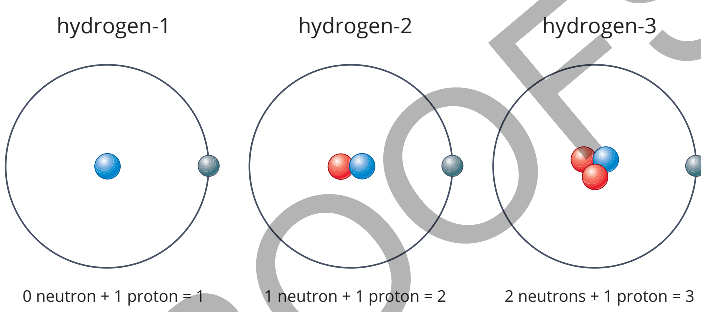

FIGURE 4.5.2 The isotopes of hydrogen

SC 1 CHECK YOUR UNDERSTANDING

Describe how isotopes of an element differ from each other.

SC 2 I can identify isotopes of atoms based on the number of protons and neutrons they contain

Mass numbers of isotopes

Isotopes are identified by their mass number where:

mass number = number of protons + number of neutrons

The number of protons is the atomic number of that element and can be found on a periodic table. For example, the isotope chlorine-37 contains atoms with 17 protons and 20 neutrons.

If you know the mass number, you can calculate the number of neutrons in an isotope:

number of neutrons = mass number – atomic number

For example, the number of neutrons in oxygen-18, is 18 minus 8, which equals 10 neutrons.

Presence of isotopes

Nearly all elements contain atoms that are isotopes of each other.

In some elements, nearly all atoms present in a natural sample of the element are one isotope. An example of this is nitrogen where 99.6% of nitrogen atoms are nitrogen-14, and only 0.4% nitrogen-15.

In some elements the composition might be more evenly spread across different isotopes. For example, around 51% of bromine atoms are bromine-79 and 49% bromine-81.

Separating isotopes

Isotopes of elements contain atoms with different masses. This means that the boiling points and melting points of the different isotopes may be different. This enables scientists to separate one isotope from another. Therefore, it is possible to produce samples that only contain one 'version' of the atoms of that element.

Examples of isotopes

Table 4.5.1 shows examples of isotopes and their relative abundance.

TABLE 4.5.1 Various isotopes and their relative abundances

Element	Atomic number	Isotope	Neutrons	Relative abundance (approximate)
Chlorine (Cl)	17	chlorine-35	18	76%
		chlorine-37	20	24%
Barium (Ba)	56	barium-134	78	2.4%
		barium-135	79	6.6%
		barium-136	80	7.9%
		barium-137	81	1.1%
		barium-138	82	71.7%
Copper (Cu)	29	copper-63	34	69%
		copper-65	36	31%
Uranium (U)	92	uranium-235	143	0.7%
		uranium-238	146	99.3%

Names of isotopes

The names of isotopes can be written out in full, such as barium-136, abbreviated with the chemical symbol of the element, for example Ba-136, or with the mass number as a superscript before the chemical symbol as shown here; ^{136}Ba.

SC 2 CHECK YOUR UNDERSTANDING

Calculate the number of neutrons in the isotope $^{34}_{16}S$.

KEY TERM

neutral having no overall electrical charge

SC 3 I can explain, using an example, the different characteristics of isotopes of the same atom

Chemical properties and electrons

Chemical properties describe how substances react with other substances. For example, do they react with water? Are they corrosive?

Therefore, chemical properties are affected by changes to the outside of atoms, and electrons on the outside of atoms.

The number of electrons in a **neutral** atom is always the same as the number of protons, and isotopes of the same element always have the same number of protons (Figure 4.5.3). This means that chemical properties of isotopes of elements are the same as each other, because the number and arrangement of electrons is the same for each isotope.

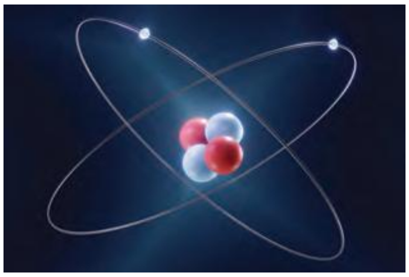

FIGURE 4.5.3 This representation of a helium-4 atom shows the electrons on the outside of the atom.

Physical properties and atoms

Physical properties, such as boiling point, melting point and density of elements are related to the mass of the atoms in the element. Each isotope has a different mass because of the different numbers of neutrons present.

Therefore, a sample of an element containing all of one isotope may have different physical properties to a sample that contains just atoms of the other isotope.

For example:

the boiling point of hydrogen-1 is −253°C

the boiling point of hydrogen-2 is −249°C.

These small differences are due to the different masses of the isotopes. The atoms of hydrogen-2 (sometimes called deuterium, Figure 4.5.4) are twice as heavy as the atoms of hydrogen-1 (sometimes called protium), and this means more energy is required to separate them, therefore the boiling point is slightly higher.

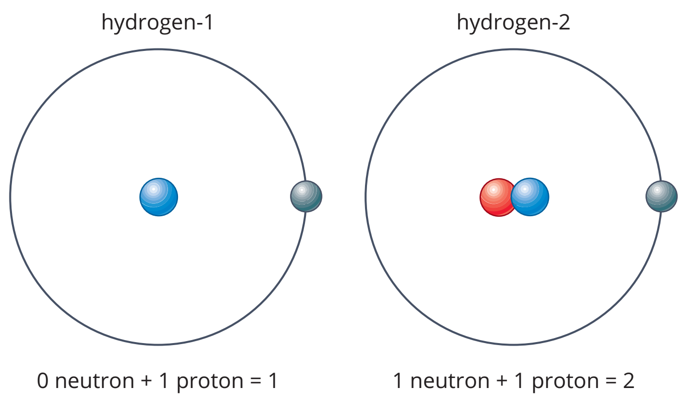

FIGURE 4.5.4 Hydrogen-2 atoms will be heavier than the atoms of hydrogen-1, and this may affect some physical properties.

Scifile

Heavy water

Heavy water is water that contains hydrogen-2 instead of hydrogen-1. It is used in nuclear reactors. Despite being chemically similar to regular water, its unique properties make it essential for specific scientific applications.

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SCIENCE IN SOCIETY

Discovering the climate thousands of years ago using isotopes

Isotopes are atoms of the same element that have different numbers of neutrons. This means they have the same number of protons but different masses. Isotopes can be stable or unstable. Stable isotopes do not change over time, while unstable isotopes undergo radioactive decay, emitting radiation as they transform into other elements. Oxygen-16, oxygen-17 and oxygen-18 are stable isotopes, whereas oxygen-15 is an unstable isotope.

Isotopes have various applications in science and industry. For instance, stable isotopes are used to determine the earth's climate over thousands of years. Ice cores, taken from Antarctica, can provide information on the past climate (Figure 4.5.5). Scientists can determine when these climate changes occurred by measuring the ratio of oxygen-18 isotopes to oxygen-16 isotopes.

Evaporation occurs more in warm ocean waters, compared to cooler ocean waters. Water containing the lighter oxygen isotope, oxygen-16, evaporates more quickly than water containing the heavier oxygen-18 isotope. This water vapour in the atmosphere then moves to the poles. During this journey, water containing the heavier oxygen-18 isotope will precipitate more quickly than the lighter oxygen-16 water molecules. Once at the poles, the water vapour in the atmosphere has a higher ratio of oxygen-16 to oxygen-18 compared to the original warm ocean, where it finally falls as snow. The snow turns to ice, and over time, is buried as time capsule.

Scientists use the ratio of oxygen-16 to oxygen-18, in combination with the changes with the world's water cycle, to determine the type of climate the earth experienced over many thousands of years.

FIGURE 4.5.5 An Antarctic ice core; the oxygen-16 to oxygen-18 isotope ratio provides information on the climate over many thousands of years.

Stability of atoms and radioactive decay

Neutrons are required in the nucleus to reduce repulsion between the positively charged protons. The more protons, the more neutrons required. However, if the nuclei of atoms contain significantly more or less neutrons than protons, this can make the nucleus unstable. This means that there is a chance that the nucleus will undergo what is called **nuclear decay**, and the nucleus splits into two or more particles. This decay causes **radiation** from the atom. Isotopes where this happens are called **radioisotopes** because they can give off radiation. The amount of radiation is described as radioactivity. Therefore, some isotopes of an element are radioactive (radioisotopes) and some are not.

For example, the nuclei in carbon-12 atoms, with 6 protons and 6 neutrons are stable, but the nuclei in carbon-14 atoms, with 6 protons and 8 neutrons are unstable (Figure 4.5.6). Therefore, carbon-14 is a radioisotope.

KEY TERMS

nuclear decay the process that occurs when an atomic nucleus undergoes a nuclear reaction and emits radiation

radiation the emission of energy in the form of electromagnetic waves or subatomic particles

radioisotope isotope that is unstable and has a nucleus that undergoes nuclear decay

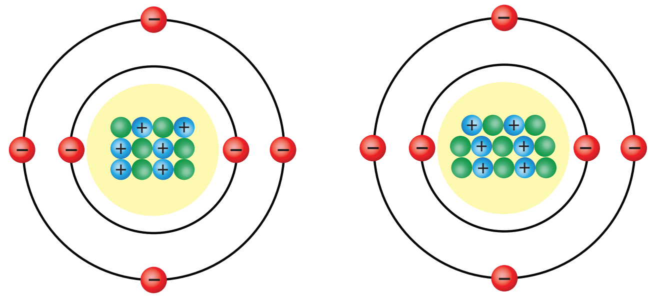

FIGURE 4.5.6 The extra neutrons in the carbon-14 atom destabilise the nucleus.

SC 3 CHECK YOUR UNDERSTANDING

List one physical property of an element that changes depending on the isotope.

Lesson review

Use these questions to check whether you have met the learning intention for this lesson.

1. Define the term isotopes.
2. Name the carbon isotope with 6 protons and 7 neutrons.
3. Explain why the mass of uranium-238 is greater than the mass of uranium-235.
4. The following questions relate to the isotopes of nitrogen.
   a. Calculate the number of protons and neutrons in a nitrogen-15 atom.
   b. Explain how nitrogen-15 differs from nitrogen-14.
   c. Nitrogen-16 is a radioisotope. Provide a definition of radioisotope.
   d. Name and explain which isotope of nitrogen you would expect to have the lowest boiling point.

4.6 Radioactivity and nuclear decay

Lesson overview

Radioactivity occurs in certain types of atoms. In most atoms, the nucleus (containing the protons and neutrons) is stable, meaning it doesn't change over time. However, in some atoms, the nucleus can be unstable. This can lead to nuclear decay which causes energy or particles (or both) to be released from the atom. This release of energy and/or matter is called radiation. There are three main types of radiation emitted by radioactive atoms: alpha particles, beta particles, and gamma rays.

Radioactivity can be used in medicine, for example in cancer treatments, as well as in industry, for example to generate nuclear power. However, high levels of radiation can cause damage to living cells and increase the risk of cancer, so it is important to know how to monitor and control radioactive materials.

In this lesson you will learn about the three main forms of nuclear decay – alpha, beta and gamma – including how they occur and the potential effects of the radiation.

SC 1	I can identify atoms that are likely to be unstable based on the number of protons and neutrons they contain

How were atoms made?

Atoms in the universe were made either in the processes during or very soon after the **Big Bang**, or later in billions and billions of stars in the galaxies (Figure 4.6.1). Simple atoms, such as hydrogen and helium were formed first. Later, these simple atoms fused together to make larger more complex atoms. This process takes place inside stars and is called **nuclear fusion**. Atoms heavier than iron require more energy to form and are therefore only produced when the star explodes. This is known as a supernova.

Today, many radioisotopes are made in laboratories using controlled **nuclear reactions**. This is to provide material for medical purposes such as radiotherapy and industrial purposes such as tracing the movements of materials 'labelled' with a small amount of the radioisotope.

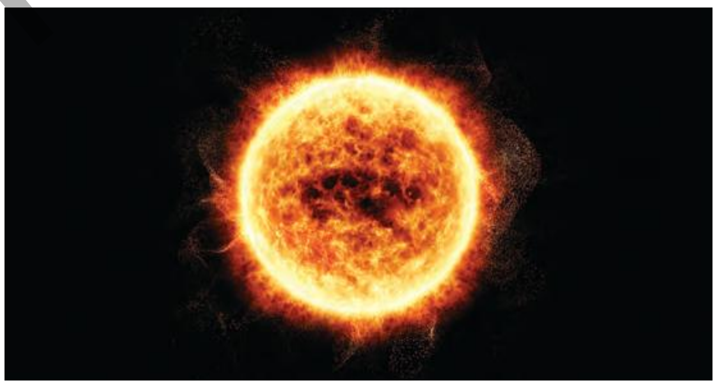

FIGURE 4.6.1 Most atoms in the universe have been formed in stars like the Sun.

Learning intention

To understand that radioactivity is caused by the decay of atomic nuclei

Success criteria

SC 1: I can identify atoms that are likely to be unstable based on the number of protons and neutrons they contain.

SC 2: I can compare alpha, beta and gamma radiation in terms of the properties of the radiation.

SC 3: I can compare alpha, beta and gamma radiation in terms of the nuclear processes that cause them.

KEY TERMS

Big Bang the sudden expansion of space from a point of dense energy which occurred at the start of the universe

nuclear fusion the process in which smaller atoms are converted into larger atoms, also producing light and heat

nuclear reaction process that causes a nucleus to change, including alpha decay, beta decay, fission and fusion

Radioisotopes

Some atoms contain nuclei that are unstable. The release of energy and/or matter from the nucleus will make these atoms more stable. This process is called nuclear decay.

Atoms that undergo nuclear decay are called radioisotopes. Radioisotopes tend to contain significantly more or less neutrons than protons because this can make the nucleus unstable.

For example, carbon can exist as three naturally occurring isotopes, carbon-12, carbon-13 and carbon-14. Only carbon-14 is a radioisotope, because the nucleus of this atom is unstable due to its two extra neutrons (Figure 4.6.2).

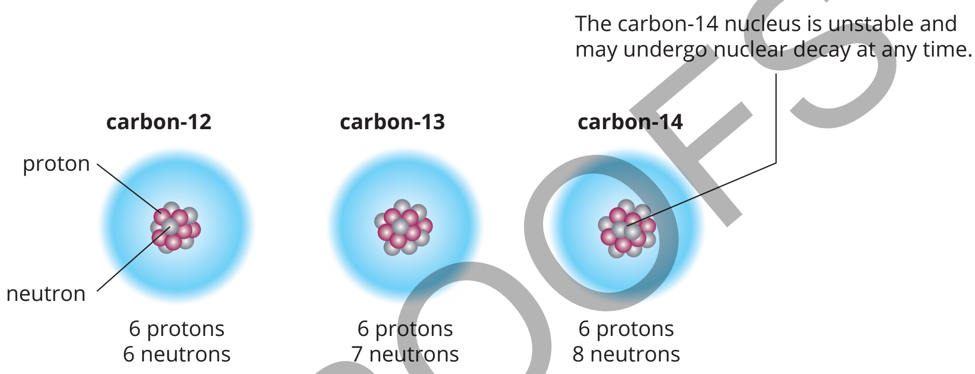

FIGURE 4.6.2 The three naturally occurring isotopes of carbon

Scifile

Where are radioisotopes sourced in Australia?

Radioisotopes required for Australian industry, medicine or scientific research are produced by Australia's Nuclear Science and Technology Organisation (ANSTO) facilities at Lucas Heights, New South Wales.

Examples of radioisotopes

The following are examples of commonly used radioisotopes.

- Cobalt-60 (27 protons, 33 neutrons)

  Used in radiotherapy for the treatment of cancer in addition to other scientific instruments.

- Iodine-131 (53 protons, 78 neutrons)

  Can be added as a tracer to water to monitor leaks in water systems as well as treating thyroid cancer.

- Radon-222 (86 protons, 136 neutrons)

  A non-odorous gas. It is a product of radioactive decay from minerals containing uranium. Radon-222 has been found in basements and non-ventilated rooms of homes around the world. Exposure to excessive amounts of radon greatly increases the risk of lung cancer.

- Americium-241 (95 protons, 146 neutrons)

  Used in household smoke detectors.

SC 1 CHECK YOUR UNDERSTANDING

Identify an isotope of uranium that is unstable.

SC 2 I can compare alpha, beta and gamma radiation in terms of the properties of the radiation

Types of radiation

The three types of radiation caused by nuclear decay are alpha particles, beta particles, and gamma rays.

Alpha radiation

Alpha particles are made up of two protons and two neutrons, the same as the nucleus of a helium atom, and are given the symbol α.

Alpha particles have a positive charge of +2 due to the positive charge of each proton. (Remember neutrons are neutral, they have no charge). Compared to other forms of radiation, alpha particles are relatively large which means they can be stopped by a single sheet of paper. They are only able to travel a few centimetres through air. However, at short ranges, alpha radiation can be dangerous because it can damage living cells. This is especially a problem if the materials giving off the alpha radiation enter the body through breathing or digestion. Americium-241, used in ionisation smoke detectors, is an example of a radioisotope that releases alpha particles (Figure 4.6.3).

Beta radiation

Beta particles are small negatively charged particles emitted from the nucleus of an atom. They are given the symbol β.

Beta particles have the same mass and charge as electrons. Beta particles are much smaller and lighter than alpha particles, which means that they can penetrate further into materials and have a range of up to six metres in air. They can be stopped by a few millimetres of plastic or a thin sheet of aluminium. Carbon-14 is an example of a radioisotope that releases a beta particle (Figure 4.6.4).

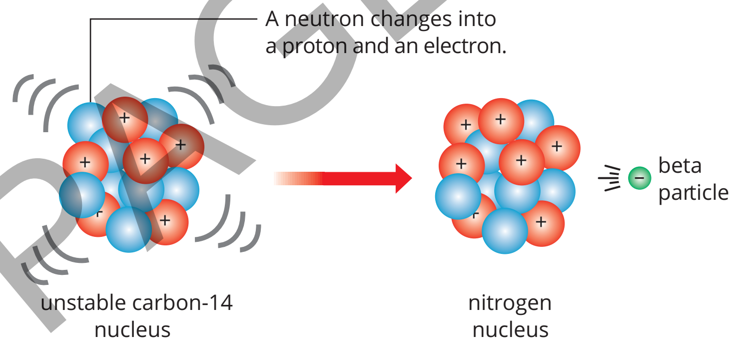

FIGURE 4.6.4 A beta particle is emitted from nucleus of a carbon-14 atom.

Gamma radiation

Unlike alpha and beta radiation, **gamma radiation** consists of high-energy **gamma rays**, which have no charge or mass. Instead, gamma radiation is a form of **electromagnetic radiation**, part of the **electromagnetic spectrum**. It is similar to X-rays or microwaves but with much higher energy. Gamma radiation is given the symbol γ.

KEY TERMS

alpha particle a particle containing two protons and two neutrons

beta particle a small, negatively charged particle that can be ejected from a nucleus during a nuclear reaction; it is identical to an electron

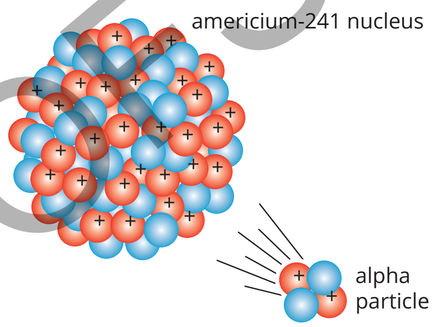

FIGURE 4.6.3 An alpha particle is emitted from nucleus of an americium-241 atom. This radiation is used in some household smoke detectors.

KEY TERMS

gamma radiation a form of ionising radiation made up of gamma rays (extremely high-frequency electromagnetic radiation emitted by radioactive materials)

gamma ray a very high-energy electromagnetic wave that is produced when the protons and neutrons in a nucleus rearrange

electromagnetic radiation a wave consisting of electric and magnetic fields travelling at the speed of light

electromagnetic spectrum the range of all electromagnetic radiation

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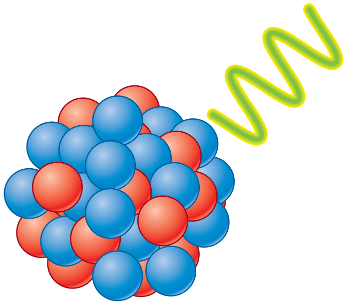


FIGURE 4.6.5 A gamma ray is a form of electromagnetic radiation with a very high energy and frequency.

This means that gamma rays can travel through most materials and can travel through huge distances, including through the vacuum of space (Figure 4.6.5). Because of this they are potentially the most harmful type of nuclear radiation. Gamma rays can be stopped by several centimetres of lead or several metres of concrete.

Comparing the types of radiation

Figure 4.6.6 compares the penetrating power of the three types of radiation. Alpha particles cannot penetrate paper or skin however beta particles and gamma rays can. Beta particles cannot penetrate aluminium foil, plastic or glass however gamma rays can. Several centimetres of lead or other dense thick material can stop gamma rays.

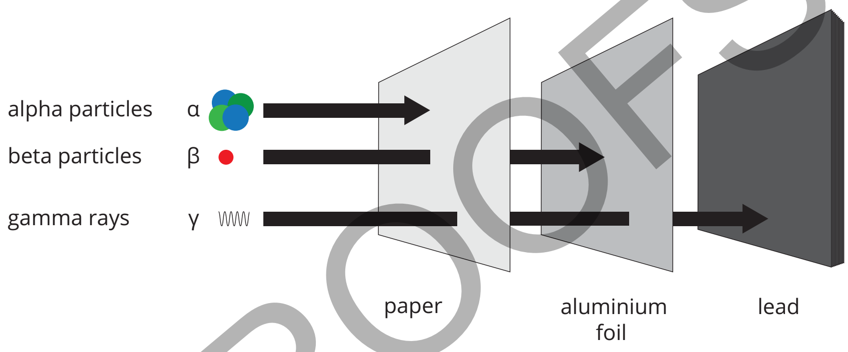


FIGURE 4.6.6 The penetrating power of the three main types of nuclear radiation. Human skin will have a similar effect to paper.

Table 4.6.1 compares the three types of radiation, their speed and charge.

TABLE 4.6.1 Summary of alpha and beta particles and gamma rays

	Alpha particles	Beta particles	Gamma waves
Symbol	α	β	γ
Simple definition (equivalent to)	helium nucleus	electron	electromagnetic wave
Approximate speed	20 000 000 metres per second (around 7% of the speed of light)	270 000 000 metres per second (around 90% of the speed of light)	300 000 000 metres per second (the speed of light)
Electrical charge	positive	negative	zero

SC 2 CHECK YOUR UNDERSTANDING

List the three types of radiation in decreasing order (highest to lowest) of their ability to penetrate materials.

SC 3 I can compare alpha, beta and gamma radiation in terms of the nuclear processes that cause them

Nuclear reactions

When nuclear decay happens and an alpha or beta particle is released, the number of protons and neutrons in the nucleus of the atom will change. These changes are called nuclear reactions. These nuclear reactions will change the properties of the atom, including sometimes actually changing the atom into an atom of a different element.

Alpha decay

An alpha particle contains two protons and two neutrons. When an atom undergoes alpha decay, the number of protons will drop by two, the number of neutrons will drop by two and the mass number will drop by four. Because the number of protons will change, the atom is now a different element, with a different atomic number. For example, when an uranium-238 nucleus undergoes alpha decay, it becomes a thorium-234 nucleus. The atom of uranium has changed into an atom of thorium with an atomic number of 90 (Figure 4.6.7).

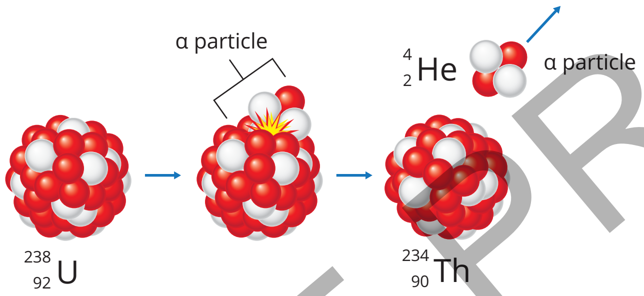


FIGURE 4.6.7 Uranium-238 nucleus undergoing alpha decay to become a thorium-234 atom

Equations for alpha decay

Nuclear reactions can be summarised using nuclear equations. The atoms are labelled with the mass number above and the atomic number below.

The alpha decay of uranium-238 can be represented like this:

$$^{238}_{92}\text{U} \rightarrow {}^{234}_{90}\text{Th} + {}^{4}_{2}\text{He}$$

The alpha decay of radium-223 can be used for the treatment of bone cancer. The equation for the process is:

$$^{223}_{88}\text{Ra} \rightarrow {}^{219}_{86}\text{Rn} + {}^{4}_{2}\text{He}$$

Note that in all cases the atomic number drops by 2 and the mass number drops by 4.

Beta decay

The best way to understand beta decay is to consider a neutron as a proton combined with an electron. The opposite charges of the positive proton and the negative electron cancel each other and makes the neutron neutral.

During beta decay, the neutron splits into the electron and the proton. The proton stays in the nucleus of the atom and the electron is released with high energy, as a beta particle.

The atom now has one less neutron, but one more proton. This is because the neutron has in effect changed into a proton when it lost the electron. As the number of protons has increased, the atomic number is also increased by one and the atom has changed to an atom of a different element.

The overall mass of the atom hardly changes, even though the electron leaves the atom, because electrons are about 2000 times lighter than protons and neutrons.

An example of this is the beta decay of carbon-14 as seen in Figure 4.6.8. The nuclear decay causes carbon-14 to become nitrogen-14 + beta particle.

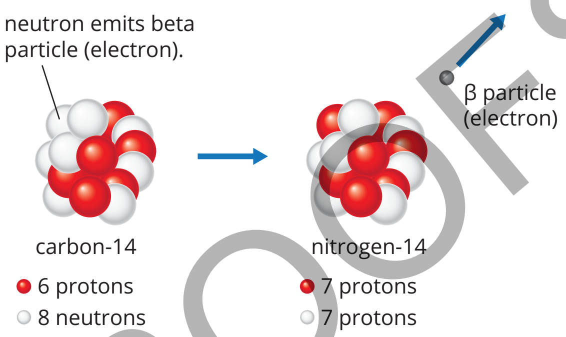


FIGURE 4.6.8 Carbon-14 undergoing nuclear decay to become nitrogen-14

Equations for beta decay

The beta decay of carbon-14 can be represented like this:

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

Note that the beta particle has a −1 where the atomic number of atoms is normally placed. This is because the beta particle (electron) is negatively charged.

The beta decay of strontium-90 can be used for the treatment of eye cancer. The equation for the process is:

$$^{90}_{38}\text{Sr} \rightarrow {}^{90}_{39}\text{Y} + {}^{0}_{-1}\beta$$

Note that in beta decay the atomic number increases by 1 and the mass number stays the same.

Gamma decay

Gamma decay involves the release of energy, but no particles are released from the atom. Therefore, the number of neutrons and protons in the nucleus remain the same. The release of high energy gamma radiation has the result of improving the stability of the nucleus of the atom. Gamma radiation is also often given off during other types of nuclear decay.

SCIENCE IN SOCIETY

Radioisotopes in industry and medicine

There are many industrial applications for radioisotopes. The most common is using radioisotopes for tracing. Radioisotope tracing is where various unstable isotopes are used to determine leaks in industrial scale pipes, oil and gas exploration, environmental and medical studies. Some examples include using radon radioisotopes to measure the amount of groundwater flowing into the surface water of a river (radon-226, 228, 223 and 224), determining the movement of iron from digestion to the bloodstream (iron-55), finding leaks in industrial machinery (sodium-24), studying the movement of phosphorus in the environment (phosphorus-32), determining the presence of oil or gas in a test drill (xenon-133, iodine-131, argon-41, manganese-56 as well as many other radioisotopes).

Radioisotopes are commonly used in medicine to determine the presence or absence of cancer or other diseases (technetium-99, fluorine-18, carbon-11, nitrogen-13 etc). For example, a PET scan (Positron Emission Tomography) is a commonly used technique to detect diseases and cancer in the body. Before a PET scan, the patient is injected with a radioactive substance called 2-fluoro-2-deoxyglucose (FDG). FDG contains fluorine-18, a radioactive isotope of fluorine.

The '2-deoxyglucose' is a type of glucose that cells convert to energy. The human body assumes FDG is glucose and transports it to all its cells.

Fluorine-18 undergoes a different type of decay called positron emission. A positron is an 'anti-electron'. The equation is:

$$ {}^{18}_{9}\mathrm{F} \rightarrow {}^{18}_{8}\mathrm{O} + {}^{0}_{1}\mathrm{e} $$

where ${}^{0}_{1}\mathrm{e}$ is the anti-electron.

The anti-electron collides with an electron, which annihilates them both and gamma radiation is produced. The PET scanner detects these gamma rays and forms images as seen in Figure 4.6.9. Radiologists can detect the diseases and cancers from the resulting images.

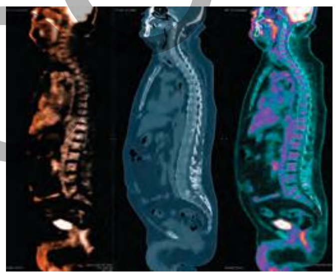


FIGURE 4.6.9 Gamma rays detected by the PET scanner are used to create images that help identify diseases such as cancer.

SC 3 CHECK YOUR UNDERSTANDING

List the forms of decays that result in a new element being formed.

Lesson review

Use these questions to check whether you have met the learning intention for this lesson.

1 Predict whether an atom with 20 protons and 30 neutrons is likely to be stable or unstable.

2 Describe beta particles and list the materials that can prevent penetration by these particles.

3 Americium-241 is produced by the nuclear decay of plutonium-241. Predict the type of radiation that is produced.

$$ {}^{241}_{94}\mathrm{Pu} \rightarrow {}^{241}_{95}\mathrm{Am} $$

4 ${}^{212}_{83}\mathrm{Bi}$ can undergo both alpha or beta particle nuclear decay to produce ${}^{212}_{84}\mathrm{Po}$ (alpha decay) and ${}^{208}_{81}\mathrm{Tl}$ (beta decay). Write the chemical equations for each of these nuclear processes.

5 Cobalt-60 is commonly used to sterilise food, cosmetics, pharmaceuticals, agricultural supplies and medical devices as it emits gamma radiation that can penetrate the packaging to kill microorganisms. The nuclear decay also emits a beta particle. Write out the chemical equation for this process.

4.7 Half-lives

Learning intention

To understand the concept of radioactive half-life

Success criteria

SC 1: I can describe radioactive decay in terms of half-lives.

SC 2: I can use half-lives to predict change in levels of radioactivity over time.

FIGURE 4.7.1 Half-lives can be used to calculate how the level of radiation will change over time. This is a warning sign near Pripyat, Ukraine, close to the site of the Chernobyl nuclear disaster that occurred in 1986.

KEY TERM

half-life the time it takes for half of a radioactive sample to decay

TABLE 4.7.2 The half-life of various radioisotopes

Isotope	Half-Life
uranium-235	704 000 000 years
carbon-14	5730 years
hydrogen-3	12.3 years
chromium-51	27.7 days
iodine-131	8 days
radon-222	3.8 days
berkelium-248	23.7 hours

Lesson overview

Radioactive decay can release different types of radiation from atoms that have unstable nuclei. However, whether a particular atom decays at a particular time is a purely random process. It is impossible to predict when an atom will undergo a nuclear reaction. However, by studying the decay rates of radioisotopes, scientists have been able to calculate the half-lives of these atoms. This information cannot be used to predict when an individual atom will decay but can predict how many atoms will decay in a given length of time (Figure 4.7.1).

In this lesson you will learn about how the idea of the half-life can be applied to the science of radioactive decay to better understand radioactivity.

SC 1 I can describe radioactive decay in terms of half-lives

Half-life for radioisotopes

When studying atoms, calculations and observations typically involve billions and billions of atoms.

However, for example, imagine that you have 80 atoms of a radioisotope, for example carbon-14. Now imagine that after a certain time, say 10 minutes, half of the atoms (40) have decayed into a different atom, and there are only 40 radioactive carbon-14 atoms left. In this case the **half-life** of the decay is 10 minutes.

Because the chance of a single atom decaying has not changed, in the next 10 minutes, another half of the atoms will probably decay, and you will be down to 20 radioactive atoms. This is how the idea of half-life works. Table 4.7.1 shows the number of radioactive atoms left after each 10 minutes period.

TABLE 4.7.1 An example of the number of atoms decreasing with a 10-minute half-life

Time from start of recording (minutes)	Number of radioactive atoms	Number of decayed atoms	Percentage of original number of atoms
0	80	0	100
10	40	40	50
20	20	60	25
30	10	70	12.5
40	5	75	6.25

In this example, the half-life is just 10 minutes. The half-life of carbon-14 is 5730 years!

Different isotopes have different half-lives, and the half-life of each isotope always stays the same. For example, all samples of carbon-14 have a half-life of 5730 years, but radon-222 atoms only have a half-life of 3.8 days. Table 4.7.2 shows the half-lives of some radioisotopes.

Leftover radioisotope atoms

How do scientists know how many radioisotope atoms are left? The simple answer is, they do not. But you can measure the amount of radiation (the radioactivity) being given off from a substance. If the measured radioactivity reduces by half, you can assume that the number of radioactive atoms has also halved.
Note that half-life can be written as $t_{\frac{1}{2}}$.

Measuring the rate of radioactive decay

Radioactive decay can be measured using a Geiger counter (Figure 4.7.2). The Geiger counter indicates the level of radioactivity, normally in counts per second or counts per minute, with each count being one particle, or burst of gamma radiation that a Geiger counter detects. Many Geiger counters make a clicking sound when this happens.

The number of **disintegrations** per second is called a becquerel (Bq). This unit is named after Henri Becquerel, the physicist who shared the Nobel Prize with Marie and Pierre Curie in 1903. The more becquerels, the higher the level of radioactivity, and the more atoms are decaying.

FIGURE 4.7.2 A Geiger counter being used to measure the radioactivity of a rock sample.

KEY TERM

disintegration the nuclear decay of an atom, indicated by a burst of gamma radiation, alpha or beta particle

Half-life patterns and trends

Sometimes it is easier to represent the idea of half-lives using a graph. As an example, in Figure 4.7.3, the mass at time 0 was 10 g. At its first half-life, there is 50% of that substance left (5.0 g). At the second half-life, there is 25% of that substance left (2.5 g).

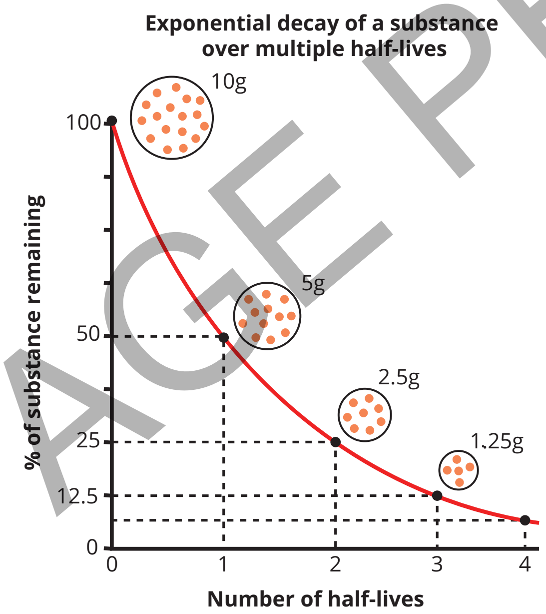


FIGURE 4.7.3 A plot representing the loss of a radioactive sample over each half-life

This type of trend is called exponential decay, with the radioactivity decreasing by half in a constant amount of time. Other examples of exponential decay include the amount of a drug in a person's body, and the healing of a scar in someone's skin although some of these may not be as easy to predict as radioactive decay.

SC 1 CHECK YOUR UNDERSTANDING

Define what a half-life is.

Scifile

Geiger counters

Geiger counters do not pick up every decay. This means that a Geiger counter does not give an exact measurement of radioactivity but can indicate the level of radioactivity.

SC 2 I can use half-lives to predict change in levels of radioactivity over time

Scifile

Application of radioisotopes in industry

Knowing the half-life allows scientists to use radioisotopes for many applications, such as oil and gas exploration, medical imaging, finding leaks or determining flow rates in high-pressure industrial pipes, investigating where elements move in the environment and food production.

Half-lives and radioactivity

The greater the chance of individual atoms decaying, the shorter the half-life of that isotope. For radioisotopes with a long half-life, the chances of an atom decaying are much smaller.

The half-life of a radioisotope is the time it takes for the number of radioactive atoms left in a sample to reduce by 50%. Because the random chance of any atom decaying remains the same, the half-life is also the time it takes for the radioactivity of a sample to reduce by 50%.

Therefore, it is possible to use the half-life of a radioisotope to predict how the levels of radioactivity will change over time. In general, if a radioisotope has a very long half-life, the radioactivity will change very slowly.

Predicting levels of radioactivity

Consider the situation shown in Figure 4.7.4. The radioactivity has dropped from 120 to 60 in four hours, and then from 60 to 30 in the next four hours. It can be predicted that the radioactivity will halve again in the next four hours to be 15 becquerel.

Figure 4.7.5 is an example of the measured radioactivity of an isotope with a half-life of 9 hours, plotted against time; this can be used to predict the measured radioactivity of the isotope at any given time – for example, at 15 hours, the level of radioactivity will be 260 counts/second.

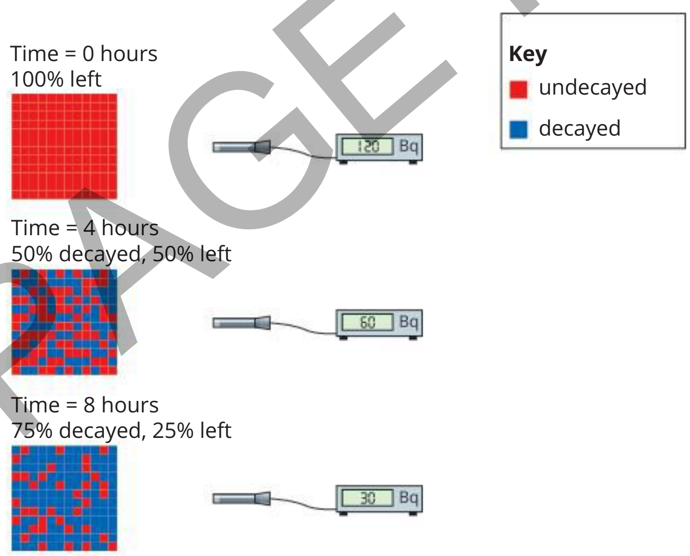


FIGURE 4.7.4 Measuring the becquerel (Bq) of a sample that has a 4-hour half-life

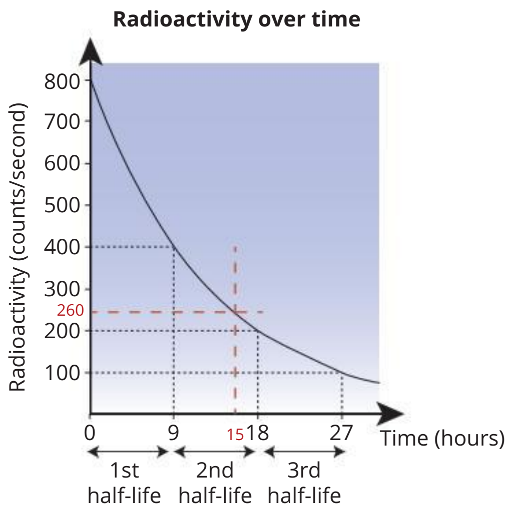


FIGURE 4.7.5 This curve can be used to predict the radioactivity at different times.

Isotopes with long half-lives

Americian-241 has a half-life of 432 years and it used to be common in household smoke detectors (Figure 4.7.6).

The long half-life means that the radioactive source will not lose its level of radioactivity and the smoke alarm will keep working. The battery will need to be replaced much sooner than the americium-241.

Plutonium-239 is used in nuclear power plants and in nuclear weapons. It is an **alpha emitter** with a half-life of 24 110 years. This means that the levels of radioactivity will not reduce significantly for hundreds of thousands of years, making the management of waste plutonium-239 very challenging.

KEY TERM

alpha emitter a radioisotope that gives off alpha particles

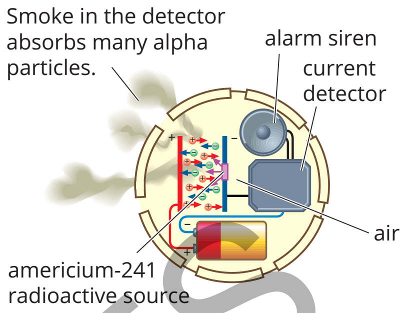


FIGURE 4.7.6 This smoke detector relies on an americium-241 source to provide a beam of alpha particles.

Isotopes with short half-lives

Iodine-123 has a half-life of just over 13 hours. It is used in medical imaging where small amounts of iodine-123 are absorbed into the body through an injection or swallowed in capsule form. The short half-life enables the flow of the iodine to be monitored through organs in the body but after a few days there will be very little radioactivity from any iodine-123 remaining in the body.

SC 2 CHECK YOUR UNDERSTANDING

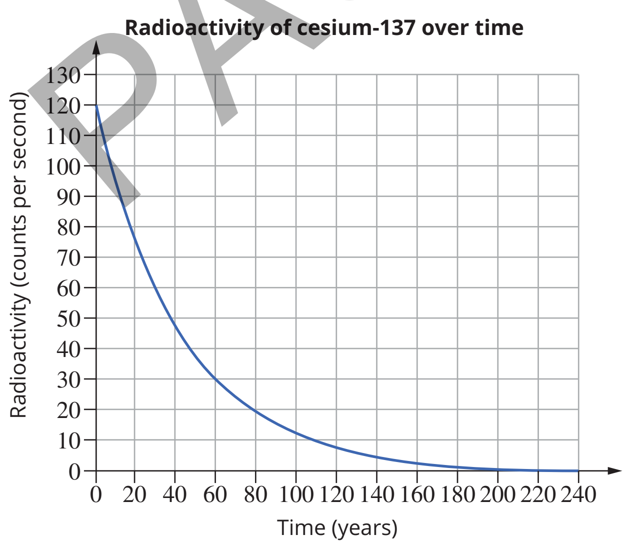
The radioisotope bismuth-210 has a half-life of 5 days. A sample of bismuth-210 initially measures 200 Bq on a Geiger counter. Calculate the level of radioactivity in becquerels after five days.

Lesson review

Use these questions to check whether you have met the learning intention for this lesson.

1 Explain how the half-life of a radioactive substance is measured using a Geiger counter.

2 The radioactivity of cesium-137 was plotted over time in years. Calculate the half-life of cesium-137 using the plot.



3 Explain how to use the half-life of a radioactive isotope to predict its level of radioactivity over time.

4 A radioactive sample has an initial radioactivity of 100 counts per second and a half-life of 5 years. Calculate its radioactivity after 15 years.

4.8 Modelling radioactive decay

Learning intention

To be able to model radioactive decay

Success criteria

SC 1: I can describe patterns in data collected from a simulation involving half-lives.

SC 2: I can compare trend patterns in simulated data to real half-life data.

FIGURE 4.8.1 A photograph of the trail produced by an electron after being expelled from a helium-6 atom from a nuclear decay event

SAFETY NOTE

- Do not eat any of the lollies.

Introduction

Nuclear decay is the process by which the nuclei of unstable atoms change in some way, sometimes causing the atom to change into an atom of another element. The process releases different types of radiation.

The decay of an atom in this way is a purely random event. You cannot predict when it will happen, but scientists can calculate the chance of it happening in a particular length of time (Figure 4.8.1). Because of this, you can use an activity based on chance to model the decay of radioactive atoms.

In this practical investigation you will use a model to represent nuclear decay and the concept of the half-life of a nuclear decay.

Background

This experiment is a way of modelling the mathematics of the radioactive decay of unstable atoms. These unstable atoms are known as radioisotopes.

Aim

To model radioactive decay and half-life

Materials

- a packet of M&Ms® or Skittles or two-sided tokens
- a clean tray or sheet of A3 paper
- a clean jar, paper bag or cup

Assessment of risk

Ensure you are aware of the risks of this practical investigation and have considered how safety can be improved before carrying out this activity.

Method

1. Use the table in the Results section, or your own table, to record results. Alternatively, construct a spreadsheet with similar columns.
2. Count the total number of M&Ms® in the packet and put them into the jar.
3. Shake the jar up to mix the lollies around. Pour the jar of M&Ms® onto the clean tray or A3 paper.
4. Count how many M&Ms® show the letter M facing upwards. Record this number in the table in the Results section.
5. Place only the M&Ms® showing the letter M back into the jar and dispose of the other M&Ms® appropriately.

6 Repeat steps 3–5 until there is only one M&M® left in the jar.

FIGURE 4.8.2 Only the M&Ms® with the letter M facing upward are counted.

Results

1 Record your results in a table like this.

Number of throws	0	1	2	3	4	5	6	7	8	9	10
Number of M&Ms® showing the letter M											

2 Construct a line graph of the number of M&Ms® remaining (those that showed the letter M) versus the number of times the procedure was repeated. Alternatively, use your spreadsheet on the computer to plot a graph for you.

Conclusion

1 Describe the shape of the graph that you produced.

2 The half-life of atoms of a radioisotope is the time it takes for half the nuclei to decay. Describe how half-life is represented in this experimental model.

Go To
Toolkit section 3.3, Identifying and describing trends in data

Evaluation

Discuss how this experiment models radioactive decay and half-life.

4.9 Carbon dating

Learning intention

To understand how radioactive decay and the concept of half-life is used in historical dating

Success criteria

SC 1: I can describe how radioactive decay is used to date artefacts.

SC 2: I can explain how dating techniques have been used to establish timelines for the presence of First Nations peoples on the Australian continent.

Lesson overview

Knowing the age of objects is important in many areas, including science, history, sociology, art and religion. For example, the dates of fossils can help establish patterns of evolution, the age of artefacts can help us understand the development of ancient civilisations, and the ages of rocks can help explain processes that have occurred in Earth's crust.

Carbon dating, also known as radiocarbon dating, uses radioactive decay and the concept of half-lives. It can be used to determine the age of objects in archaeological and historical contexts (Figure 4.9.1 as an example). In Australia carbon dating methods have been used to more accurately date sites of cultural and spiritual significance to First Nations peoples. This has enhanced understanding of the history and culture of First Nations Australians.

In this lesson you will learn about how the radioisotope carbon-14, which is present in all living matter, can be used to establish the age of objects that contain organic material.

FIGURE 4.9.1 The Shroud of Turin, originally thought to be the material used to wrap the body of Jesus, was shown to be inauthentic when carbon dating estimated that the material was less than 800 years old.

SC 1 I can describe how radioactive decay is used to date artefacts

Carbon dating, also known as radiocarbon dating, is one of the most used dating techniques in archaeology, geology and evolutionary studies. The process centres on the radioisotope carbon-14, which undergoes beta decay to form nitrogen-14. The reason it is considered so valuable is that all living things contain carbon, and in any sample of natural carbon, there will be a certain quantity of carbon-14. Therefore, any object that contains **organic** material (material from a once living source) such as wood or bone can be dated using radiocarbon dating.

KEY TERMS

carbon dating a method for judging the age of artefacts or fossils by analysing the amount of carbon-14 in the fossil

organic describes a compound that is or was part of a living thing; containing carbon

digestion the process of breaking down food into a useable form

Carbon in living things

Living organisms exchange carbon with the atmosphere around them through **digestion**, respiration and photosynthesis. This means that the proportion of carbon-14 in the bodies of these organisms remains similar throughout their lives because although the carbon-14 they contain will be decaying, it is replaced by 'new' carbon-14 from the environment.

When the organism dies, however, the processes of digestion and respiration stop, and the decaying carbon-14 is no longer replaced. The carbon-14 that is present in the organism at this point, therefore, will subsequently decay at a rate that can be predicted from the half-life of carbon-14, which is 5730 years (Figure 4.9.2).

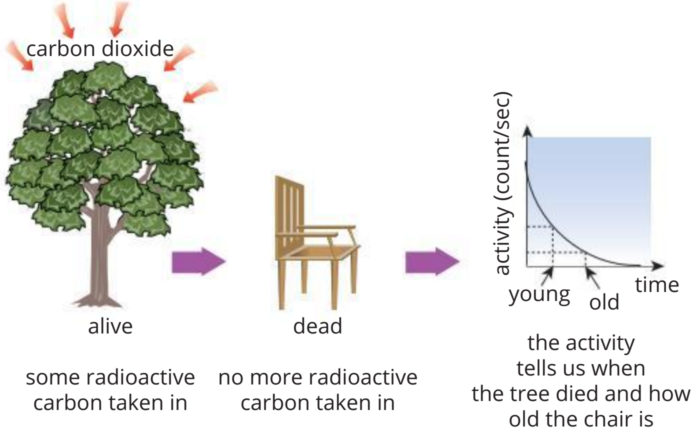


FIGURE 4.9.2 The wood in this chair can be dated from the time that the wood stopped growing.

The process of carbon dating

Using mass spectrometry, a technique for measuring particle mass, scientists can determine the amount of carbon-14 in an object, then compare it with known environmental levels. This comparison allows them to calculate how long the object's carbon-14 has been undergoing the process of decay, indicating the time since the organic matter within the object stopped growing.

Mass spectrometry allows objects containing organic material to be dated with an accuracy of approximately 100 years. However, its precision may vary depending on factors such as sample contamination, size and quality. It is also important to note that this technique is less effective for some objects over 50 000 years old because, beyond this point, the quantity of remaining carbon-14 in a sample may be too small to measure accurately.

The mathematics of carbon dating

When an organism is alive, it contains a ratio of stable carbon-12 and radioactive carbon-14 that is similar to the atmospheric ratio.

However, when the organism dies, the carbon-14 in the remains gradually decays at a known rate, halving approximately every 5730 years. This predictable rate of decay allows scientists to calculate the age of an object if they know the initial amount of carbon-14 as each 5730-year period corresponds to a 50% reduction in the remaining carbon-14 content.

Consider a sample containing a living organism with 100% carbon-14. After 5730 years (one half-life), the carbon-14 in the sample decreases by half, leaving 50% carbon-14 and 50% nitrogen-14. If another 5730 years pass (two half-lives), the remaining carbon-14 further reduces by half to 25%, while nitrogen-14 increases to 75%. This pattern persists, with each successive half-life halving the percentage of remaining carbon-14 (Figure 4.9.3).

Scifile

Dating inorganic materials

Other radioisotopes are used for dating rocks and other non-organic materials. For example, chlorine-36 has a half-life of 301 000 years and is used to study the age and sources of chloride in rocks, salt and water. Silicon-32 has a half-life of 144 years and is used to date ice, glaciers and groundwater. Lead-210 has a half-life of 22.3 years and is commonly used to determine whether the lead found in the environment is present naturally or is from human impacts.

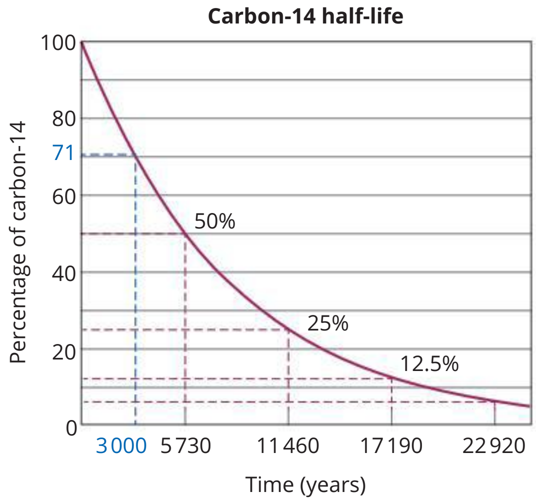


FIGURE 4.9.3 A drop in carbon-14 by half in a sample means around 5730 years have passed due to its natural decay.

KEY TERMS

algorithm a process followed in calculations used, most commonly in computer software, to process data

midden an ancient dump site containing shells, bones and other debris from human activity

As shown in the graph in Figure 4.9.3, if the carbon-14 in a sample is 50% of the natural (or living) percentage, it indicates that around 5730 years have passed since the organic material in the object stopped growing. The dates for other percentages can also be determined by referring to graphs like this one. For example, if an artefact contains 71% of the natural percentage of carbon-14, it is estimated to be around 3000 years old.

In radiation dating laboratories, this calculation will be carried out by a computer using a simple **algorithm**.

Reference points for carbon composition

You might wonder how scientists know the original proportions of carbon isotopes in a sample they don't know the age of. This problem is solved by comparing these proportions to those in objects that have been dated through other techniques, such as counting the rings inside tree trunks that are produced each year (Figure 4.9.4). The process of comparing something unknown to something known is called calibration, a common technique in science.

In carbon dating, therefore, calibration gives scientists a good idea of the expected proportion of carbon-14 in a sample that can be then used to calculate the age of the object.

SC 1 CHECK YOUR UNDERSTANDING

Explain how radiocarbon dating is used to determine the age of an artefact.

SC 2 I can explain how dating techniques have been used to establish timelines for the presence of First Nations Peoples on the Australian continent

FIGURE 4.9.4 Tree rings can be used to measure the age of trees accurately.

FIGURE 4.9.5 Soil, shells and bone fragments in middens can be used to date human activity in an area.

Evidence of First Nations histories and cultures

Scientists throughout Australia have harnessed the power of carbon dating to establish timelines of land use by First Nations Australians, as well as the ages of many artefacts. This process involves collecting organic material samples such as charcoal, bone fragments, soil, shells from **middens** (Figure 4.9.5), and even preserved spiders and caterpillars trapped within ancient wasp nests. Remarkably, these samples have allowed researchers to pinpoint when specific activities, like site occupation or the creation of rock art, took place, unveiling human occupation of the Australian continent dating back over 60 000 years.

Carbon dating techniques at First Nations sites

While carbon dating is a valuable tool, it is limited by the availability of natural resources and the finite lifespan of such materials. Nevertheless, it has provided compelling evidence that aligns with the oral histories and cultural knowledge of First Nations peoples in Australia.

Rock painting in the Kimberley

A rock art painting of a kangaroo in Balanggarra Country in north-east Kimberley, Western Australia, was analysed by researchers from the University of

Melbourne using carbon dating as part of the Kimberley Rock Art Dating project from 2014 to 2017. The painting was found to be between 17 500 and 17 100 years old; at the time of discovery, it was considered the oldest rock painting in Australia. The paint used was ochre made from iron oxide and because this paint is not derived from organic materials it could not be carbon dated. However, fossilised wasp nests built underneath and on top of the artwork could be analysed instead to provide a date for the painting (Figure 4.9.6). Say, using the example in Figure 4.9.6, the organic material in the mud wasp nest was radiocarbon dated to be 5000 years old. If the mud wasp nest was underneath the artwork, then the painting would be less than 5000 years old. If the mud wasp nest was built on top of the artwork, then it would be at least 5000 years old (possibly even much older).

KEY TERM

megafauna group of large land animals that evolved after the dinosaurs became extinct

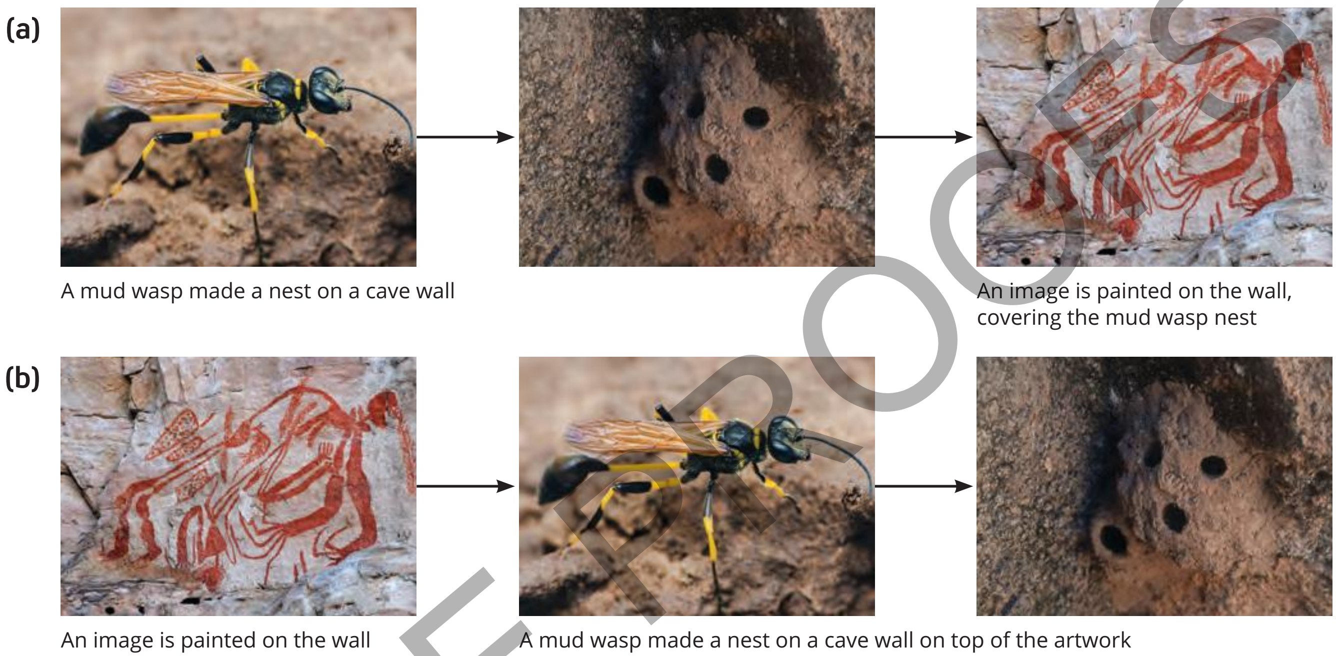


FIGURE 4.9.6 Dating First Nations' paintings based on organic material found in old mud wasp nests; in (a) the painting is on top of the mud wasp nest, whereas in (b) the painting is underneath the mud wasp nest.

Megafauna in the Flinders Ranges

In 2015, scientists from the Australian Nuclear Science and Technology Organisation (ANSTO), working in collaboration with representatives of the Adnyamathanha people, collected samples of shells, charcoal, tools and **megafauna** (Figure 4.9.7) bones from a rock shelter in the Flinders Ranges of South Australia. The material was then tested using advanced carbon dating techniques in the laboratories of Lucas Heights in Sydney.

Findings concluded that the shelter is around 49 000 years old. By examining the conditions of the bones and comparing the ages of these remains with the signs of human activity, it could be established that First Nations Australians not only were alive at the same time as these large mammals but that they also interacted in some ways through cultural or spiritual connections.

FIGURE 4.9.7 Model of *Diprotodon optatum*, an extinct wombat-like megafauna and the largest marsupial to have ever lived; bones from *Diprotodon* found in a rock shelter in the Flinders Ranges, South Australia, provide evidence that First Nations peoples lived alongside these megafauna.

Other dating techniques used at First Nations sites

Archaeological research has focused on extending dating methods beyond the limits of carbon dating, particularly for First Nations Australian sites. This pursuit has led to the use of alternative techniques such as uranium-series dating, cosmogenic nuclides, and optically stimulated luminescence (OSL) dating. These methods have significantly expanded the ability to date sites and their occupation history, providing deeper insight into Australia's ancient past and the enduring connection of First Nations communities to the land.

Uranium Series (U-series)

KEY TERM

speleothem mineral deposit, including stalactites and stalagmites, formed from groundwater in caves

Uranium series dating measures the radioactive decay of uranium isotopes in calcium carbonate deposits, such as **speleothems** found in caves. It is used to date geological formations associated with human occupation that sit beyond the range of carbon dating. For instance, minerals forming over rock art may contain uranium-234. As time passes, this uranium-234 decays into thorium-230. By comparing the relative quantities of uranium-234 and thorium-230, therefore, it becomes possible to calculate the age of the mineral layer above the artwork and give a minimum age for the painting beneath.

Cosmogenic isotopes

Cosmic rays, high-energy radiation from the Sun and other stars in the galaxy, continually reach Earth's surface. While exposure to these rays is constant and presents minimal risk, they can interact with surface materials to create new isotopes, particularly after a rock has broken away and become exposed to cosmic radiation. The presence of 'cosmogenic isotopes' in the rock allows researchers to determine when the slab separated from the parent rock. This method offers another valuable tool for dating geological features associated with First Nations sites, as rock art, for example, could not have been created before the rock slab was exposed.

Optically stimulated luminescence (OSL)

OSL is used for dating minerals exposed to light or heat, such as sediments and rock shelter minerals at First Nations Australian sites, and is based on the behaviour of electrons in the outer shells of atoms. For example, quartz found in rock, sand, or mud gathers electrons in darkness, while sunlight expels them. The longer quartz stays in the dark, the more electrons it accumulates, which can then be measured.

OSL dates materials up to 150 000 years old, including rock art, often by analysing the wasp nests on or around it. If a wasp brings mud containing minerals into the darkness of its nest, the electrons those minerals have lost through exposure to sunlight accumulate again, a bit like resetting a stopwatch. Analysing the mud can therefore reveal the electron count of the minerals and time passed since the nest's creation. An artwork painted beneath a wasp nest must, in turn, be older than the wasp nest itself.

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The world's oldest continuous culture

In July 2017, advanced scientific dating techniques revealed that evidence of people's occupation in the northern region of Australia dates to at least 65 000 years ago. An international team of scientists collaborated with the Mirarr, traditional owners of the land, to conduct excavations at a rock shelter named Madjedbebe in the Kakadu area of the Northern Territory (Figure 4.9.8).

By employing a combination of techniques, including carbon dating and OSL, thousands of artefacts were securely dated (Figure 4.9.9). These artefacts included axe heads, bones, shellfish remains, charcoal, seeds and human remains. The results conclusively established that the site had been occupied much earlier than previously believed. Furthermore, the artefacts unearthed at the site shed light on the advanced technologies used by these First Nations Australians, such as using grinding-stone technologies to produce ground-edge axes and to grind seeds and process other plant foods.

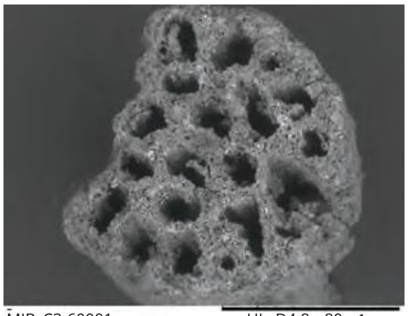


FIGURE 4.9.9 A charred waterlily (*Nymphaea* sp.) stem found at Madjedbebe rock shelter in Kakadu, Northern Territory (scanning electron micrograph).

FIGURE 4.9.8 Madjedbebe site custodian, May Nango, sharing cultural knowledge about rock art with Djurrubu rangers Axel Nadjamerrek, Amroh Djandjomerr and Cuisak Nango.

SC 2 CHECK YOUR UNDERSTANDING

List two First Nation artefacts that can be dated by using carbon-14.

Lesson review

Use these questions to check whether you have met the learning intention for this lesson.

1 Describe how radiocarbon dating would be used to date a piece of ancient wood.

2 A woolly mammoth fossil was found buried in the permafrost near the Artic. The carbon-14 was 12.5%. Use Figure 4.9.3 to calculate the approximate age of the fossil.

3 List two reasons why carbon-14 dating may not be precise.

4 Explain how the mud wasp nests are used to date rock paintings.

Inquiry activity

4.10 Radioactivity in medicine

Learning intention

To be able to explain the use of radioactivity in medicine

Success criteria

SC 1: I can describe how radioactivity can be used in the diagnosis and treatment of cancer.

SC 2: I can identify and suggest risk mitigation strategies for the use of radiation in medicine.

SC 3: I can predict how advances in technologies will affect the use of radiation in medicine.

Introduction

The uses of radiation in medicine can be considered under two main headings: diagnostic and therapeutic. Diagnostic methods are aimed at identifying causes of medical problems, such as the location of a tumour, the site of bone fractures or checking the function of an organ, such as a kidney. Therapeutic methods use radiation to treat the medical condition. This often involves using high-energy radiation in a controlled way to reduce the growth of cancer cells, by damaging the genetic material (DNA) within the cells. This will stop the cells growing and reproducing and it is often used in conjunction with other treatments such as chemotherapy.

In this inquiry activity you will learn about the ways that radiation can be used in medicine (Figure 4.10.1) and conduct some guided research into a particular example of its use.

FIGURE 4.10.1 A doctor examining an image produced by X-ray radiation

Background

X-ray radiation was discovered in 1895, and within a year, X-rays were used in medicine, initially to see bone fractures and identify foreign objects that had entered bodies. X-ray radiation was also used to treat breast cancer in 1986. At this time the use of such treatments was very experimental, and as such, very risky. There was not a lot of data about risks, safe dosages and potential side effects.

After scientists such as Henri Becquerel and Pierre and Marie Skłodowska-Curie discovered the radioactive nature of atoms such as radium, this radioisotope was used for the first time in 1901 to treat a disease called lupus. Lupus is type of autoimmune disease, where a person's immune system acts against their own organs.

J.J. Thomson, the discoverer of the electron, suggested that water in some natural springs was radioactive due to the water having passed through rocks that contained radium. As a result, 'radium baths' were prescribed for a range of ailments (Figure 4.10.2). There is even a town in British Columbia, Canada called 'Radium Hot Springs', named after it was found that the natural spring water contained low levels of radium.

FIGURE 4.10.2 The radium bath department of 'Hotel Will Rogers' in Oklahoma in the USA

Today there are many uses of radiation in medicine. They include the following:

Radiography

X-rays are not produced from the decay of radioisotopes but are a type of radiation used in medicine. The X-ray radiation is produced by bombarding a metal with a beam of high energy electrons which can produce images of bones, tissues and organs inside the body. X-rays have similar properties to gamma rays (but with less energy), so they pass through some parts of the body and not others. For example, bones show up white on X-ray images because the X-rays do not pass through the substances that bones are made from (Figure 4.10.3).

Diagnostic nuclear medicine

This technique is used to identify medical problems inside the body. A small amount of a substance containing a radioisotope is injected into the body. For example, positron emission tomography (PET) scanning, uses a substance called fluorodeoxyglucose (FDG) that has similar properties to glucose but contains the radioisotope fluorine-18 (Figure 4.10.4).

The radiation from this radioactive source can be detected using a camera that is sensitive to the radiation emitted as isotope decays. In this way, the material that has been added can be traced as it moves around the body, through organs or into tissues. This process can reveal abnormalities such as blocked arteries, poor liver and kidney function and can also detect tumours.

FIGURE 4.10.3 Two X-ray images of a broken forearm

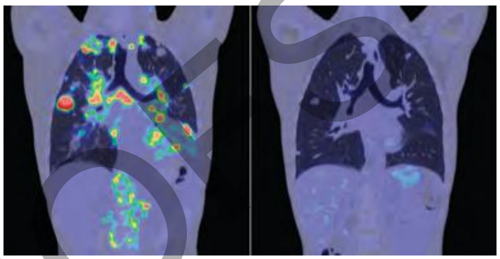


FIGURE 4.10.4 PET scans of a patient before and after cancer treatment, revealing the disappearance of the tumours in his chest and torso

Radiation therapy

Cancer is caused by certain cells growing uncontrollably in the body that causes the formation of a tumour. The radiation targets these cells, damaging the DNA and the cells are no longer able to reproduce or grow. In normal radiotherapy, a relatively large area of the body is subjected to radiation from outside of the body.

Brachytherapy

This is an advanced treatment that involves a high dose of radiation being applied to a specific site (Figure 4.10.5). To do this, the radioactive source that contains the radioisotope is placed as close as possible to the site of the tumour. Brachytherapy can be used to treat breast, cervical and prostate cancers and will involve surgery to place the radioactive source in the correct position.

FIGURE 4.10.5 An X-ray image showing tiny titanium capsules containing iodine-125 implanted in a patient as treatment for prostate cancer

Stereotactic radiosurgery

When the application of the radiation needs to be focussed on a small, precise area, but high doses are required, stereotactic radiosurgery can be used. It uses three-dimensional imaging technologies to deliver a high dose of radiation, and is non-invasive, meaning that surgery is often not required. Because of this it is often used to treat brain cancer. This type of treatment is often referred to as 'gamma knife', because there is no need for an actual surgeon's knife.

Aim

To conduct research to explain the use of one example of radioactivity in medicine

Plan

Decide on the example of the use of radioactivity in medicine that most interests you.

Decide on how you are going to present your findings, guided by your teacher. This could be a slide show, a written article or an audio-visual presentation.

If you are working in group, assign roles to people in the team.

Go To
Toolkit sections 4.2, Evaluation of secondary data and 5.1, Using AI in science writing

In your presentation or text, you will need to answer the following questions based on the context that you have chosen for your inquiry.

- How is radioactivity used in the diagnosis or treatment of a form of cancer?
- What are the risks associated with this use of radiation in medicine and how are these risks reduced?
- How might advances in technologies affect the use of your chosen use of radiation in medicine into the future?

You can record your initial ideas.

Conduct

Create your article or presentation based on your planning notes and guidance from your teacher. Ensure that you have included answers to the three questions listed in the plan. Read the notes below for elaboration.

- How is radioactivity used in the diagnosis or treatment of a form of cancer?

  Consider whether the technique that you are investigating is used to identify, locate or monitor an existing form of cancer or if it is used to reduce the harm caused by the disease. In diagnosis, you can comment on how the data is analysed, how reliable or accurate it is, and whether there are any ethical issues related to the use of the data. For radiotherapy, you can explore how successful the treatment is, whether it involves invasive surgery, the potential length of treatment plans and the financial costs of the therapy. Include the names, and where possible the properties, of the radioisotopes used in the treatments.

- What are the risks associated with this use of radiation in medicine and how are these risks reduced?

  Consider the type of radioactive sources used in the treatment in terms of the type of radiation that is emitted, and the half-lives of the radioisotopes used in the procedures. You can consider the short-term risks and the long-term effects if radioactive material is left in the body, or multiple treatments are required. You can also investigate the potential risks for the health professionals administering the treatments, as well as the patients themselves, and potential alternate treatments if required.

- How might advances in technologies affect your chosen use of radiation in medicine into the future?

  Consider factors such as the miniaturisation of technology, the increase in computer speed and capacity, the improvements in three-dimensional imaging and modelling and the influence of increased use of artificial intelligence. Future societal demands and influences, including changing attitudes to risk, could also influence the use and development of radio medicine, and this can be investigated here.

Improve

After receiving feedback on your presentation or article, describe one improvement that you could make to your inquiry that would improve how you have communicated your findings and ideas.

Topic review

4 Atomic structure and radioactivity

Topic summary

The key concepts included in this topic are:

- Marie Curie's impact on the scientific knowledge of radioactivity.
- Atoms are made up of subatomic particles – protons, neutrons and electrons.
- Our understanding of the structure of atoms has changed over the decades as new discoveries have been made.
- The atomic number and mass number of elements are based on the number of protons and neutrons.
- Isotopes are atoms that have the same number of protons but different number of neutrons.
- Unstable isotopes decay, producing either alpha, beta or gamma radiation.
- The decay rate of radioisotopes can be measured in half-lives.
- Radioisotope half-lives aid researchers in calculating the age of artefacts.
- Cancer diagnosis and treatment regularly use radioisotopes.

Review questions

The following questions will assess your success in achieving the learning intentions for this topic.

Remember

1 List two of Marie Curie's advancements in science.

2 Define atomic number and mass number.

3 Chlorine-35 and chlorine-37 are stable isotopes of chlorine. Identify a process to separate these two isotopes.

Understand

4 Describe the key features of protons, neutrons and electrons.

5 Explain how dating techniques have been used to establish timelines for the presence of First Nations Peoples on the Australian continent.

Apply

6 Describe how Ernest Rutherford's gold foil experiment contributed to the modern understanding of atomic structure.

7 Draw a two-dimensional representation of a carbon atom (atomic number 6, mass number 12).

8 Describe alpha, beta and gamma radiation in terms of their properties.

9 Briefly explain an experiment to model radioactive decay and half-life using 100 coins.

Analyse

10 Compare the characteristics of carbon-12 and carbon-14 isotopes.

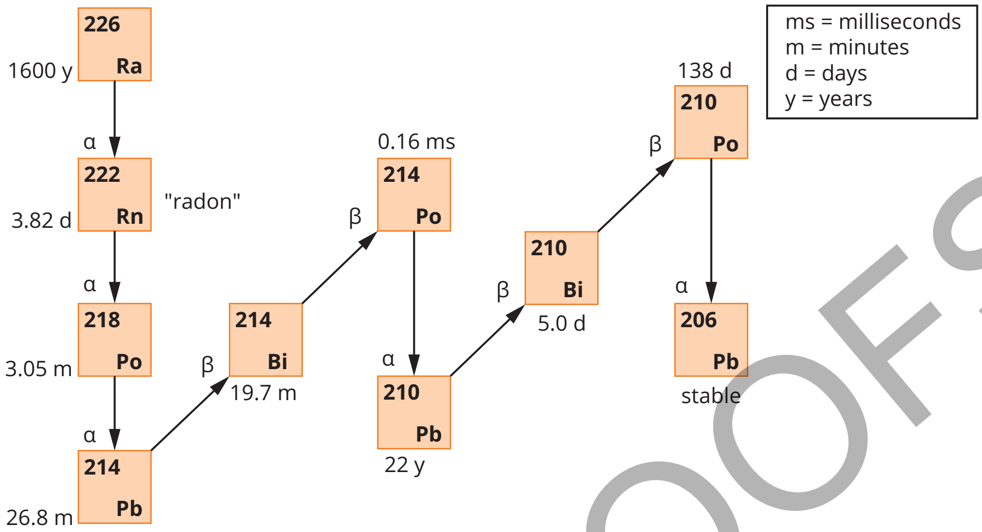
11 The half-life of iodine-131 is 8 days, while that of potassium-40 is 1.25 billion years. Predict the use of these two radioisotopes by scientists.

12 An archaeological investigation into ancient ruins discovered some human bones. Carbon-14 dating found the bones had 25% of the natural amount of carbon-14. Calculate the age of the human bones, knowing the half-life of carbon-14 is 5730 years.

13 Describe how radioactivity is used in the diagnosis and treatment of cancer.

14 Radium-226, which Marie Curie discovered and isolated, has many radioisotopes as it decays to lead-206. The image below is radium-226's decay chain, showing all these radioisotopes and the type of radiation they emit.

Using this information, explain why Marie Curie's body is buried in a lead-lined coffin.



Extension: Research task

15 There are many common radioisotopes used for medicine, scientific research and industry. And you have learnt about some of these applications in this topic. Another use for radioisotopes is sterilisation. The gamma rays that are emitted by various radioisotopes are used to sterilise many different products. Your task is to investigate the following and present it as a poster. Consider the following points when researching.

- The radioisotopes used in sterilisation and their half-lives
- The reasons why sterilisation is important
- The methods available to sterilise products
- The types of products that are sterilised
- Why radioisotopes are most common technique for sterilisation

Topic reflection

The learning intentions for this topic are given in each lesson and at the beginning of the topic. Consider how well you have achieved them. Note down any particular areas that you are confident in, and others where you are not so sure.

4 Glossary

algorithm a process followed in calculations used, most commonly in computer software, to process data

alpha emitter a radioisotope that gives off alpha particles

alpha particle a particle containing two protons and two neutrons; the equivalent of a nucleus of a helium atom

atomic number the number of protons in the nucleus of an atom, indicated in the periodic table

beta particle a small, negatively charged particle that can be ejected from a nucleus during a nuclear reaction; it is identical to an electron

Big Bang the sudden expansion of space from a point of dense energy which occurred at the start of the universe

carbon dating a method for judging the age of artefacts or fossils by analysing the amount of carbon-14 in the fossil

digestion the process of breaking down food into a useable form

disintegration the nuclear decay of an atom, indicated by a burst of gamma radiation, alpha or beta particle

electromagnetic radiation a wave consisting of electric and magnetic fields travelling at the speed of light

electromagnetic spectrum the range of all electromagnetic radiation

electron negatively charged subatomic particle, located around the nucleus of an atom

electron cloud the region of negative charge surrounding the nucleus, containing the electrons

gamma radiation a form of ionising radiation made up of gamma rays (extremely high-frequency electromagnetic radiation emitted by radioactive materials)

gamma ray a very high-energy electromagnetic wave that is produced when the protons and neutrons in a nucleus rearrange

half-life the time it takes for half of a radioactive sample to decay

ionising radiation any form of radiation that can remove electrons from atoms and molecules

isotope group of atoms with the same number of protons but different numbers of neutrons

luminous an object that releases or emits light

megafauna group of large land animals that evolved after the dinosaurs became extinct

midden an ancient dump site containing shells, bones and other debris from human activity

mineral naturally occurring solid substance with a known chemical composition

neutral having no overall electrical charge

neutron a subatomic particle with no electric charge located in the nucleus of an atom

nuclear decay the process that occurs when an atomic nucleus undergoes a nuclear reaction and emits radiation

nuclear fusion the process in which smaller atoms are converted into larger atoms, also producing light and heat

nuclear reaction a process that causes a nucleus to change, including alpha decay, beta decay, fission and fusion

ore rock containing valuable minerals

organic describes a compound that is or was part of a living thing; containing carbon

proton a subatomic particle with a positive electric charge located in the nucleus of an atom

radiation the emission of energy in the form of electromagnetic waves or subatomic particles

radioactivity amount of radiation emitted from a nucleus undergoing nuclear decay

radioisotope an isotope that are unstable with a nucleus that undergoes nuclear decay

speleothem mineral deposit, including stalactites and stalagmites, formed from groundwater in caves

subatomic particle particle that atoms are made of—protons, neutrons and electrons

X-ray high-frequency electromagnetic radiation that can penetrate many materials

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