SCIENCE

Unit 2

Matter and materials

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Language skills	Interpreting scientific text	Writing logical and coherent responses to questions

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Language skills	Writing logical and coherent responses to questions

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Language skills	Writing logical and coherent responses to questions

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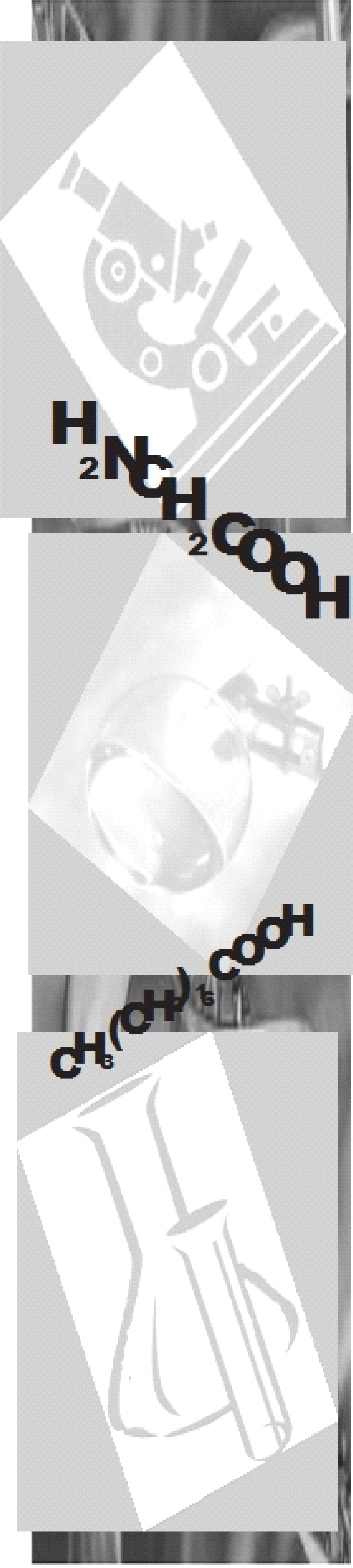
Science process skills	Interpreting tables and extracting data from tables to draw conclusions
Language skills	Writing logical and coherent responses to questions

LESSON 1

What Makes Up Matter



About this lesson

A substance can be either an element, a compound, or a mixture of elements and compounds. We find out how the Mass Laws of the 18th century helped scientists to tell the difference between these substances. We will study examples of steel, gold, salt, water and milk, and learn the meaning of the scientific terms ‘homogeneous’ and ‘heterogeneous’. We then learn about the theory that matter is made up of atoms.

In this lesson you will:

- learn what makes up a substance and the different kinds of substances
- find out about the particle nature of matter
- discover how scientists learned about the particle nature of matter
- draw ‘magic spectacles’ diagrams
- tell the difference between pure and impure substances
- learn about the Mass Laws
- learn about heterogeneous and homogeneous mixtures
- understand some scientific terms.

Introduction

To learn Physical Science, we first need to understand it. To understand Science, it is important to know the meaning of the laws, observations, theories and models that we learn about in Science. Here is a way of understanding some of the most important scientific words or ‘terms’ that we use in Science:

Scientists are people who notice something interesting (such as the Sun rises in the east) and then wonder why and how it happens. We call what we notice, an ‘observation’. Observations are things we see, hear, smell, taste and feel. Observations need not be true; they are **not** necessarily facts. If we make many similar observations about one phenomenon, then we can summarise these observations.

We call the summary of many observations a scientific ‘law’. In order to understand their observations, scientists think out an explanation. We call this explanation, a theory. The explanation need not be true or correct, but it must make sense according to the observations that people have made at that time.

For example, the Ancient Greeks noticed that the Sun rises in the east, travels across the sky, then sets in the west. They wondered how the Sun could move in this way. Scientists then explained the Sun's motion in the sky by saying that, every morning, slaves made an enormous fire on a chariot and harnessed beautiful white horse to it. Then a ‘god’ got on to the chariot, cracked his whip, and the white horses pulled the chariot across the sky, from east to west. But they could not explain why the Sun sets at night.

Nowadays we have a different theory. We believe that the Sun does **not** move across the sky, but that the Earth is moving around the Sun. And this makes it look like the Sun rises in the east and sets in the west.

Thus a theory is simply the best explanation that we have for our observations at a particular time. A theory is not necessarily correct!

The effects of Chemistry – for better or worse – are all around you. Your body works by means of a complicated series of chemical reactions, which we still only partly understand. Scientist have made thousands of chemicals in the laboratory that we use to treat symptoms, or even causes, of illnesses.

All our efforts at producing chemicals that will help people are based on the knowledge of how we can control chemical reactions. To do this, we need to know and understand the fundamental particles of matter and how they behave and why. This unit deals with the development of our understanding of these important aspects of chemistry.

What makes up matter?

Our world is made up of different substances. We say that substances are made up of 'matter'. But what exactly makes up matter? Chemistry is all about the study of matter, and so, in this lesson, we will use chemical ideas to answer the question. Most people feel curious about their world. They wonder why things happen, such as why does water seem to disappear when you heat it? And why are some substances solid, while some are liquid, and others gases? What exactly makes up a substance?

The invention of the mass meter (chemical balance) made it possible for scientists to work out the 'Mass Laws'. These laws are very important.

The beginnings of chemistry

Chemistry is the study of the nature of matter. Until the 18th century, 'traditional scientists', or alchemists, carried out this study in an unsystematic way.

However, during the 18th century, the chemical balance was invented. This instrument measured the mass of a substance accurately. Scientists were able to measure the masses of the reactants and the products formed during a chemical reaction. In this way, Chemistry started to emerge as a science (i.e., not guesswork).

Doing experiments helped scientists to identify the simplest kind of substances, which they named ‘elements’. They had identified about 20 elements by the end of the 18th century. Scientists also began to understand the difference between elements and compounds, as well as the differences between pure substances (elements and compounds) and impure substances (mixtures).

physical property: *behaviour that does not involve any chemical changes;*
chemical property: *behaviour that is to do with chemical changes.*

Elements are made up of one type of atom, for example Iron. Compounds are composed of more than one sort of atom, but in a fixed ratio; for example, pure water. The elements combine chemically.

Mixtures are substances that are physically blended together in any proportion; for example, blood, air and sugar in water. Mixtures can be homogeneous or heterogeneous. If the substances are in the same phase (both liquids or both gases), then the mixture is homogenous; for example, a mixture of nitrogen and oxygen gas. A sugar and water mixture can be considered heterogenous because it is a solid and liquid mix.

In their experiments, chemists compared the masses of substances that react (the reactants) with the masses of the substances made (products) during a reaction. They summarised their findings in a set of three important laws, called the **mass laws**, which are:

The Law of Conservation of Mass

The Law of conservation of Mass states, ‘During a chemical reaction, the mass of a system remains the same.’ This means that the mass of the products equals the mass of the reactants. This Law was first thought out in the 18th century.

Example:
Suppose we do an experiment with a photographer's flash bulb. The flash bulb represents an isolated system where no substances can leave the system (the bulb) and no substances can enter the system. We now pass an electric current through the bulb. Its magnesium filament flashes and forms a white solid, all inside the bulb. The magnesium disappears. When we measure the mass of the bulb and its contents, we find that the mass is exactly the same as before.

Many scientists have carried out similar experiments, all with the same result. We can summarise these results in the Law of Conservation of Mass, which states, ‘During a chemical reaction, the mass of the chemical system remains the same.’

The Law of Fixed Proportions

“Different samples of a pure compound always contain the same elements in the same composition (proportion)” According to this law, elements in pure substances are always present in the same definite mass ratio, irrespective of where the substance is made or found. By making use of this law, it is possible to determine the exact composition of each element to manufacture a compound.

Example:
Whenever we make carbon dioxide, the ratio, by mass, of carbon to oxygen is 3:8. Thus, if we use up 6 g of carbon, how many grams of oxygen will be used up?

Answer:
We make use of the Law of Fixed Proportions. The ratio by mass of carbon to oxygen of 3:8 means that, for every 3 g of carbon that is used up to make carbon dioxide, 8 g of oxygen will also be used up. Therefore, if we use up 6 g of carbon (twice as much as the 3 g), then 16 grams of oxygen (twice as much as the 8 g) will be used up.

The Law of Multiple Proportions

This law states, ‘When one element, A, is able to form different compounds when it reacts with a second element, B, then the masses of B that react with the same mass of A will always be in a simple ratio.’

A good example is water and hydrogen peroxide. Both compounds have hydrogen and oxygen in different fixed ratios. Water: (H_2O); hydrogen peroxide: (H_2O_2). Water is a clear harmless liquid and hydrogen peroxide is a clear toxic chemical.

ACTIVITY 1

1. Jane does an experiment where she takes 40 g of calcium and reacts it with 36 g of sulphur. The reaction produces a white solid, calcium sulphide. She finds that, at the end of the reaction, the mass of the calcium sulphide is 72 g and there is 4 g of sulphur left over. Use this information to illustrate the Law of Conservation of Mass.

2. Thabo does an experiment where he reacts 40 g of calcium with 16 g of oxygen, in a gas jar. When the reaction is over, he finds that he has made calcium oxide. What is the mass of the calcium oxide?

3. How many grams of magnesium are used up when a sample of magnesium reacts with 32 grams of sulphur, to form 56 g of magnesium sulphide?

4. Rani reacts 24 g of magnesium with some oxygen and forms 40 g of magnesium oxide. What mass of oxygen was used up?

5. Water is a compound made up of hydrogen and oxygen. The mass ratio of hydrogen to oxygen is 1:8. If we analyse some water and find that the water sample is made up of 36 g, what is the mass of hydrogen and the mass of oxygen in this sample?

6. Sodium reacts violently with water. Is this a physical or chemical property?

7. The melting point of ice is 0°C. Is the melting point of a substance a physical or a chemical property?

ANSWERS ON PAGE 127

Particles at the macroscopic and sub-microscopic level

We have all noticed that the world is made up of different substances. For example, a motor-car is made up of substances such as steel, rubber, plastic, glass and oil, and in our homes we use sugar, flour and water to cook with. In this lesson, we aim to understand how these substances behave. If we can see a substance, we say that it is 'macroscopic'. 'Macro' means 'big', while 'scopic' is to do with 'seeing'. In order to understand how substances behave, we draw sub-microscopic diagrams of macroscopic ideas.

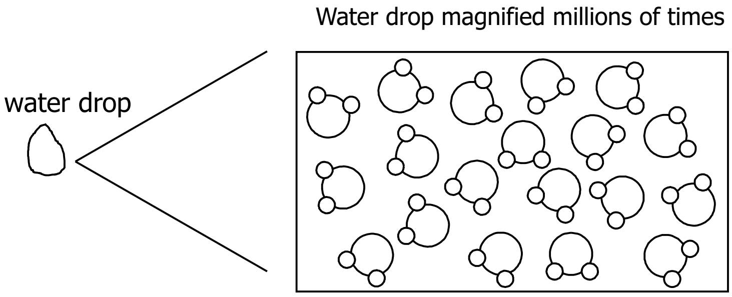
Gold is a solid, while water is a liquid and air is made up of gases. We can make a drawing of an object made of gold, such as a ring; we can also draw some water in a river; and we can feel air when the wind blows on us. Solids, liquids and gases are macroscopic ideas.

sub-microscopic: *cannot be seen through a microscope*

Sub-microscopic particles cannot be seen with the naked eye and cannot be seen through a microscope. In order to depict particles that are sub-microscopic we can provide diagrams at the symbolic level.

We are all familiar with the substance that we call 'water'. But what makes up water? If we pass an electric current though some acidified water, the water breaks up into hydrogen and oxygen. So we conclude that water is made up of two simpler substances: hydrogen and oxygen.

We call the smallest part of any substance, for example water, which still behaves as that substance, a ‘molecule’. If we could put on some ‘magic spectacles’, so that we could see the water molecules that make up a drop, we would see something like this:



We call this diagram, a ‘sub - microscopic representation’ of water

Key:

water molecule: made up of two hydrogen and one oxygen atoms

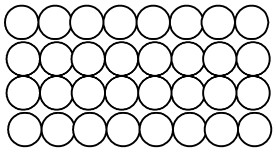
We say that this diagram is a ‘magic spectacles’ representation of a water drop. The water drop that we can see and feel is the ‘macroscopic’ idea, while the diagram of molecules, which we cannot see, is a ‘sub-microscopic’ idea.

Here is another example of a microscopic representation of a macroscopic idea:

Gold is a beautiful metallic substance. An object made of gold shines when you rub it. Gold feels hard and smooth. These are macroscopic ideas. Gold is an element and is made up of tiny atoms that are arranged very closely to each other. This is a **sub-microscopic** idea.

Key: one gold atom:

○



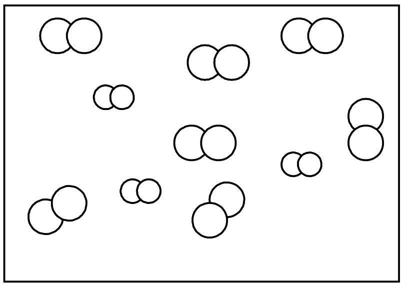
This is a sub-microscopic representation of a small piece of gold.

When the wind blows, we can feel the air pushing against us. This is a **macroscopic** idea. But we cannot see air. Air is made up of mainly nitrogen and oxygen molecules. Molecules are sub-microscopic ideas. We can make a sub-microscopic diagram of the air in this way:

KEY:

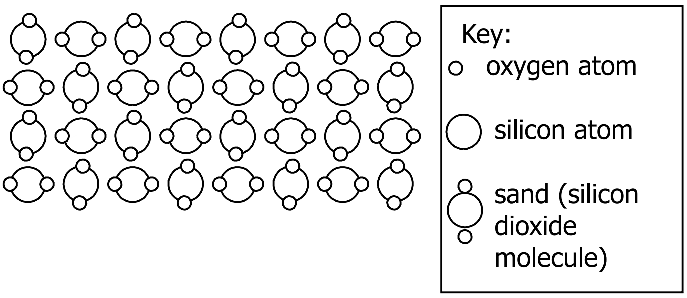
○○ oxygen molecule

○○ nitrogen molecule

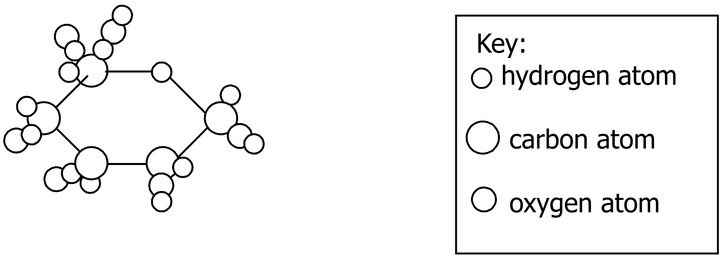


We can divide substances into elements and compounds. Elements and compounds are 'macroscopic' ideas. We can see sand, and taste sugar. Sand and sugar are compounds, so we are using macroscopic ideas. If we draw the tiny molecules that make up sand (silicon dioxide) or those that make up sugar, then we are using microscopic ideas.

Sub-microscopic representation of many molecules of sea sand:



Sub-microscopic representation of a single sugar molecule:



ACTIVITY 2

a. What is the main difference between:
   i. a macroscopic and a sub-microscopic diagram?
   ii. an atom and a molecule?

b. Are all molecules about the same size? Give a reason for your answer.

c. 'Di' means two. Why do you think we call sand silicon dioxide?

d. Tabulate three ways in which iron and sulphur are different from iron sulphide (the compound that is produced when iron reacts with sulphur).

e. Classify the following as mixtures or pure substances:
   - pure honey
   - pure tomato juice
   - iron ore
   - magnesium sulphide

ANSWERS ON PAGE 128

COMMENT

Chemists needed a simple theory that could help them explain and understand the many reactions and laws they knew. The idea that matter is not continuous, but that it is made of separate bits or particles, began to give them this understanding.

CHECKLIST

Are you able to:

☐ explain what we mean by a ‘theory’?
☐ tell the difference between a macroscopic and a microscopic idea?
☐ draw a ‘magic spectacles’ diagram of an element?
☐ describe what makes up a pure substance?
☐ use microscopic ideas to explain the difference between an element and a compound?
☐ tell the difference between pure and impure substances?
☐ explain what we mean by a ‘heterogeneous’ and ‘homogeneous’ mixture?
☐ give an example of a pure and impure substance?

NOTES

LESSON 2

What atoms are made of

About this lesson

We have been learning about matter and what makes up matter. Scientists agreed that matter is made up of atoms. But then they asked themselves, 'What makes up an atom?’

An ancient Greek philosopher, Democritus, proposed the idea that all matter is made up of small indivisible particles. 2000 years later, John Dalton, a British chemist, revived the idea that matter is made up of atoms. However, Dalton also considered the atom as a solid sphere like a billiard ball with no sub-atomic particles.

At the end of the 19th and beginning of the 20th centuries, scientists such as Rutherford, Bohr and Chadwick conducted experiments that finally gave us the answer to the question, 'What makes up an atom?' This lesson describes and explains the pattern of experiments and thinking that eventually led scientists (and us) to feel sure we know that an atom is made up of a nucleus of protons and neutrons, with electrons in energy levels arranged around the nucleus.

To understand this we examine the ideas of Democritus, Thomson, Rutherford and Crookes.

In this lesson you will:

- find out how these scientists solved the problem of what makes up 'matter’
- examine different models of the atom.

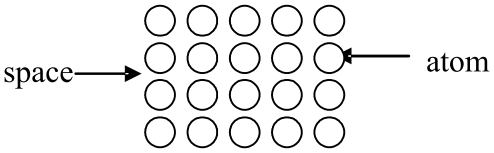
What is 'Matter'?

Even though we cannot see an atom, scientists have used the results of experiments to work out what an atom must look like.

We call what we think an atom looks like, an 'atomic model'.

Democritus suggested that matter is made up of tiny, 'uncuttable' particles that he called 'atoms'.

He also suggested that these atoms are arranged with spaces between them.



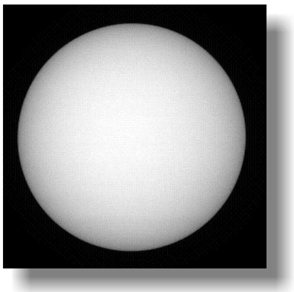
Example of how Democritus thought that atoms are arranged

Democritus thought that we are not able to divide an atom into even smaller particles. This was based on philosophy and not on scientific and experimental reasoning.

What puzzled the scientists of the time was what could possibly be in the spaces between the atoms.

The particle nature of the atom

John Dalton resumed with the theory of the atom many years later. He found out that substances always combine in fixed ratios by mass.



John Dalton's billiard ball model

His theory can be summarised as follows:
1. All matter is made of small indestructible particles (called atoms).
2. Each element is made of atoms of the same kind.
3. Different elements have different types of atoms.
4. The atoms combine in fixed ratios to form compounds.

However, Dalton's theory could not explain why atoms combine with each other in fixed ratios or why their chemical and physical properties differ. For example, he could not explain the formula of water. He said that it was HO. So the atom must have contained particles inside to explain the formula of water, instead of being a solid sphere.

Early in the 20th century, scientists proved conclusively that an atom is made up of small particles and is mostly made up of empty space, with a nucleus in the centre and electrons moving around this nucleus.

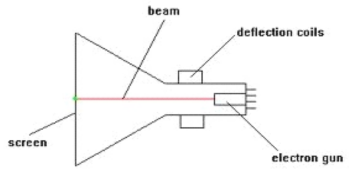
These small particles are arranged in a pattern. This means that an atom has a 'structure'.

Yet no one had ever seen an atom, even though they were sure that atoms existed. During the 19th century, scientists tried to understand more about atoms, realised that they had to find a way of proving this and so designed laboratory experiments to find out more about the atom.

Cathode rays and discovery of the electron

In the 1870s, William Crookes, an English scientist, invented a piece of apparatus that he hoped would help him to understand the nature of electrical charges. The apparatus, called a 'Crookes tube', has a cathode (negative terminal) and an anode (positive terminal).

The cathode ray tube (CRT) is used in oscilloscopes, radar, monitors and television receivers.



Study the diagram of a Crookes' Tube.

Crookes' cathode ray tube

i. One end of the tube is a negative terminal: the cathode. The other end is a positive terminal: the anode.

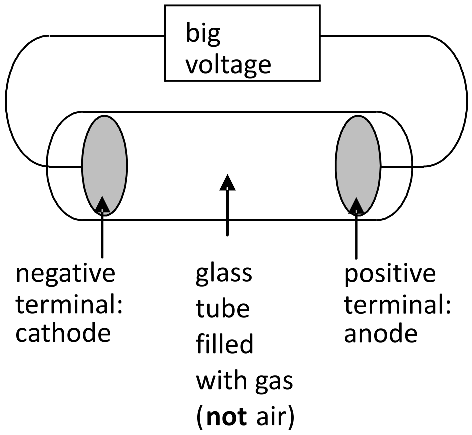
ii. Crookes used a **vacuum** pump to pump out all the air from the inside of the tube. He then filled the tube with another gas, at very low pressure.

iii. When Crookes connected the wires to a strong source of electricity, he saw a glow appearing on the wall of the tube!

iv. He proved that it is rays coming out of the cathode that cause this 'glow'.

v. He called these rays 'cathode rays', and so he called the tube the 'cathode ray tube'.

Diagram of Crookes' cathode ray tube



vacuum:
a region in space where there are no particles at all.

Explanations

Crookes and his colleague, J.J. Thomson, repeated his experiments with other gases in order to find out more about these 'cathode rays'. Thomson placed a positively charged rod near the glass tube and found that the rod attracted the cathode rays.

This made him feel sure that the particles moving along the tube must be negatively charged.

But the result that surprised him was that all the particles behaved in the same way! They all hit the same spot on the end of the tube, no matter which metal he used to make the disc, or what kind of gas he put into the tube. So Thomson concluded that all the particles must have exactly the same mass and charge.

Thomson now gave these particles a name: he called them 'electrons'. He then used more cathode tube experiments to measure the mass of one electron. He calculated that the mass of an electron is more than a thousand times smaller than the atom of the element of smallest mass: hydrogen.

What Crookes and Thomson suggested

Crookes and Thomson now suggested that the electrons must come from the inside of atoms. There was a partial vacuum in the tube so the cathode tube was almost completely free of particles. Therefore, Crookes thought that, in this space, the positive terminal of the tube was attracting, and so pulling, negatively charged particles loose from the atoms of the cathode. These particles then moved along the length of the tube. They produced the glow when they hit the other end of the tube.

Crookes and Thomson could only explain their observations by saying that an atom is not solid. And, because they had already proved that cathode rays are identical to electrons, Crookes and Thompson concluded that there must be electrons in all atoms.

ACTIVITY 1

a. Do opposite charges attract or repel each other?
b. i. What is an electron?
   ii. What is a cathode?
c. Explain why Crookes thought that the positively charged terminal of the tube could pull negatively charged particles loose off the atoms of the cathode tube.
d. What do we call the negative electrode in a cathode ray tube? What are cathode rays made of?
e. What were some of the shortcomings of Dalton's model?

ANSWERS ON PAGE 128

How Thomson's results changed the model of the atom

Other scientists checked Thomson's experimental results and found that they agreed with them. These scientists eventually decided that the tiny particles **must be part of the atom** themselves.

This means that the scientists had to give up the old idea that no one can break down an atom into anything simpler. They had to accept a new idea: an atom is not solid and indivisible, as Dalton had thought!

Scientists started to ask themselves this question: 'Since an atom is partly made of negatively charged particles, and all atoms are neutral, are there other particles that are positively charged so that the charges are balanced?' They then set out to find methods of finding out what these other positively charged particles could be.

The next step in finding out the structure of the atom came about because of experiments to do with radioactivity.

How the knowledge of radioactivity helped to solve problems about the atom

In 1896, the scientists Marie Curie and Henri Becquerel discovered that a certain substance called 'pitchblende' gives out tiny particles that have lots of energy and which can move right through ordinary substances. Curie and Becquerel worked hard to find out what these particles are and where they come from. They called the **phenomenon** of giving out tiny particles, 'radioactivity'. When a substance is radioactive, it gives out, of its own accord, tiny particles that are invisible to the naked eye.

phenomenon:
strange happening

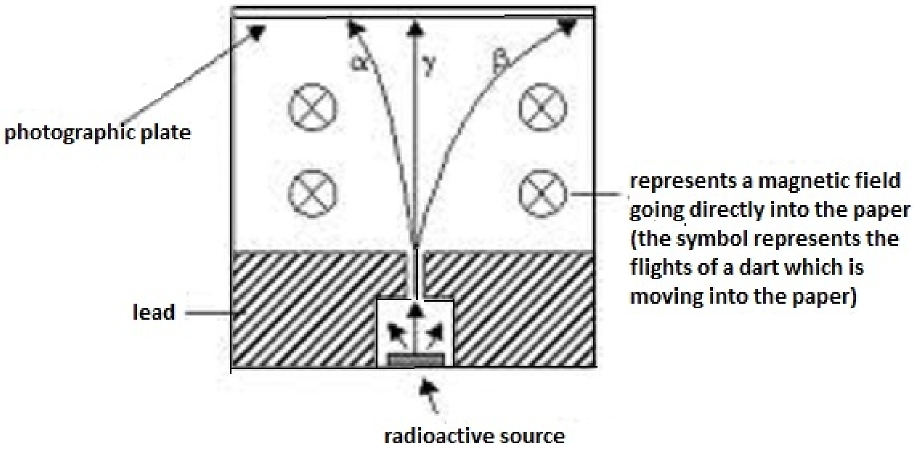
alpha, beta and gamma:
first three letters of the Greek alphabet; like a, b and c

Ernest Rutherford was a student of J.J. Thomson. He and Marie Curie did experiments with the elements radium, thorium and uranium. They found out that all these elements are radioactive. We say that radium, thorium and uranium atoms are 'unstable'. All radioactive substances are made up of unstable atoms.

From their experiments, Curie and Rutherford discovered that radioactive substances give out three different kinds of radiation. They called the three kinds of radiation **'alpha'** rays, **'beta'** rays and **'gamma'** rays.

From the way these rays bend in a magnetic field, Curie and Rutherford found out that an alpha ray is attracted to a negative charge, while a beta ray is attracted to a positive charge. So they concluded that an alpha ray must be positively charged, a beta ray must be negatively charged, while a gamma ray has no charge.

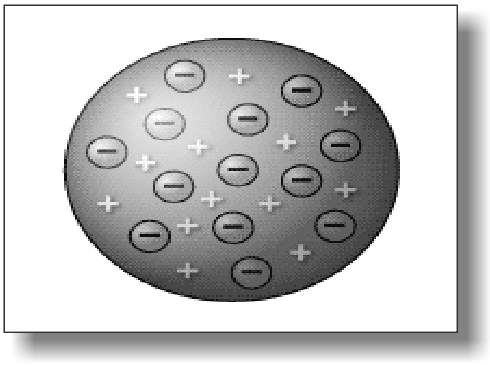
This diagram shows how alpha, beta and gamma rays behave in a magnetic field.



Notice that a gamma ray does not change direction at all. This is why Curie and Rutherford were sure that a gamma ray has no charge.

Thomson's atomic model (1897)

Because of the discovery of electrons, J.J. Thomson suggested a new model for the atom. He thought that an atom must be made up of positively and negatively charged particles. He knew that an atom is always neutral, so he thought that these particles must be arranged so that they are evenly divided in the space that the atom takes up. Thomson's new model was a sphere of what he called 'massless positive charge' with electrons stuck into it, like raisins in a bun.



Thomson's raisin bun atomic model

According to Thomson, however, the atom was still a solid sphere, but one which consisted of identical positive and negative charges distributed evenly. In addition, he could not use his model to explain why and how atoms join each other to make molecules.

ACTIVITY 2

Compare the atomic models proposed by Dalton and Thomson. State three differences between the models.

ANSWERS ON PAGE 129

The experiments that led to a new atomic model (1911)

Once scientists knew that the atom is not 'solid' inside, they tried to find out more about what the inside of an atom must be like.

In his famous oil-drop experiment, begun in 1909, Robert Millikan discovered that the charge on the electron is equal and opposite to the charge of the proton.

Later, in 1911, the physicist Ernest Rutherford did experiments with cathode rays that showed that alpha rays are positively charged helium atoms, beta rays are like electrons, while gamma rays are high frequency electromagnetic radiation.

Rutherford's first experiments

Rutherford already knew about radioactivity. The atoms of certain elements are unstable. For example, uranium atoms give out particles that have so much energy that they can go through very thick sheets of lead. Lead is a very dense metal, so it is difficult for particles to go through it. We call these particles radioactive 'rays'. Rutherford decided to find out more about what these rays can do.

He experimented with a radioactive substance that gives out 'alpha', 'beta' and 'gamma' rays. He discovered that he could make alpha and beta rays change direction by applying electric and magnetic forces. But he could not make gamma rays bend at all.

Rutherford showed by experiment that alpha rays are positively charged helium atoms (He^{2+}), while beta rays are ordinary electrons. The gamma rays are electromagnetic waves, rather like X-rays, so they do not have an electric charge.

The properties of alpha, beta and gamma rays

Alpha rays are not very strong; a sheet of paper stops them completely. Beta rays are much stronger than alpha rays; they can go through a thick brick wall. Gamma rays are the strongest rays. They can go through a thick stone wall.

gold foil:
a very thin sheet of gold

deflected:
swung, bounced back

To find out more about these invisible rays, Rutherford decided to aim a stream of alpha particles at some very thin **gold foil** and then see what happens. Rutherford chose gold because gold atoms are very stable. This means that the substance gold does not react easily with any other substances.

Rutherford's famous 'Scattering Experiment' (1911)

Suppose you stretch a piece of tissue paper across a hoop and then set it up in your garden. Then you throw tennis balls at it. What would you expect to see? You would surely expect the balls to go through the thin paper.

This is rather like what Rutherford expected when he bombarded the gold foil with alpha particles. He used a sheet of gold foil that was much thinner than paper.

When he did the experiment, he was very surprised! He found that although most of the particles went through the gold foil, as though there were nothing there, some of the alpha particles were **deflected** to the side by different amounts, and a few even bounced right back in the direction from which they had come.

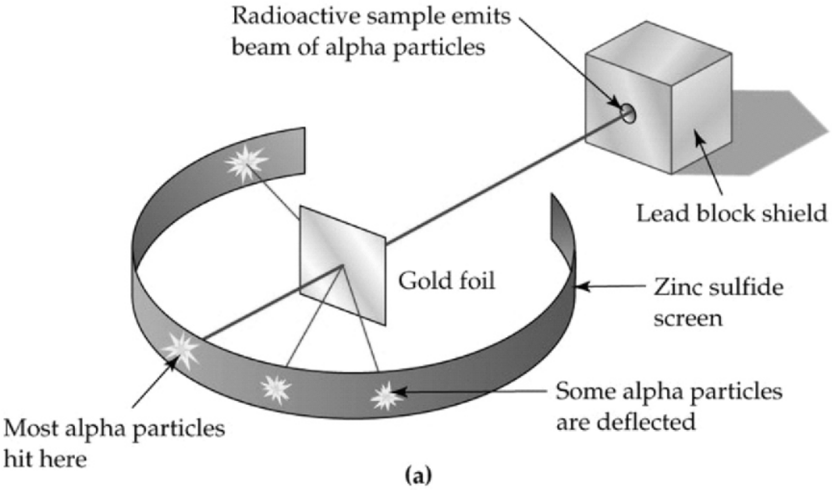


Diagram of the apparatus that Rutherford used to bombard gold foil with alpha particles (The Scattering Experiment)

Rutherford was very surprised. He said, 'It was quite the most remarkable event at ever happened to me in my life. It was almost as incredible as if you had fired a 15- inch cannon shell at a piece of tissue paper and it came back and hit you.'

How Rutherford interpreted his observations

He first said, 'An atom must be made up of mostly empty space.' This theory explains the observation that most of the alpha rays went through the gold foil as though nothing was there.

Most of the alpha particles went right through the atoms of the gold leaf instead of between them. Rutherford concluded from this information that the mass of the atom must be concentrated in its centre and that the centre must be very small compared to the size of the atom.

Rutherford decided to call this centre the nucleus of the atom. He said that the nucleus of an atom must be positively charged. This explains why some of the alpha rays, which are also positively charged, were deflected. The nucleus repelled them.

To explain why only a few of the alpha particles bounced back, he said that the positively charged particles are not distributed evenly through the whole atom. He was sure that they must be grouped in the centre of the atom. That is why a few of the alpha particles bounced back: the nucleus repelled them.

Rutherford decided that the electrons must be in the rest of the atom. Because they are negatively charged, he said the electrons are attracted to the nucleus, but have enough energy to keep on moving around the nucleus.

Because all atoms are neutral, scientists were now sure that there must be positively charged particles that make up an atom. But no one had yet observed these positively charged particles.

From the observations he made in his experiment, Rutherford realised that, because these positively charged particles are in the centre of the atom, nearly the whole of the mass of the atom must be concentrated in this nucleus.

Rutherford's new model of the atom

Rutherford used his observations to make a clear description of his model of the atom. He said that all atoms consist mostly of empty space; that the mass of the atoms is concentrated in the centre and that we call this centre, the nucleus;

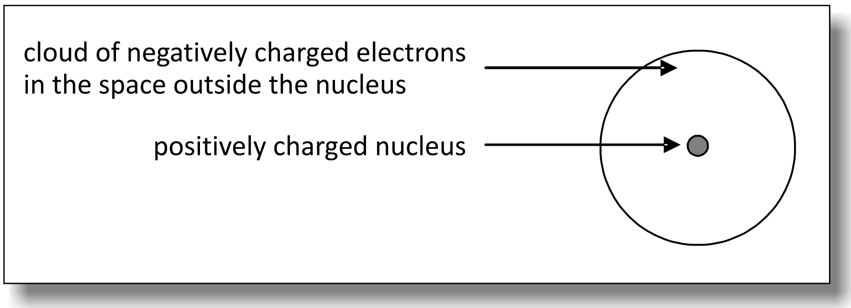


Diagram of Rutherford's Atomic model

(Not to scale)

that the nucleus is positively charged because protons make up the centre of the atom; that electrons are in the rest of the atom and that they move around the nucleus. The atom is neutral so the number of protons is equal to the number of electrons.

To give you an idea of the size of the nucleus compared with the rest of the atom, we can use this comparison. Think of a soccer stadium. If this stadium represents the whole atom, and we placed a marble in the centre of the field, the marble would represent the nucleus, and a full-stop on a spectator's programme would represent one electron!

proton:
A proton is a particle that has a mass that is nearly 2 000 time greater than the mass of an electron.

We call the number of **protons** that make up the atom of an element the 'atomic number' of that element. The atoms of one particular element have the same atomic number. This means that the atoms of different elements always have different numbers of protons.

Rutherford bombarded nitrogen gas with alpha particles. He used nitrogen because nitrogen atoms are very stable. He found that very small, positively charged particles were knocked out of the nitrogen nuclei. These particles had a mass that is about equal to the mass of a hydrogen atom, the smallest atom.

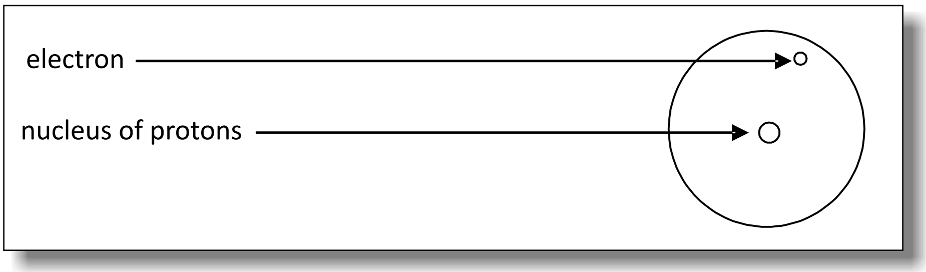


Diagram of Rutherford's Atomic model
(Not to scale)

The size of the charge on one proton proved to be the same as the size of the charge on one electron. Thus one proton and one electron, together, are neutral (have no charge). All atoms are neutral, so Rutherford realised that every atom must have **equal** numbers of protons and electrons. So the atomic model changed again, to look like this:

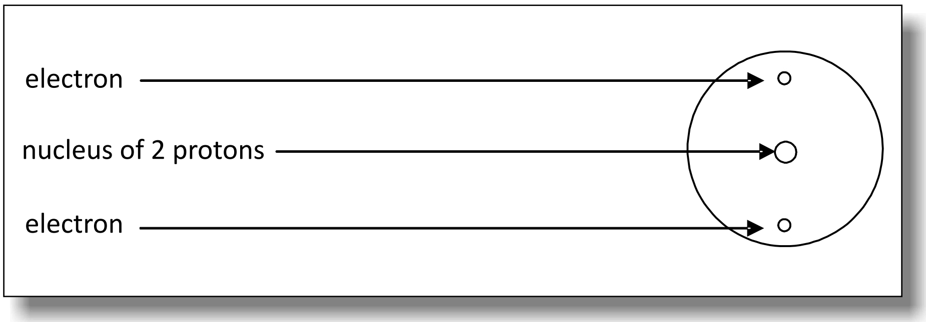


Diagram of Rutherford's Atomic model
(Helium example)

The nucleus of an atom is made up of positively charged particles called protons. Protons make up most of the mass of the atom. The protons and electrons together make the atom neutral.

ACTIVITY 3

a. Name three pieces of evidence that indicate that atoms have an electrical nature.
b. How do we know that the particles in a beam of cathode rays are negatively charged?
c. Give a reason why Rutherford came to the conclusion that an atom must have a nucleus.

ANSWERS ON PAGE 129

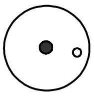
It was not until 1934 that James Chadwick discovered the neutron and the description of the nucleus was further refined.

Why was the discovery of the neutron important?

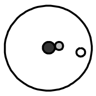
Physicists have been able to find out that all atomic nuclei are made up of protons and neutrons. It is the number of protons that decides to which element an atom belongs. We call the number of protons and neutrons of an atom, its 'nucleons'. So the mass number of an element is equal to the number of protons and neutrons that it possesses.

Neutrons come from the nuclei of atoms, and they contribute to the atomic mass of an element but do not decide to which element an atom belongs.

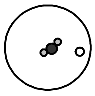
This explains the relative atomic mass of elements and the existence of **isotopes**. All atoms of the same element, which have the same number of protons but differ in mass, are referred to as **isotopes** of that element. For example hydrogen has three different isotopes and different names for each isotope.



no neutrons
Hydrogen



one neutron
Deuterium



two neutrons
Tritium

The helium nucleus, for example, is made up of two protons and two neutrons, so its mass is 4 times greater than the mass of a hydrogen atom. In addition, it is the presence of neutrons in an atom that explains how atoms of the same element can have different masses (reminder: we call these atoms, isotopes).

Scientists had been able to measure the mass of an atom compared to the mass of other atoms. For example, the mass of a nitrogen atom is 14 times greater than the mass of a hydrogen atom. But they did not know how to measure the **actual** mass of an atom.

Neutrons come from the nuclei of atoms. We call the number of protons and neutrons of an atom, the '**mass number**'. For example, the mass number of the element calcium is 20. This means that a calcium atom has 20 particles (protons and neutrons) in its nucleus.

Problems with Rutherford's atomic model of 1919 and what Rutherford suggested

Other scientists asked many questions about Rutherford's model. But their main query was, 'Where are the electrons and what are they doing?'

Because he knew that, in his famous experiment, most of the alpha particles travelled through the gold foil without changing direction, Rutherford decided that the atom must have a very open structure.

He also realised that the positively charged nucleus and the negatively charged electrons attract each other. He wondered why the nucleus and electrons did not move towards each other. If they did, the volume of the atom would become smaller and smaller. He knew that this does not happen.

He was sure that electrons must remain in the atom because the positively charged nucleus attracts the negatively charged electrons.

So he now suggested that electrons must be moving around the nucleus. If they did not move, they would fall into the nucleus. He said that the electrons must be travelling in a space that is relatively far away from the nucleus and that the electrons make up the volume of the atom.

He was also sure that the electrons in an atom must be moving all the time. But, according to Newton's First Law of Motion, a moving electron, like any other object, will travel in a straight line unless a resultant force acts on it. But the electrons could not be travelling in straight lines.

So Rutherford suggested that, if his ideas were correct, and the electron must be changing direction all the time, then it must be changing velocity.

Thus the electrons should be gaining kinetic energy all the time. The electrons would then all spiral into the nucleus. This would make the atom collapse inwards into itself.

Rutherford knew that this does not happen, and his Atomic Model could not explain why.

ACTIVITY 4

Choose the correct answer in question 1 and answer the other questions in your notebook.

1. A beam of particles in a uniform electric field is bent towards the positive plate. From this information we can conclude that the particles are:
   a. hydrogen nuclei;
   b. negatively charged;
   c. electrons;
   d. neutrons.

2. Carbon contains 6 protons, 6 neutrons and 6 electrons.
   a. What is the atomic number of carbon?
   b. Where are the protons found?
   c. Why is the atom electrically neutral?
   d. Give another isotope for carbon.
   e. Give the mass number of carbon.

3. Sodium has 11 protons.
   a. How many electrons are there in a neutral sodium atom?
   b. Where are the electrons found?
   c. Which other particles are found with the protons.

4. How can you be certain that the electrons in an atom do not spiral into the nucleus? Give a detailed reason for your answer.

ANSWERS ON PAGE 129

COMMENT

Rutherford's model of the atom is the basis of our modern understanding of atomic structure. His model transformed physics because it led to a very important question: 'Since unlike charges attract each other, just as like charges repel each other, why don't the negative electrons fall into the positive nucleus?'

The answer paved the way for the development of quantum theory and the work of the Danish physicist Niels Bohr (1885-1962).

CHECKLIST

Are you able to:

☐ work out how scientists began to understand the nature of 'matter';
☐ picture models of the atom proposed by Thomson and Rutherford.

LESSON 3

Bohr’s model of the atom

About this lesson

Niels Bohr was a Danish physicist who studied at Cambridge for a year, under J.J. Thomson and Ernest Rutherford. He returned to Copenhagen in 1913, knowing about the scattering experiment, and then worked out his famous theory about the structure of the hydrogen atom. In this lesson, you will learn how Bohr thought up the idea of an electron orbit and why this idea addressed the problem of why electrons do not spiral into the nucleus of an atom.

From about 1914 to 1918, Niels Bohr tried to solve the mystery of the behaviour of the electrons in an atom: why do they not spiral into the nucleus? He tried to explain why, since the positive charge of the nucleus should surely pull the negatively charged electrons into it, the electrons in an atom do not fall into the nucleus.

He suggested that electrons must be arranged in orbits and that an electron would remain in this orbit unless some force acted on it to make it move away. He said that an electron is in a 'fixed orbit'.

In this lesson you will:

- discover how Bohr explained why the electrons in an atom must be in fixed energy levels
- learn about the arrangement of electrons in the atom
- discover the meaning of a 'quantum of energy’
- learn about ionisation energy.

Electron orbits and potential energy

Bohr decided that the electrons must be moving in fixed circular pathways, inside the atom, and around the nucleus of the atom. He called these pathways 'orbits'. He was comparing the behaviour of electrons with the way the planets move around the Sun and he also knew about Rutherford's suggestions.

The problem was that the nucleus would be attracting the electrons. But Bohr thought that if the electrons moved fast enough the atom would not be able to draw them into its nucleus. So he decided that the electrons must be moving all the time.

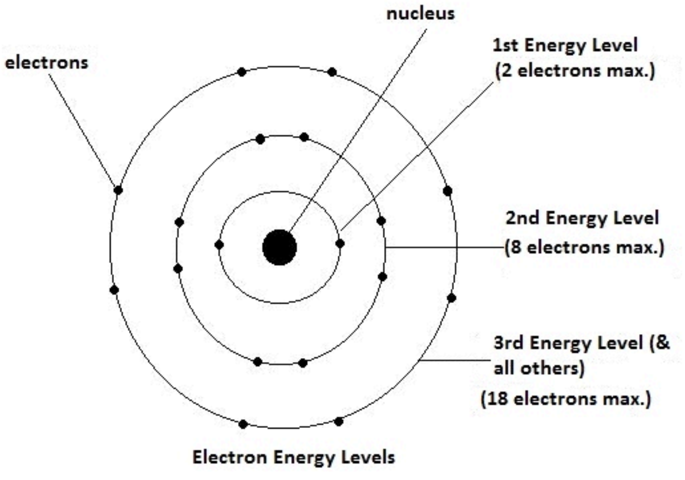
He also decided (without having any good evidence) that the electrons in the same orbit must have the same amount of potential energy. He said that as long as an electron remains in the **same** orbit, it would not lose or gain any energy. He could not explain why; he just said it must be so! (He was right, and scientists discovered why later!)

Bohr said that if the electrons inside an atom move all the time, they must have **kinetic** energy. But they must also have **potential** energy because electrons and protons have opposite charges. Thus the nucleus and electrons attract each other. We call this an electrostatic force of attraction.

The further the electron is from its nucleus, the more potential energy it will have. And so, the electron in the orbit closest to the nucleus must have the least amount of potential energy.

Bohr was sure that the potential energy of an electron in a particular orbit does not change. He said these orbits are 'fixed'. So we say that the electron in an orbit is at a 'fixed energy level'.

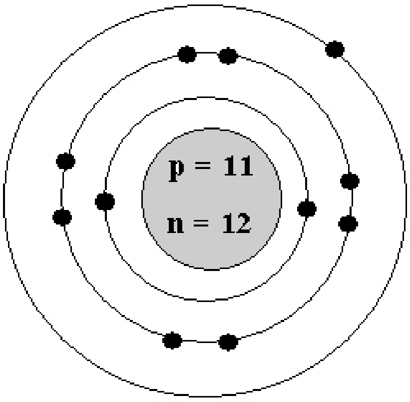
Bohr's theories led to a new model of the atom that we call the 'Planetary' or 'Shell' model of the atom.



Electron Energy Levels

The arrangement of maximum electrons around the nucleus per energy level is 2; 8; 18.

The example below is the model for Sodium. Sodium has 11 protons and 12 neutrons.



This model is rather like how the planets move around the Sun. Bohr did not know why electrons behave in this way, but his theory explained why electrons do not spiral into the nucleus.

Scientists now regarded an atom as a tiny particle that is mostly empty space. They would have described it in this way:

> 'At its centre is a very small region that we call the 'nucleus'. Negatively charged electrons that move in the space around the nucleus supply an equal but opposite charge.'

But no one was sure exactly where the electrons were or what they were doing!

Energy levels

Bohr called the energy of an electron in the fixed pathway in which it travels, an 'energy level'. He suggested that an electron can be in different 'energy levels', depending on how much potential energy it has.

Because the positively charged nucleus attracts the negatively charged electron, it means that if an electron moves away from the nucleus, something must transfer energy to, or do work on, that electron.

The electron would then gain potential energy. If an electron moved closer to the nucleus, it would lose potential energy.

ACTIVITY 1

1. Why would you expect negatively charged electrons to fall into the nucleus of an atom?

2. Make a list (in words) of all the models of the atom you now know about.

3. Copy the diagram of Bohr's Planetary Model of the atom and label:
   a. the electrons with the most potential energy;
   b. those with the least potential energy.

4. Draw a Bohr diagram of an atom that has 8 protons and 8 electrons.

ANSWERS ON PAGE 130

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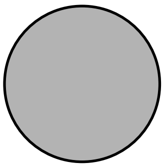
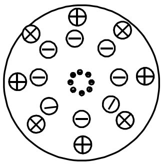
ACTIVITY 2

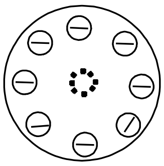
1. Does the potential energy of an electron increase or decrease as its distance from the nucleus increases? Explain your answer.

2. Where does an electron in an atom have the:
   a. most potential energy?
   b. least amount of potential energy?

3. Study the summary of atomic models below. Give the name of the person who suggested each model and the year when this took place.







ANSWERS ON PAGE 130

Bohr realised that he had to explain why electrons, as they accelerate round the nucleus of an atom, do not lose energy. This is what he suggested:

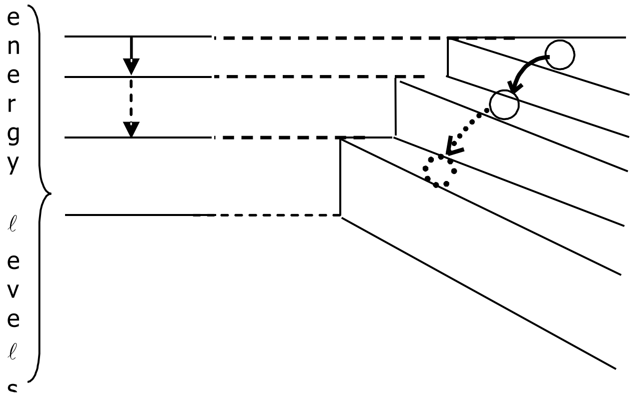
An electron can only move in certain, fixed, 'allowed' orbits. If an electron that is moving in a fixed orbit has a definite amount of energy it cannot change while the electron is moving in that particular orbit. We call these allowed orbits, 'fixed energy levels'. An atom has only certain 'allowed energy-levels'. This means that an electron cannot give out or absorb energy while it is moving in an allowed orbit. If an electron radiates energy then this electron must first 'fall' from a higher to a lower energy level, and conversely, if it is to gain energy, the electron must first 'jump' to a higher energy level. This means that the energy of an electron is '**quantised**'.

quantised:
limited to certain energy levels. It is the allowed or permitted energy levels that decide which energy values an electron may have.

Explanation of the diagram

The ball on the top of the steps has the most potential energy, because it is on the 'highest level'. If this ball falls to a lower step, its potential energy will decrease. The smallest potential energy decrease that can take place is a fall down one step at a time. The potential energy cannot, for example, decrease by half a step. In the same way, to raise the ball from one step to a higher one requires a certain definite (or 'fixed') increase in potential energy. If too little energy is available, then the ball does not move at all.

Here is a way of understanding what we mean by 'quantised': Think of walking up or down some steps. We cannot walk up half a step, neither can we walk down half a step. We can only walk up or down whole steps. (The bottom of the steps is like the nucleus.)



The meaning of a 'quantum' of energy

We can compare a single step in the diagram with a 'quantum' of energy. The energy of a particle like the electron can change only in fixed amounts, or 'quanta'. But the energy of an electron is not exactly like that of a ball. This is because an electron has both potential **and** kinetic energy. When an electron moves from one energy level to another, there is a change in its total energy: potential and kinetic. So the total energy of an electron is the sum of its kinetic and potential energies.

The terms that we use to describe these ideas

When an electron is not moving at all, we say that it is in its 'lowest allowed energy level' and that this electron is in its 'ground state'. It cannot give out any energy.

But when an electron is **further away** from the nucleus, it **gains** potential energy. We say that the electron is 'excited'. An excited state is unstable. This means that an electron in its excited state will not remain in this state for long.

So an excited electron will return to its ground state. To do this, it will give out or 'radiate' energy.

How Bohr used these theories

Bohr used these ideas to calculate the energy levels of the hydrogen atom. First, he gave numbers to the orbits, according to the potential energy of an electron in that orbit.

The symbol for the number of an orbit is 'n'. For example, an electron that is closest to the nucleus, and so has the least potential energy, is in an orbit with n = 1. An electron in energy level 2 has more potential energy than an electron in level 1. Electrons in energy levels 3 and 4 are even further away from the nucleus and so they have even more potential energy.

The arrangement of electrons inside an atom

Between about 1914 to 1920, J. J. Thomson worked out the arrangement of the electrons in an atom from experimental data on 'ionisation energy'.

An atom is neutral. But by heating an element, it is possible to make its atoms lose electrons.

Example: $Na \xrightarrow{\triangle} Na^+ + e^-$

In chemistry, the symbol $\triangle$ means, "heating".

Na^+ is a sodium 'ion'. We call the energy that makes an atom lose an electron and so become an ion, 'ionisation energy'.

Thomson did experiments where electrons were ejected from atoms. He placed a gas at low pressure in a tube. ('Low pressure' means that there are very few atoms in the space of the tube.) He then applied a potential difference (pd) across the tube. The pd exerted a force on each particle in the tube. This pd was just big enough to make each atom lose an electron.

These electrons formed a current and Thomson measured the size of that current. From this, he could calculate how much energy is needed to remove one electron from each atom. We call this energy, the 'First Ionisation Energy'.

He then applied the pd again, until another current was produced, and measured that current in order to find out how much energy was required to remove a second electron from each atom. He called this energy the 'Second Ionisation Energy'. And so on…

We can write equations to represent what takes place:

First Ionisation Energy: neutral atom $\rightarrow$ atom^{+}+ e^{-}

Second Ionisation Energy: atom^{+} $\longrightarrow$ atom2^{+}+ e^{-}

Third Ionisation Energy: atom2^{+} $\longrightarrow$ atom3^{+}+ e^{-}

Thomson now used these results to work out how many electrons an atom has and how these electrons are arranged.

Element	Atomic number	First Ionisation Energy (aJ)
hydrogen	1	2.18
helium	2	3.94
lithium	3	0.86

An 'aJ' is a unit of energy.
The 'J' after 'a' stands for 'joule'.

The First Ionisation Energy of helium is nearly twice as big as that for hydrogen. Thomson interpreted this result as meaning that a helium atom has two times as many electrons as does a hydrogen atom.

But the lithium atom result was a surprise! Thomson expected the result for lithium to be three times that for hydrogen. However, he was able to explain this result. He said that the third electron must be in a different orbit from that of the other two electrons.

From results like these, Thomson was able to work out that the first orbit can only be made up of 2 electrons and that the second orbit is made up of 8 electrons, and so on.

How Thomson used the results of these experiments

By using the results of experiments like these, Thomson worked out the number of electrons that can be in the electron orbits of an atom. Remember that the symbol for the number in an orbit is 'n'. The orbit closest to the nucleus is n = 1, the next orbit is n = 2, and so on. Thomson finally worked out that the number of electrons that can be in any orbit of an atom is $2n^2$.

As the atom is a three-dimensional object, Thomson suggested that we think of the orbits, which are also three-dimensional, as being like the skins of an onion.

ACTIVITY 3

1. What is the number of electrons that can be in an orbit of n = 3?

2. Complete the missing information in the table below.

Element	Number of electrons lost	Ion
Na	1 lost	Na^+
Ca		Ca^{2+}
Li	1 lost	
Mg		Mg^{2+}

3. Fill in the correct missing words in the following sentences:

   a. Orbit number 1 is closest to the nucleus. Orbit 1 is small, so only ______ electrons, (or one electron p______) can exist in the first orbit.

   b. Orbit number 2 is larger than no. 1 and the number of electrons that can be in this orbit is ________. (i.e. __ pairs)

   c. Orbit number 3 can 'accommodate' ______electrons.

ANSWERS ON PAGE 130

The identification of atomic nuclei: how scientists decided to which element an atom belongs

The Proton

You may remember that, in 1920, scientists discovered the existence of positive charges in an atom. They called these particles, protons. The size of the positive charge on a proton is equal to the size of the negative charge on an electron. This means that, if a nucleus is made up of one proton and one electron, then that nucleus will be neutral. The mass of a proton was measured to be 1 840 times greater than that of an electron.

What decides the different kinds of elements?

Scientists realised that when atoms bond, the bonding must have something to do with the electrons, because they are on the **outside** part of the atom. They realised from their experimental work that an atom can lose or gain electrons, but still be an atom of the same element as before.

Thus it must be the number of **protons** in each atom that decides what kind of element a substance is. The smallest number of protons in a nucleus must be one.

The element with the smallest mass is hydrogen. Thus the hydrogen atom must have only one proton in its nucleus.

Neutrons, because they have no charge, do not decide to which element an atom belongs. Neutrons simply add to the mass of an atom. We call protons and neutrons, because they are both found in the nucleus of an atom, 'nucleons'.

Scientists now realised that there are two **properties** that help us to tell the difference between one atomic nucleus from another.

properties:
how something behaves

They are:

- the number of protons, which we call the 'proton number' (symbol 'Z') and:
- the number of particles that make up the nucleus, which we call the 'mass number' (symbol 'A').

The proton or atomic number of an element (Z)

The atoms of a specific element all have the same proton number. So if you know an atom's proton number, you will know to which element the atom belongs.

The size of the charge on one proton equals the size of the charge on an electron. Thus if the atom is neutral, then hydrogen atom will have equal numbers of protons and electrons.

A hydrogen atom has one proton in its nucleus. So each neutral hydrogen atom also has one electron that is moving around its nucleus. The atomic number (Z) of hydrogen is 1.

A helium atom has two protons in its nucleus. Thus the atomic number of helium (Z) is 2. A uranium atom has 92 protons. Thus a neutral uranium atom has 92 electrons and its atomic number is 92.The number of protons in the nucleus of an atom determines the size of the charge on the nucleus.

Because a proton has a much bigger mass than an electron, the mass of an atom is concentrated in its nucleus. The proton number tells us:

- the number of protons in an atom
- the charge on the atom
- the number of electrons in the atom
- the position of that element on the Periodic Table

The nucleon or mass number of an element

The symbol for the nucleon number is 'A'. The nucleon number of an element tells us the sum of the number of protons and neutrons in the nucleus of an atom of that element. Thus nucleon number = number of protons + number of neutrons.

Because the number or protons and neutrons determine the mass of an atom, we can also call the mass number the relative atomic mass number.

Some carbon atoms have 6 protons and 6 neutrons in their nucleus. Thus the proton number is 6 and the nucleon number is (6 + 6) = 12.The symbol for this kind of carbon atom is:

$$\boxed{{}^{12}_{6}\mathrm{C}}$$

ACTIVITY 4

1. Fill in the missing words:

   a. The number of neutrons in an atom = mass number – _____.

   b. A positively charged object and a negatively charged object are ____________ to each other by an electrostatic force. So, in the atom, the __________ charged electrons are attracted to the___________ charged protons in the nucleus.

2. The symbol for the element radium is

88
Ra
226

   a. What is the atomic number of radium?
   b. How many protons make up an atom of radium?
   c. What is the mass number of radium?
   d. What is the nucleon number of radium?
   e. How many neutrons are there in one atom of radium?
   f. How many electrons make up one atom of radium?
   g. Do we know exactly where an electron is in an atom?

ANSWERS ON PAGE 131

Ionisation energy

First and second ionisation energies

We can study the orbitals of an atom in a different way by examining the minimum energy required to remove an electron completely away from its nucleus.

An atom that has lost an electron is positively charged. We call any charged particle, an 'ion'. That is why we call this energy, 'ionisation energy'.

When an electron is far away from its nucleus, it is easy to remove an electron from its atom, so its ionisation energy is small.

Once the first electron has been removed, even more energy is needed to remove another electron from its atom as the atom is even more positively charged. We call this energy the 'second ionisation energy'.

If we then remove more electrons from the same atom, the ionisation energies become even bigger.

The values of the first, second and third (or more) ionisation energies of one particular atom tell us about the orbitals and main energy levels of that atom.

Study the following table of ionisation energies for the first three elements on the Periodic Table.

TABLE OF IONISATION ENERGIES

Atom number	Element	1st	2nd	3rd	4th
1	hydrogen	1 315 J			
2	helium	2 376 J	5 249 J		
3	lithium	520 J	7 296 J	11 812 J	
4	beryllium	901 J	1 757 J	14 844 J	21 001 J

analyse:
look for patterns

Analysis of the values on the table above:

(i) **Atom no. 1: hydrogen**
There is only one ionisation energy value for hydrogen. This must mean that a hydrogen atom has only one electron.

(ii) Atom no. 2: helium

- There are two values for helium. This means that a helium atom must have two electrons.
- The first value is small. This means it must be the energy needed to remove an electron in the outside orbital of the helium atom.
- The second value is only a bit bigger. This means it must be the value for removing an electron that is in the same energy level, but, because the first electron has been removed, the nucleus is attracting this electron more strongly than usual.
- All of this means that the electron structure for a helium atom is: $1s^2$.

(iii) Atom no. 3: lithium
There are three ionisation energy values for lithium.

- The first ionisation energy is small. This must represent the value for removing one electron in the outermost energy level of the atom.
- The second value is a bit bigger. It must be the value for removing an electron in an energy level that is closer to the nucleus.

- The third ionisation energy value is even bigger than the second. It represents the energy needed to remove one electron from the atom in the energy level that is closest to the nucleus.

All of this means that the electron structure for a lithium atom is: $1s^2\ 2s^1$.

ACTIVITY 5

1. Here is a table of the 1st and 2nd ionisation energies for lithium, sodium, beryllium and magnesium.

	1st ionisation energy(MJ per mole)	2nd ionisation energy(MJ per mole)
lithium: Li	0,5	7,3
beryllium:Be	0,9	1,8
sodium:Na	0,5	4,5
magnesium:Mg	0,7	1,5

a. Which two elements have the lowest first ionisation energy?
b. How many electrons is lithium likely to lose when it reacts with other substances? Justify your answer with data from the above table.
c. How many electrons does magnesium lose when it bonds with other substances?
d. Name another element (from the table) which loses the same number of electrons as magnesium does.
e. Which of magnesium and beryllium is likely to be the more reactive element? Justify your answer with data from the table.
f. Write down an equation to show the formation of the magnesium ion.

ANSWERS ON PAGE 131

COMMENT

By 1922 the electrons in Bohr's model of the atom were believed to move in three-dimensional 'shells'. These were not physical shells, but energy levels within atoms around which electrons seemed to cluster. Bohr proposed that the atom of each element in the row of the Periodic Table is built up from the previous element by the addition of another electron to the outer electron shell. Since only electrons outside the closed shells, called valence electrons, took part in chemical reactions, atoms with the same number of valence electrons shared similar chemical properties and occupied the same column in the Periodic Table.

CHECKLIST

Are you able to:

☐ explain why the electrons in an atom must be in 'fixed' energy levels
☐ describe the arrangement of the electrons in the atom
☐ give a definition of a 'quantum of energy'
☐ describe the relationship between ionisation energy and the reaction of an element.

LESSON 4

The Periodic Table and Electron Configuration in the Atom

About this lesson

In the 1600s Hennig Brandt discovered the element phosphorus by accident. He was actually searching for gold. He believed that because his urine was yellow it probably contained gold! He collected his urine in a bottle and heated it gently to evaporate the water. He was left with a white paste which glowed in the dark. In fact he had separated the element phosphorous (P) from the other elements in urine. Phosphorous was one of the first elements to be separated out and identified as an element.

By the late 1800s many elements had been separated out and identified. The Russian scientist Dimitry Mendeleyev attempted to organise these elements into some sort of system. He used their atomic weights and chemical properties to organise the elements into a chart. He found that there were patterns that repeated themselves in his chart of the elements. He called these repeating patterns periods. His early work led to the formation of the chart of the elements we call the Periodic Table.

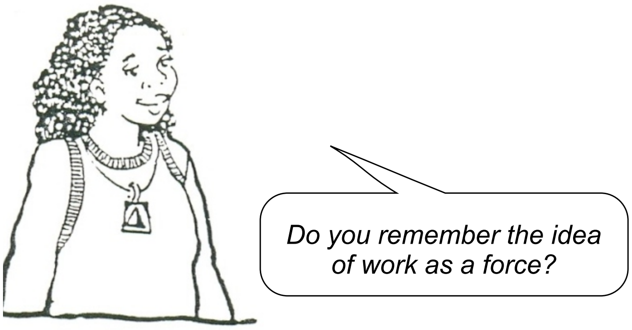
But Mendeleyev did not know what it was that caused the atoms to be grouped in that way. In this lesson you will be learning more about the structure of the atom. You will then be able to explain why Mendeleyev's system worked.

In this lesson you will:

- explain the idea of energy levels in atoms
- work out electron configurations for atoms of different elements
- identify the characteristics of groups and periods and how they relate to valency.

Energy levels in an atom

You have learnt about different models to describe the structure of the atom. All the models are useful for different purposes. For example, Dalton's model of the atom as a solid sphere is still useful for describing the behaviour of gases. Another model you learnt about was Bohr's model. There are more complicated models available these days, but Bohr's model is good enough for our purposes.



In Bohr's model, electrons with the same energy move in a certain path around the nucleus. These paths are called 'orbits' or energy levels. We will call them energy levels. Remember that according to Coulomb's law, oppositely charged particles which are closer together are attracted more strongly than those which are further apart. So we would have to do more work to separate the charges which are close together. This means that the particles which are closer together are at a lower energy than those which are further apart.

In the case of the atom, the positively charged particles form the nucleus and the negatively charged particles are the electrons. So electrons further away from the nucleus are at a higher energy than those close to the nucleus. Each energy level has a number. The one closest to the nucleus is called n=1 and the next one is called n=2, and so on.

One way of testing this idea of energy levels is to look at the minimum energy needed to remove an electron from an atom. This is called ionisation energy. When an electron is easy to remove from an atom, the ionisation energy is low. When it is difficult to remove, the ionisation energy is high.

Why is it called ionisation energy?

ion:
a charged atom

Remember that atoms are electrically neutral, which means they have the same number of protons as electrons. When an electron is removed there is one extra proton, so the atom has a positive charge. A charged atom is called an **ion**.

For example, sodium (Na) has 11 protons and 11 electrons. If one electron is removed, the Na atom becomes an ion with 11 protons and 10 electrons. It is now written as Na^+.

ACTIVITY 1

Calcium (Ca) has 20 protons and 20 electrons. What ion would be formed if 2 electrons are removed?

ANSWERS ON PAGE 131

COMMENT

After the two electrons are removed the calcium ion will have more positive protons than negative electrons.

The first electron to be removed is one which is furthest from the nucleus. The energy needed to remove this electron is called the first ionisation energy. After the first electron has been removed, even more energy is needed to remove a second electron from the same atom. This energy is called the second ionisation energy. The removal of more electrons from the same atom results in third, fourth and fifth ionisation energies.

Table 1 on the next page shows the ionisation energies for the atoms of the first 20 elements. The unit of measurement is kilojoules per mole or kJ mol-1.. However, you should not worry about the units at this stage. We are only going to compare the values and see where there are big jumps from one value to the next.

Notice the following about Table 1:

- The atomic numbers are listed 1-20 in the left hand column
- The elements are identified by their symbols, starting with hydrogen (H)
- The 1e column refers to the first electron to be removed from the atom. The numbers in this column are the first ionisation energies for each atom – the minimum energy required to remove the first electron from the atom. Remember that this will be the electron furthest from the nucleus.
- The other columns refer to the second to ninth electrons to be removed from the atom. The numbers in the column are the second to ninth ionisation energies.

	Element	Ionisation Energy/ kJ mol^{-1}								
		1e	2e	3e	4e	5e	6e	7e	8e	9e
1	H	1316								
2	He	2376	5249							
3	Li	520	7296	11812						
4	Be	901	1757	14844	21001					
5	B	800	2427	3659	25019	32818				
6	C	1089	2352	4619	6221	37821	47263			
7	N	1404	2855	4576	7473	9442	53253	64340		
8	O	1316	3387	5296	7467	10987	13323	71314	84051	
9	F	1684	3375	6044	8408	11020	15160	17863	92009	106000
10	Ne	2078	3963	6127	9361	12186	15236			
11	Na	494	4563	6920	9541	13351	16604			
12	Mg	737	1450	7732	10545	13627	17994			
13	Al	578	1816	2744	11574	14837	18373			
14	Ai	788	1577	3231	4354	16087	19790			
15	P	1064	1903	2910	4955	6272	21267			
16	S	1001	2258	3377	4563	6995	8494			
17	Cl	1257	2296	3850	5162	6542	9330			
18	Ar	1521	2665	3946	5769	7236	8809			
19	K	415	3069	4438	5876	7970	9620			
20	Ca	591	1145	4941	6465	8142	11057			

Table 1: Ionisation energies of the first twenty elements in kJ mol^{-1}

Now look at the numbers on Table 1. Remember that a low number indicates a small ionisation energy and a high number indicates a high ionisation energy.

Notice the following:

- hydrogen has only one electron so it only has a first ionisation energy. This is higher than most of the other first ionisation values on Table 1, which means that hydrogen's electron is not easy to remove.
- helium (He) has two electrons. They are both difficult to remove but the second one is even more difficult to remove than the first.
- lithium (Li) has three electrons. The outermost one is relatively easy to remove - notice that the first ionisation energy is only 520 compared to 7296 for the second ionisation value and 11812 for the third ionisation value.

The big jump from 520 to 7296 shows us a jump in main energy level, i.e. the first electron comes from the outermost energy level and the next two come from an inner one. See Figure 2.

Change in main energy level

↓

Li	520	7296	11812

Figure 2. Big jumps in energy indicate a change in main energy level

Remember that when we are talking about energy levels we are referring to Bohr's atomic model. He suggested that the electrons moved in fixed paths or shells around the nucleus. He called these shells energy levels. The outer shell contains the electrons that are furthest away from the nucleus. So, the electrons in the next energy level are closer to the nucleus than those in the outer energy level. It therefore requires more energy to remove the electrons from the next energy level. This is because they are closer to the nucleus and the force of attraction between the electrons and the protons in the nucleus is stronger than the force of attraction between the protons and the electrons in the outer energy level. So, when there is a big jump between the numbers in the ionisation energy it means that the electron has been removed from the next energy level.

Can you see the change in main energy level for beryllium (Be)?

Look for a big jump between figures. The change in energy level comes between the second and third ionisation energy values which jump from 1757 to 14844. Look at Table 1 again. A big jump usually means multiplying the number by a factor greater than 5.

ACTIVITY 2

Look at Table 1. How many electrons are there in the outer energy levels of:

1. sodium (Na) and potassium (K)?

2. nitrogen (N) and phosphorous (P)?

ANSWERS ON PAGE 132

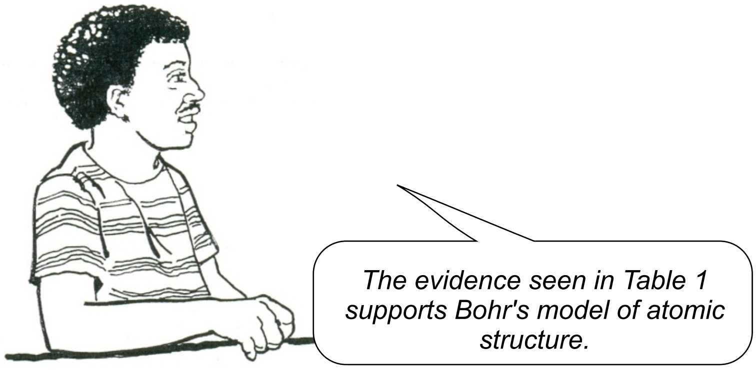
COMMENT

Atoms with the same number of electrons in the outer energy level are grouped together.

How to work out electron configurations for atoms of different elements

The values of the ionisation energies in Table 1 give us evidence that the electrons in atoms are in energy levels. There are big jumps in amount of energy required to remove electrons from energy between the energy levels. You can see this because there is always a big change in ionisation energy just before the last two electrons. You can only be sure of this when all the electrons are shown.

For example, for oxygen there is a big jump from the 6th ionisation energy to the 7th. So the last two electrons are in an energy level by themselves. You will also see that for fluorine, the last two electrons are much harder to remove than the rest.



We can draw diagrams to represent the electron structure of these atoms, as shown in Figure 3. The large, central circle represents the nucleus. The circular lines represent different energy levels. The black dots represent electrons circling the nucleus.

Figure 3. Diagrams of the electronic structures of H and He

Lithium has two electrons in the first energy level, but the third electron has to go into the next energy level, because the first level only takes two electrons. So we could draw a diagram for lithium's atom as shown in Figure 4.

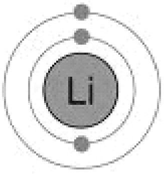


Figure 4: Diagram of the electronic structure of lithium (Li)

We call the arrangement of electrons the electron configuration. Lithium has an electron configuration of 2,1. This means that the first energy level has two electrons and the second energy level has one electron.

The second energy level accommodates 8 electrons. The maximum number of electrons that a level can accommodate has been found to be $2n^2$ where n is the number of the energy level. So in the second energy level, n = 2, the number of possible electrons is

$$2 \times 2^2 = 8.$$

In Activity 2 you found that nitrogen has five electrons in its outermost energy level. Nitrogen has seven electrons altogether, so the first two electrons are in the first energy level. So we say that the electron configuration for nitrogen is 2,5.

ACTIVITY 3

Draw diagrams showing electron configurations for atoms of nitrogen (N), oxygen (O) and fluorine (F). Find out how many electrons they have by looking at Table 1, or the Periodic Table.

ANSWERS ON PAGE 132

COMMENT

Table 1 and the Periodic Table are important sources of information for scientists. They summarise a lot of information about the elements.

Neon, the element after fluorine, has a full eight electrons in the second energy level. Sodium has only one electron in the outer level, which is now the third energy level. (See Figure 5.)

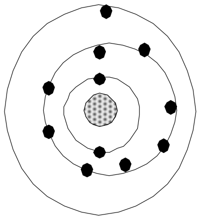
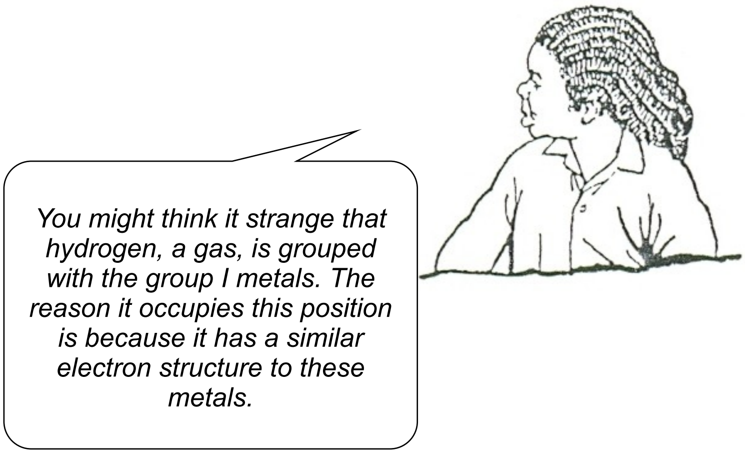


Figure 5. Diagram of the electronic structure of sodium (Na)

The electrons in the outer energy levels are of great interest to chemists because they give them an idea of the way in which the substance will react. We call these outer electrons **valence electrons**. So sodium has one valence electron and fluorine has seven. The number of valence electrons has a close relationship to the Periodic Table.

The structure of the Periodic Table

Look at Figure 6 which shows a part of the Periodic Table of the elements. Notice the metals on the left and the non-metals on the right of the table. Notice, too, the transition elements in the middle which contain many metals, for example iron (Fe) and zinc (Zn).The elements in the Periodic Table are identified by their symbols. The atomic number for each element is written at the top of the box. Remember that the atomic number tells us the number of protons in an atom of that element. Since the atom has the same number of electrons as protons, the atomic number also shows us how many electrons the atom has. So the atomic number is a very important fact to know about an element.



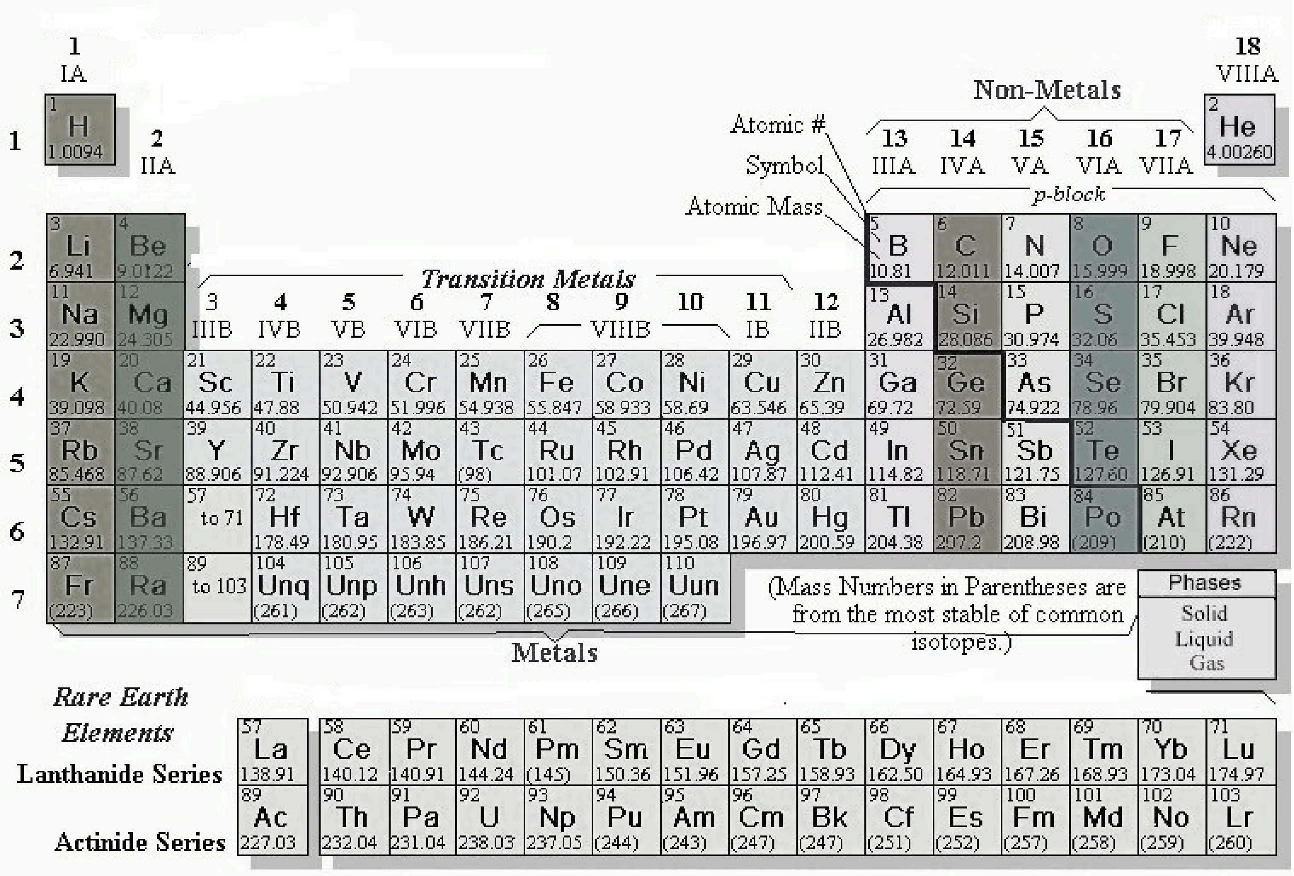


Figure 6. The Periodic Table

Periods

The arrangement of electrons is very closely linked to the horizontal rows or periods on the Periodic Table.

Look at period 1. Hydrogen (H) and helium (He) belong to period 1. The atoms of these elements have enough electrons to occupy the first main energy level of the atom, the n = 1 level (you saw the electronic structure in Figure 3).

Now look at period 2. All the elements in period 2 have atoms with electrons in the first two energy levels. On the left hand side of period 2 there is lithium (Li). Its atoms have one electron in the second energy level. By the time we get to neon (Ne) at the end of the row, the second main energy level is full.

Now look at period 3. All the elements in period 3 have atoms with their first two main energy levels full of electrons. The remaining electrons are in the third energy level. By the time we get to argon (Ar) at the end of the period, the third energy level is temporarily full.

ACTIVITY 4

1. Find sulphur (S) on the Periodic Table. How many electrons does it have?

2. Draw a diagram to show the arrangement of the electrons in an atom of sulphur (S). Also give its electron configuration.

3. Find period 4 on the Periodic Table and give the symbols of the first two elements.

4. What are the atomic numbers for those elements?

5. In period 4, how many energy levels contain electrons for each atom?

ANSWERS ON PAGE 132

Groups

So far you have seen that the electron structure of the atoms of the elements on the Periodic Table follows a horizontal pattern. This horizontal pattern is that of the periods. The electron structure also follows a vertical pattern.

We often use Roman numbers for groups. I, II, III, IV, V,VI, VII and VIII are Roman numbers for 1, 2 ,3, 4, 5, 6, 7, and 8.

Look at the Periodic Table in Figure 6 again. The vertical columns are called groups. There are 18 groups, but we will be interested in 8 main ones. Look at group I. As you can see in Figure 6, the first four group I elements are hydrogen (H), lithium (Li), sodium (Na) and potassium (K). From the activities you have done so far, you can see that the atoms of each of these elements have one electron in the highest occupied energy level. In other words, they have one valence electron. The elements in this group are known as the **alkali metals**.

Now look at group II elements. Notice that the atoms of the elements of group II each have two electrons in the highest occupied energy level, or two valence electrons. The elements in this group are known as the **alkaline earth elements**.

Valence electrons are very important in chemistry. It is these electrons which are available to form bonds, which happens in chemical reactions. So the valence electrons are the key to understanding the chemical properties of the elements.

Two other groups are so well known that they have been given names. Group VII elements are known as the halogens, while group VIII are so un-reactive that they are called the inert, or noble gases.

The inert gases have eight valence electrons (except for helium which has two).

Before you do the activity, label the alkaline, alkaline earth, halogens and the noble groups on the Periodic Table in Figure 6.

ACTIVITY 5

Study groups III, IV, V, VI and VII on the Periodic Table in Figure 6. Then answer the following questions:

1. Name two elements that belong to group III? How many valence electrons does each of the elements have?
2. How many electrons does an atom of oxygen (O) need to fill its highest occupied energy level?
3. To which group do the elements with atoms having seven valence electrons belong? Give the symbols for three of these elements.

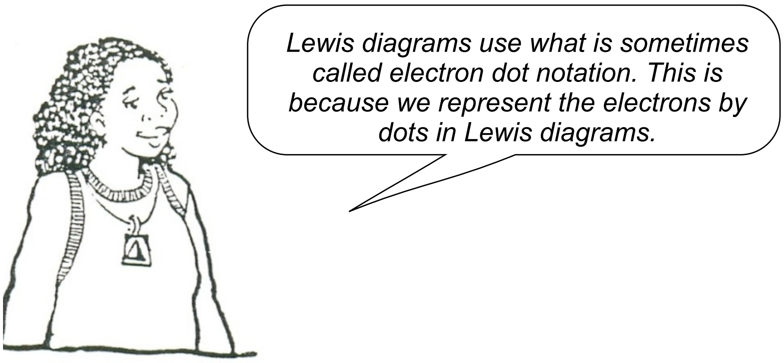
ANSWERS ON PAGE 133

COMMENT

The Periodic Table shows how the elements have been grouped together.

From the activity you should see that the number of valence electrons is the same as the group number. Group one has one valence electron, group three has three valence electrons and so on.

We can represent the valence electrons of atoms using **Lewis diagrams**. How do you draw Lewis diagrams? Look at the next section.



Lewis Diagrams

In Lewis diagrams we draw the valence electrons as dots. For example, we can represent the hydrogen atom with its one electron in a Lewis diagram in Figure 7.

H·

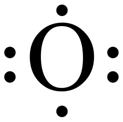
Figure 7. The Lewis diagram for hydrogen

The Lewis diagram of any element in group I would look the same as that for hydrogen. For example, the Lewis diagram for sodium is shown in Figure 8.

Na·

Figure 8. Lewis diagram for sodium. The Lewis diagram for all group one elements is the same

Lewis diagrams usually show electrons in pairs. For example, the Lewis diagram for an oxygen atom (group VI) would show the six valence electrons as shown in Figure 9.



$$:\overset{\cdot}{\underset{\cdot}{O}}:$$

Figure 9. The Lewis diagram for oxygen. Oxygen is in group VI and has 6 valence electrons.

If there is more than one electron, but less than eight, the rule is that you put the first 4 dots singly and then you start to pair off the electrons.

It does not matter where you put the pairs, as long as there are two pairs and two single electrons shown.

You can also represent ions with Lewis diagrams. For example, the ion Ca^2+ has no valence electrons, because both electrons have been lost. The ion F+ would have six valence electrons because Fluorine has seven when it is neutral. So the F+ ion would have its electrons arranged like the atom of oxygen shown in Figure 9.

ACTIVITY 6

Draw Lewis diagrams for the atoms of the following elements: Al, Cl, Ca, C^+.

ANSWERS ON PAGE 133

COMMENT

The Lewis diagrams are only representations or models to help us understand atomic structure better.

Another term you need to know is valency.

Valency

Valency is a number which shows the capacity of an atom to bond with other atoms to form molecules and compounds. You have just learnt that the number of valence electrons in an atom is the same as the group number. The valency of elements in groups I to IV is also the same as the group number; group I elements have a valency of 1, group II elements have a valency of 2, and so on.

When we get to group V, the atoms of these elements sometimes have a valency of 5, but more often, atoms of these elements have a valency of 3. This valency is 8 minus the group number. Experiments show that the valency of atoms of elements in groups VI, VII and VIII work out in a similar way.

Using this information, what do you think the valency of groups VI and VII usually are?

Group VI atoms have a valency of 2 (8 minus 6). Group VII atoms usually have a valency of 1 (8 minus 7).
The group VII atoms usually have a valency of 0 (8 minus 8). As you have already learnt, group VIII elements are inert gases which generally do not react with other elements. In other words, their atoms have zero capacity to form bonds.

ACTIVITY 7

What is the valency of an atom of C, F, P?

ANSWERS ON PAGE 133

COMMENT

You can determine what the valency of an element is by the group that it is in.

In the introduction to this lesson you read about Mendeleyev and how he used the properties of elements to predict their positions on the Periodic Table. Mendeleyev did not know anything about electrons as they were discovered long after his death. But you have seen now how the electronic configuration of atoms is related to the position of their elements on the Periodic Table.

ACTIVITY 8

1. Answer the following questions for atoms of the elements Al, S, K.
    a. Write the electron configuration.
    b. Draw a Lewis diagram.
    c. How many valence electrons does it have?
    d. What is its valency?

ANSWERS ON PAGE 133

CHECKLIST

Are you able to:

☐ explain the idea of energy levels in atoms
☐ work out electron configurations for atoms of different elements
☐ identify the characteristics of groups and periods and how they relate to valency.

LESSON 5

Stable and unstable atoms

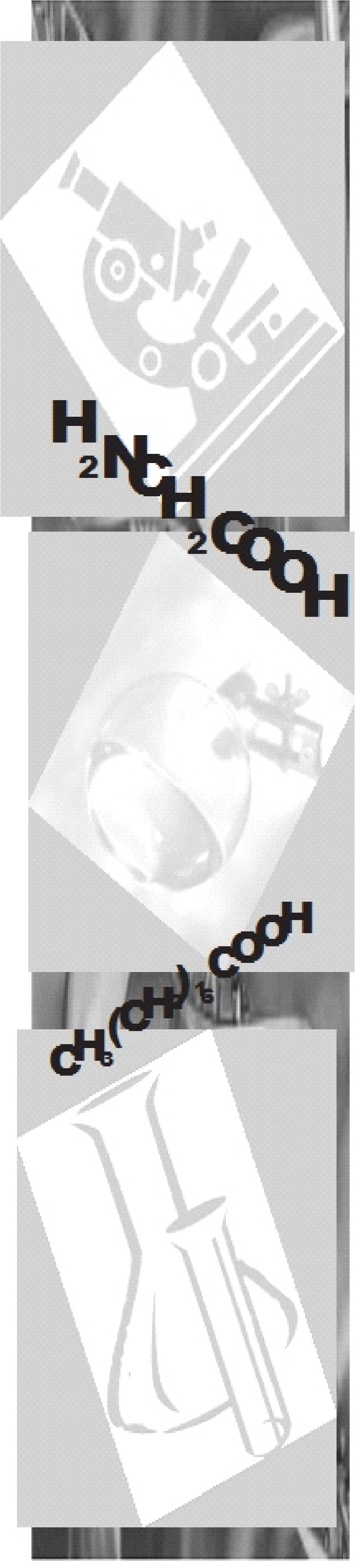
About this lesson

Some atoms are naturally radioactive. The nucleus of a radioactive atom is unstable and can suddenly break up, throwing out high speed particles and radiations that **ionize** the substances through which they pass. There are 3 types of rays that can be emitted from a radioactive source. These rays can be separated by passing them through a magnetic field.

You will also look at the process of what happens to the nucleus during nuclear fission and the benefits and dangers of nuclear power.

In this lesson you will:

- learn about stable and unstable atoms
- describe some of the uses of radioactive isotopes
- learn about half-life and different types of radiation
- balance nuclear reactions
- compare the advantages and disadvantages of radioactivity
- describe the process of nuclear fission
- describe and give an opinion on the dangers of nuclear power.



Forces inside the nucleus

You looked at models of the atom so you already know that the nucleus contains **positively charged** particles called **protons** and that all atoms of the same element have the same number of protons called the **atomic number**. You also know that it contains **neutrons** which have no charge and have about the same mass as protons.

Atomic number and atomic mass

If you look at any element on the periodic table, you will see that each element is represented by a symbol and there are two numbers associated with each element. These numbers are the **atomic number** (top) and the **atomic mass** number (bottom).

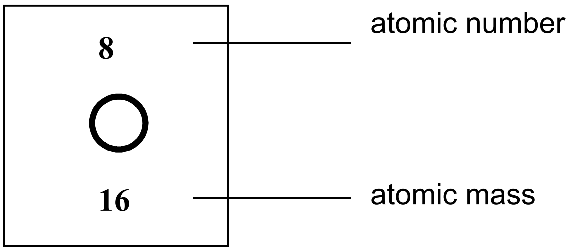
The **atomic number** equals the number of **protons** in the nucleus.

The **atomic mass** tells us the number of **protons** and **neutrons** in the nucleus. You will notice that atomic masses are not whole numbers. Don't worry about this. We normally round off the atomic mass to the nearest whole number. Let's consider oxygen for example. The round number for 15.999 is 16. The number 16 is the atomic mass – the number of protons and neutrons. The number 8 is the atomic number – the number of protons in the oxygen atom nucleus.

ionize:
the process of converting an atom or molecule into an ion by adding or removing electrons or ions

atomic number:
the number that represents the number of protons in the nucleus of an atom.

atomic mass:
the number that represents the number of protons and neutrons in the nucleus of an atom.



Oxygen on the periodic table

Protons and neutrons

Ever since the discovery of protons and neutrons, scientists have conducted experiments to see if there are any more subatomic particles. They have found over 100 subatomic particles! But these are so tiny that it is really only protons and neutrons which make up the bulk of the mass of the atom.

The number of protons plus the number of neutrons of an atom is called the mass number. So, for example, the mass number for an atom of calcium is 40 because a typical atom of calcium has 20 protons and 20 neutrons.

Strong forces within the nucleus

You already know that positively charged particles repel one another.

All the forces which occur in nature can be thought of as different types of interactions between bodies. These interactions are grouped in four categories. These categories are known as the fundamental forces of nature. They are the gravitational force, the electromagnetic force, the weak nuclear force and the strong nuclear force.

So what would you expect the protons in the nucleus to do?

You would expect the protons to repel each other and blow the nucleus apart.

But this does not happen! Scientists have come to the conclusion that there is another force which operates within the nuclei of all atoms. This force is one of the four fundamental forces in the universe. It is called the 'strong force' and it holds the protons in the nucleus together. It is a property of all protons and neutrons. Although it is stronger than the electrical forces of repulsion, it only operates over very short distances.

Weak forces within the nucleus

The protons and neutrons consist of smaller subatomic particles. When they are hit with fast moving particles, they break up into these smaller particles. There must be a force which holds these smaller particles within the protons and neutrons together which breaks down when the proton or neutron is hit. This force is called a **weak nuclear force**.

The neutrons play a very important role in the nucleus. Their presence adds to the total amount of the strong nuclear force. When an atom has the optimum (or most appropriate) number of neutrons we say that it is **stable**. If a nucleus contains too few or too many neutrons it will be **unstable** and may be radioactive. However, some atomic nuclei are just too big (and 'wobbly') to be stable, no matter how many neutrons they contain. This happens with elements with atomic numbers greater than Bi (bismuth). These atoms are all unstable and radioactive. This brings us to the next part of the lesson.

Stable atoms

An atom changes when it loses or gains an electron. Another atom must pull off this electron (or electrons). To pull an electron off an atom requires another atom to lose energy. We call this energy, 'ionisation' energy. How easily an atom can lose or gain an electron depends on that atom's nuclear control of its valence electrons.

The atoms of Groups I, II and VII on the Periodic Table have a weak control of their valence electrons and so are unstable. The atoms of Group VIII have energy levels that are full and are therefore the most stable. These stable atoms are known as the inert or noble gases.

Atoms that have a big nuclear control of their valence electrons, are quite stable; while those that have a weak control of their valence electrons are unstable.

isotopes:
different atoms of the same element

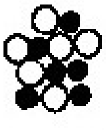
Isotopes are different atoms of the same element. Their nuclei contain the same number of protons but different numbers of neutrons. For example, some atoms of the element chlorine have 17 protons and 18 neutrons. Other chlorine atoms have 17 protons and 20 neutrons. These atoms are isotopes of chlorine. Their chemical reactions are the same but they differ in mass.

What can you say about the atomic number and the mass number of isotopes?

Isotopes of an element all have the same atomic number because they contain the same number of protons. But isotopes of an element have different mass numbers because they contain different numbers of neutrons. Scientists have a way of showing these facts about isotopes. For example, one isotope of chlorine is $^{35}_{17}$ Cl (sometimes shortened to chlorine –35). These chlorine atoms have an atomic number of 17 and a mass number of 35. Another isotope of chlorine is $^{35}_{17}$ Cl or chlorine –37. This isotope still has an atomic number of 17, but has a mass number of 37 because of extra neutrons. Both of these isotopes of chlorine are stable.

ACTIVITY 1

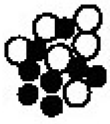
1. The diagrams below represent the nuclei of two isotopes of carbon. (Remember that these diagrams are only models and that they are magnified thousands of times). Write the symbols and numbers for these two isotopes.



Nucleus of an isotope of carbon

● *neutron*

○ *proton*



Nucleus of an isotope of carbon

2. Look at the table which gives information about atoms numbered (a) to (l). Use the table to answer these questions.

    a. Which atoms are isotopes of the same element? (There are isotopes of 4 different elements in the Table).
    b. Name the elements you found in a. (Refer to the Periodic Table).
    c. How does the Table show you that some of these atoms are isotopes?

	Protons	**Neutrons**	**Mass number**
atom (a)	6	6	12
atom (b)	9	10	19
atom (c)	1	1	2
atom (d)	17	18	35
atom (e)	92	146	238
atom (f)	7	7	14
atom (g)	1	0	1
atom (h)	17	20	37
atom (i)	6	7	13
atom (j)	92	143	235
atom (k)	5	6	11
atom (l)	1	2	3

Table of information about different atoms

ANSWERS ON PAGE 134

Remember that an atom with the optimum number of neutrons in its nucleus was more stable than an atom without the optimum number of neutrons in its nucleus. Look at one of the examples from the Table you have just used – uranium. Both these isotopes of uranium, ($^{235}_{92}$ U and $^{238}_{92}$ U) have very large nuclei so they are unstable. There are actually six isotopes of uranium and all are unstable and radioactive.

Radioactive atoms can become more stable by losing some of the energy in their nuclei. The release of energy from the nucleus is called radiation. Isotopes whose atoms emit radiation are called radioisotopes, e.g. $^{238}_{92}$U or uranium –238.

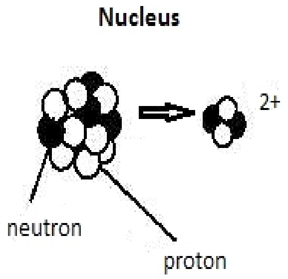
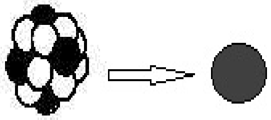
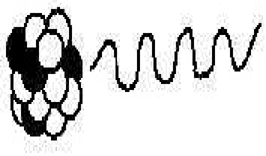
Let's take a closer look at how atoms lose energy by radiation.

What is radioactive decay?

When an atom emits radiation we say that it is undergoing radioactive decay. The decay process continues until the atom becomes stable.

For example, an atom of uranium –238 changes into atoms of different elements at each stage of decay and eventually becomes lead –206 ($^{206}_{82}$ Pb), which is stable, and radioactive decay stops.

There are different types of radiation which leave the nucleus during the decay process. Study the Table below which describes the three main types of radiation and the power of penetration of each.

Types of Radiation		
	**Alpha (α) particles** consist of 2 protons and 2 neutrons and so are positively charged. This is equivalent to a helium nucleus so α particles are sometimes referred to as helium nuclei. When an α particle is emitted from a radioactive atom the mass of the nucleus changes and it becomes a different element.	**Penetration and damage** α particles cannot penetrate paper or skin, but they are very dangerous when emitted inside the body.
	**Beta (β) particles** are emitted when a neutron becomes a proton. β particles are equivalent in mass and charge to an electron, and so are negatively charged.	β particles can penetrate paper or several millimetres of skin. They can be very dangerous when emitted inside the body.
	**Gamma (γ) rays** are short intense bursts of energy emitted as electromagnetic rays. γ rays have no electrical charge or mass.	γ rays can even penetrate thin layers of concrete and lead. They can easily pass through the human body damaging tissue in the process.

Use the information in the table to help you answer these questions.

ACTIVITY 2

emit:
give off

1. Explain why the emission of an alpha particle causes the atom to change into an atom of a different element.

2. How do you think it is possible for α particles and β particles to be emitted inside the body?

3. Read this story and then answer the question.

> *A few years ago, in a village in Brazil, four people died and 249 people suffered some degree of radiation sickness - all because children picked up a block of blue powder which they found on a rubbish dump.*
>
> *The children were fascinated by the way the powder glowed and they passed it from hand to hand. One little girl rubbed it over her face and then ate a sandwich - she later died. A young boy put a piece in his pocket - soon he could hardly walk. The blue powder was the radioactive isotope cesium 137 which was inside a piece of hospital equipment which had been dumped.*

The children handled a piece of cesium 137. This is a radioisotope undergoing decay. Which two types of radiation do you think caused their injuries and deaths?

ANSWERS ON PAGE 134

Nuclear Equations

α - decay

We can represent nuclear reactions by equations in much the same way as we represent chemical reactions. We will look at alpha and beta radiation.

In alpha radiation, the atom decays by losing an alpha particle. You have already learnt that an alpha particle is a helium nucleus. So it is a helium atom that has lost both its electrons. An alpha particle therefore has a charge of 2+. Let us see what happens to an atom of uranium 238 when it gives out an alpha particle.

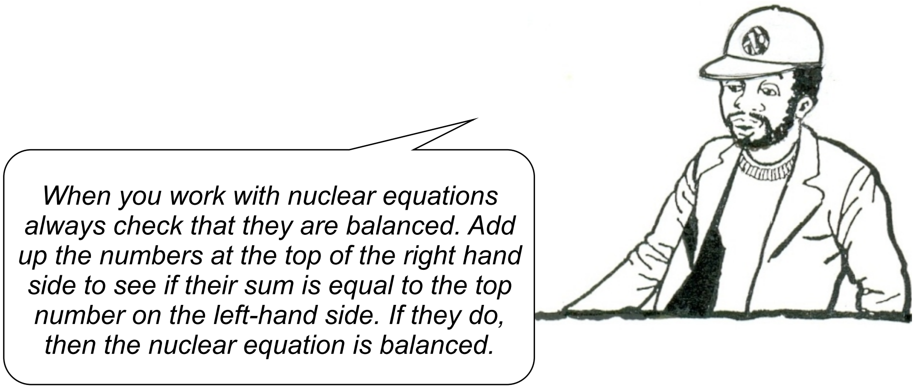
Helium has 2 protons and 2 neutrons, so we write an alpha particle as ${}_{2}^{4}He^{2+}$. If the alpha particle leaves the uranium atom, the atomic mass must go down by 4 and the atomic number must go down by 2.

What element will the resulting atom be?

Well, the atomic mass of the new element must be 4 less than that of uranium 238, but it is the atomic number that will tell us what element it is because that will give us the number of protons. The new element will have atomic number 90, since uranium has atomic number 92. If you look at the periodic table, you will find that thorium (Th) has atomic number 90. So the new element formed (called the **daughter element**) is thorium. We write the equation like this:

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

We do not show the charge on the helium ion because we are concentrating on what is happening in the nucleus.



When you work with nuclear equations always check that they are balanced. Add up the numbers at the top of the right hand side to see if their sum is equal to the top number on the left-hand side. If they do, then the nuclear equation is balanced.

So uranium atoms decay to form thorium atoms.

β - decay

β particles are simply electrons. However β particles come from the nucleus. They are not the electrons on the outside of the nucleus. As you saw in the table on page 58, the β particles are formed by the decay of a neutron to form a β particle (an electron) and a proton. We can show this by an equation as follows:

$$^{1}_{0}n \rightarrow {}^{1}_{1}p + {}^{0}_{-1}e$$

Notice the electron is given an ‘atomic number’ of –1. This means that this equation is also balanced, just like the one for alpha decay above.

So the β particle is emitted, leaving an extra proton in the nucleus. This means that during β decay, the atomic number of the atom increases by 1 and the atomic mass remains the same.

So the daughter element is one to the right of the original element on the periodic table. For example in the equation below, bismuth (83) is decaying to form polonium. Beta radiation usually occurs together with γ radiation. γ rays are photons of radiation, very much like visible light, but much more penetrating. They are included in the equation, but have no effect on the masses in the equation as they have no mass themselves.

$$^{212}_{83}Bi \rightarrow ^{212}_{84}Po + ^{0}_{-1}e + \gamma$$

Again you can check if the equation is balanced by adding up the numbers at the top on the left hand side and adding up the numbers on the right hand side of the equation. You will see that both come to 212. Also check the numbers at the bottom on both sides and see that they come to 83.

ACTIVITY 3

1. What is meant by the term radioactive isotope?

2. Complete and balance the following nuclear equation. Check to see if it is balanced.

$$^{232}_{90}Th \rightarrow \text{..........} + ^{4}_{2}He$$

3. Radon 222 undergoes alpha decay to give a new daughter particle. Write down the equation.

4. Balance this nuclear equation.

$$^{32}_{15}P \rightarrow \text{...........} + ^{0}_{-1}e + \gamma$$

ANSWERS ON PAGE 134

COMMENT

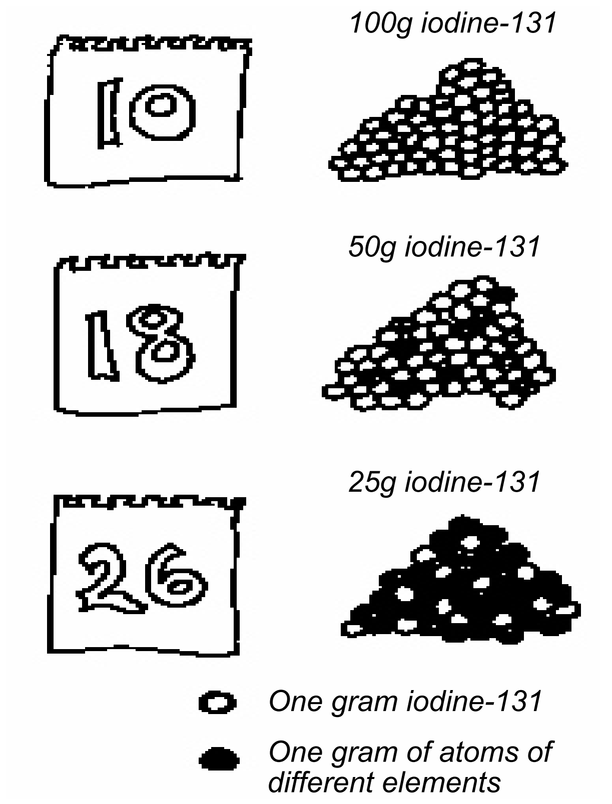
To complete these equations you first have to see if you need to work out what the daughter element will be or if you have to work out what the mother element was.

Half-life

half-life:
the period of time in which the activity of a radioactive substance falls to half its original value

You may be be wondering how long radioactive decay takes. Scientists have found that every isotope takes a different length of time to decay. They measure this length of time in terms of 'half-life'.

This is the length of time it takes for half the atoms of a radioisotope to decay into atoms of different elements. Here are some diagrams to help you understand this statement.



Look at the first diagram. This is a diagram of 100g of the radioisotope iodine-131. Let's suppose we are looking at this 100g ofiodine-131 on 10 May. Eight days later, on 18 May, we look again at our sample of iodine-131. Now there are only 50g of iodine-131 in the sample. The rest of the sample of iodine-131 has decayed into atoms of different elements.

If we study the sample 8 days later, on 26 May, we find that there are now only 25g of iodine-131 in the sample. In the 8 days between May 18 and May 26, half of the 50g of iodine-131 decayed into has decayed into atoms of different elements.

So the half-life of iodine -131 is 8 days.

The half-lives of some radioisotopes are so short that they cannot be measured accurately. Others are so long that decay during our lifetime is hardly noticeable.

Look at the examples of radioisotopes and their half-lives in the table on the next page. Use the information in the table and what you have learnt about radioisotopes and half-life to answer the questions in the activity.

Radioisotope	Half-life
Polonium -212 0,	16 seconds
Sodium -24	15 hours
Iodine -131	8 days
Phosphorus -32	14,3 days
Cobalt -60	5,3 years
Hydrogen -3	12,3 years
Carbon -14	5 760 years
Uranium -235	7 100 000 000 years (7 billion one hundredmillion years)
Thorium -23214 000 000 000	14 000 000 000 years (14 billion years)

Table of the half-life of different radioisotopes

ACTIVITY 4

1. Which is less stable, iodine-131 or phosphorous-32? Explain your answer.

2. Suppose you have a block of pure sodium-24 at 08h00 (8am).
   a. At what time will you have a block containing only 50g of pure sodium-24?
   b. What has happened to the rest of the block?

3. How much cobalt-60 will be left from a 1000mg sample after 15,9 years?

4. Which radioisotope do you think would give off the more intense radiation (i.e. which one would be most dangerous to be near), sodium-24 or cobalt-60?

ANSWERS ON PAGE 135

How can radioactivity be useful?

Tracers

Radioisotopes are useful for investigating the inside of someone's body without having to cut open the person. For example, a doctor can use a radioactive tracer such as iodine-131 to test the thyroid gland in the neck. This can be necessary when a patient's thyroid gland is overactive (causing too high a concentration of thyroid hormones in the blood) or underactive (causing too low a concentration of thyroid hormones in the blood).

Our thyroid gland takes in iodine from the food we eat, so it will absorb any iodine entering the body.

The doctor gives the patient a drink containing iodine-131. After a few hours the iodine-131 has been collected by the thyroid gland. The radiation coming from the thyroid gland is detected by an instrument called a scanner. The scanner produces a scan or picture of the thyroid gland on a TV screen.

The tracer detects an overactive or underactive thyroid by the length of time the thyroid takes to absorb the tracer.

However radioactivity does not only have uses in medicine and science. Historians and archaeologists also have a use for it, as you will see in our next example.

Dating

Organisms, such as plants and bones, contain carbon. A certain amount of this carbon is the radioisotope carbon -14. The proportion of carbon -14 to carbon -12 in a living plant is the same as in the CO^2 in the atmosphere which plants photosynthesise into carbohydrates.

When the organism dies, the carbon -14 continues to decay inside the dead wood or bones, causing the amount of carbon-14 to become less and less.

Historians and archaeologists can date objects they find, such as bones and wood, by measuring how much carbon-14 is left in them. This is called carbon-14 dating and can be used to date objects up to 40 000 years old.

Archaeologists have proved that there were Khoi living in the Western Cape 2000 years ago by dating bones using carbon -14.

Using Isotopes in Industry

In industry, radioactive isotopes are most useful for detection in places where we cannot look because a unit or area is sealed.

In a car you can't see what is happening to the piston rings when the engine is working. So manufacturers use radioactive piston rings in a car. When the rings wear, bits of the material from the rings gets into the oil and technicians can measure the radioactivity in the oil. This will tell them how much the rings have worn in the engine.

Radiation can pass through materials such as plastic, but some is absorbed. More is absorbed when the material is thick, so radioactive rays can be used to tell how thick the layer is.

The same property can be used to trace cracks in metals.

You can use liquid radioactive material to look for leaks in underground pipes by sending the liquid radioactive material through the pipe and then using a detector to find the leak.

Coastal authorities dump radioactive waste in the sea beds by the mouths of rivers so that they can monitor the movement of sand under water. If they know what is happening to the sand, they can stop the river mouth from blocking up. For this work they use radioactive isotopes with a short half-life.

Use in Agriculture

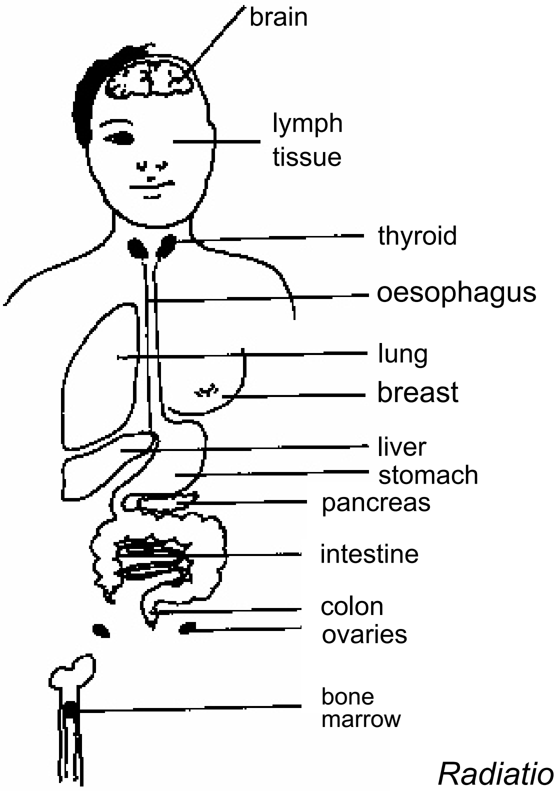
We can check exactly how plants absorb fertiliser by mixing radioactive tracers with the fertiliser and then detecting them in the plant at a later stage.

We can delay sprouting of potatoes and onions with rays.

These are a few examples of the many good uses of radioactivity.

Another side to radioactivity

Humans cannot survive large doses of radiation because it damages cells in the blood and the brain to the extent that the body cannot recover and death occurs. γ rays are particularly dangerous because they can easily penetrate the body.



Radiation's effect on the body

When a person is exposed to a lower dose of radiation they may not die immediately but they can get cancer. A pregnant woman could give birth to a deformed child. This is because when radiation penetrates living tissue it destroys the atoms and molecules in its path. For example, the DNA molecule's genetic code can be scrambled. The DNA's genetic code in the nuclei of cells is exactly copied when the cell divides; this occurs when the body grows or new cells are needed to replace old ones.

High energy radiation breaks the forces which hold the bonds in the molecules together and this changes or `scrambles' the code, so that the DNA may reproduce abnormally for years. This can cause cancerous cells and eventually tumours to form.

Certain organs and parts of the body are more likely to be affected by radiation than others, and it is in these parts of the body that tumours develop. Look at the drawing on the previous page which shows the parts of the body with high and moderate sensitivity to radiation.

The brain, thyroid, ovaries and bone marrow have a high sensitivity to radiation. The other organs are all moderately sensitive to radiation.

As you can see, too much radiation can cause terrible pain, suffering and death. There are pros and cons to the effects of radiation.

Energy in Nuclear Reactions

Nuclear Fusion

Nuclear fusion takes place when two light nuclei fuse into one heavier nucleus. During this process there is a loss of mass and a large amount of energy is generated. For example two nuclei of deuterium (an isotope of hydrogen) can combine to form helium.

Two nuclei will only combine if they can overcome their mutual electrostatic repulsion. This may happen if they collide at very high speed; for example when they are raised to a very high temperature. Temperatures of 108K are needed to start a fusion reaction. If fusion occurs, enough heat will be produced to keep the reaction going, so this process is called thermonuclear fusion. If a fusion reaction could be controlled we would be able to use deuterium from the oceans to generate almost unlimited quantities of electricity.

The heat and light generated by the sun and the stars are also produced by nuclear fusion.

We are now going to look at what happens to the nucleus during nuclear fission.

Nuclear fission

Splitting the nucleus of the atom is called **nuclear fission**. This was first done by hitting atoms with fast moving particles. This is basically how nuclear fission is done today, although modern equipment is far more sophisticated.

fission:
to divide or split. Nuclear fission is the splitting of the nucleus of an atom into two roughly equal parts. This is always accompanied by a great release of energy

Which atoms do you think are suitable for nuclear fission?

You have learnt that atoms which have nuclei with more than 83 protons are too big to be really stable. These atoms are likely to be radioactive. These big atoms are more easily split and are therefore suitable for fission.

What do you think is released when fission occurs?

Remember that the protons and neutrons in the nucleus are held together by a strong force and the particles within protons and neutrons are held together by weak forces. When the nucleus splits apart this energy which was holding the particles together is released.

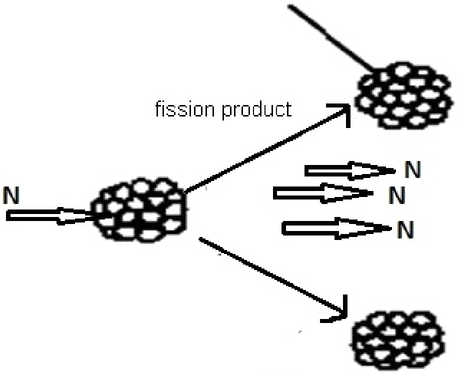
Let's look at an example.

Uranium –235

23592 U or uranium –235 is a very unstable atom. If a neutron hits one of these atoms the extra energy causes it to split into two smaller nuclei which are also radioactive. As the nucleus splits, the two nuclei try to become more stable and energy is released.

For a single uranium atom the amount of energy is small. But one gram of uranium contains billions of atoms. If all these atoms were split the amount of energy released would be equivalent to burning 2 700 kg of coal!

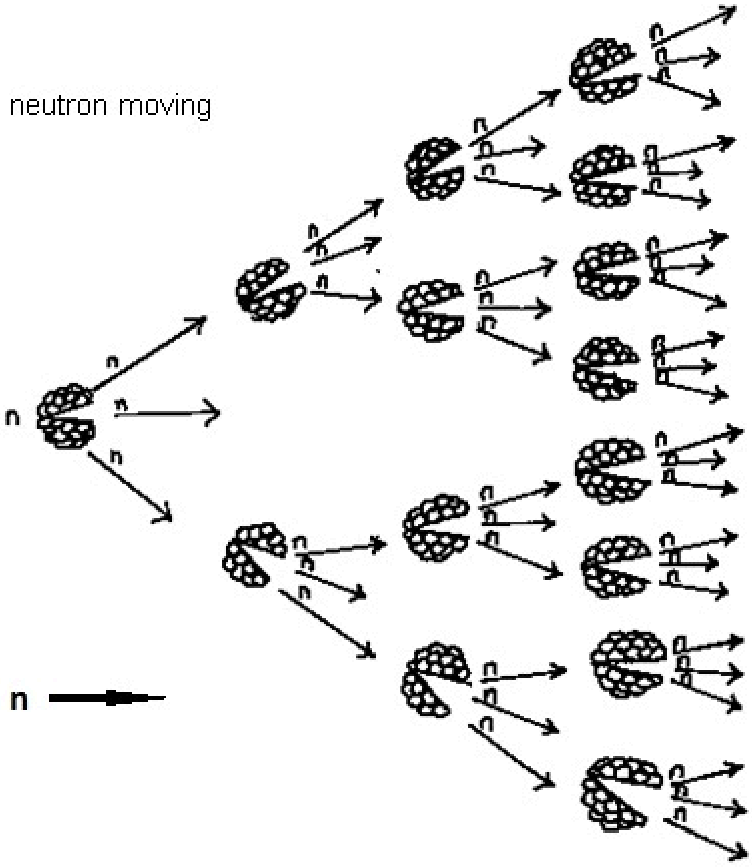
Look at the drawing on the next page which represents the fission of a uranium –235 nucleus.



Nuclear fission of $^{235}_{92}U$

Notice that the uranium –235 nucleus is hit by a neutron which splits it into two smaller nuclei. The atoms formed from these smaller nuclei are called fission products. Neutrons are also released during the process.

These neutrons can hit other uranium –235 atoms resulting in a chain reaction as shown in the drawing below.



The nuclear fission and chain reaction of $^{235}_{92}U$

The chain reaction will continue until all the uranium -235 atoms in the sample have been split into fission products which do not split when they are hit by neutrons. The whole process happens in a fraction of a second.

ACTIVITY 5

1. What is the meaning of nuclear fission?

2. Describe, in a few sentences, how nuclear fission results in a chain reaction.

3. Why is there so much energy released during a nuclear explosion?

4. Why do people who have been exposed to radiation from a nuclear bomb sometimes develop cancerous tumours?

ANSWERS ON PAGE 135

You have seen how uncontrolled nuclear fission results in an explosive release of energy. But nuclear fission can be controlled, and the release of energy can be used to generate electricity.

The uncontrolled fission of uranium –235 occurs in a nuclear or atomic bomb. If the mass of uranium –235 is great enough the chain reaction continues until all the uranium –235 atoms have been split. The energy released causes a massive explosion with a temperature of 1 000 000 ºC at its centre. All this happens in a fraction of a second.

In March 1984 South Africa's first nuclear power station at Koeberg, near Cape Town, began generating electricity. It can supply about one tenth of the electricity used in South Africa.

There are also coal-fired power stations and hydro-electric power stations in South Africa, all supplying electricity to the national grid. All these different types of power stations are energy converters. They convert heat to electricity. In a coal-fired power station the heat comes from burning coal. In a nuclear power station the heat comes from the fission of uranium.

Even when nuclear power is used for peaceful means such as generating electricity, there is a chance of the nuclear reactor going wrong. Although very careful safety measures are taken, people do make mistakes.

The dangers of nuclear power

Radioactive waste

Wastes from nuclear power stations are more of a problem than wastes from other power stations because the waste products from a nuclear power station are radioactive.

The waste has to go through a period of radioactive decay before it is harmless. Some of the fission products, such as plutonium –239 with a half-life of 24 400 years, take many generations to become harmless. Remember that for all those thousands of years the fission product emits radiation. The biggest challenge is to find a way of getting rid of nuclear waste.

Leakage of radioactive material

The worst thing that can happen in a nuclear reactor is a meltdown.

Let's look at the results of a meltdown.

Radiation sickness

Radiation affects human cells and there are certain organs of the body that are most likely to develop cancerous tumours.

Contaminated milk

One of the fission products released when there is a leak is iodine -131. If this settles on grass and is eaten by cows it affects the cows' milk. If humans drink the milk the radioactive iodine is absorbed by their thyroid glands and this causes cancer. Since the half-life of iodine-131 is 8 days it is safe to drink the milk again after a few weeks.

If radioactive materials leak into the sea, fish can absorb them. If humans eat the fish they too will absorb the radiation.

Damage to soil

The soil surrounding a nuclear power station is contaminated for many years with radioisotopes such as strontium -90 and caesium -137. Crops which grow in this soil are not safe to eat because they absorb the radioactive atoms.

Obviously every effort is made to avoid leakage of radioactive material. Safety measures at nuclear power stations are very strict.

However, in 1979, the fuel rods burned at a nuclear reactor at Three Mile Island in the USA. No radioactive material escaped because the reactor was contained, but thousands of people were moved away from the area as a safety precaution.

Then, in 1986, a disaster happened at Chernobyl nuclear power station in the USSR (now Ukraine). The fuel rods burned, there was no containment, and radioactive material was released into the atmosphere.

COMMENT

In this lesson you have learnt about stable and unstable atoms, the nucleus of the atom and discovered why some atoms are radioactive. You have found out about the different types of radioactivity and looked at some of the benefits and harmful effects of radiation.

CHECKLIST

Are you able to:

- ☐ describe stable and unstable atoms
- ☐ describe some of the uses of radioactive isotopes
- ☐ describe the ideas of half-life and different types of radiation
- ☐ balance nuclear reactions
- ☐ compare the advantages and disadvantages of radioactivity
- ☐ describe the process of nuclear fission
- ☐ describe and give an opinion on the dangers of nuclear power.

NOTES

LESSON 6

Atomic Bonding

About this lesson

We know that there are only 113 known elements in the universe. Yet we are surrounded by many more than 113 different types of substances on earth.

This is possible because elements bond to each other to make many more than 113 different substances. In a previous lesson, we also discussed the existence of elements and how they can be arranged on the Periodic Table. However, most substances in the world don't exist as elements.

Atoms combine together to form molecules and large network structures which make up salts.

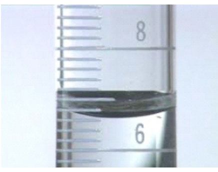
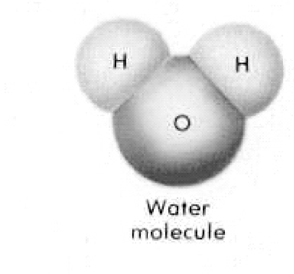
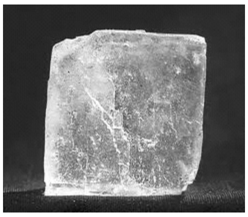
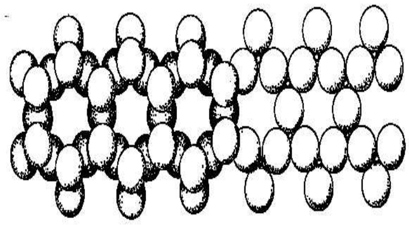
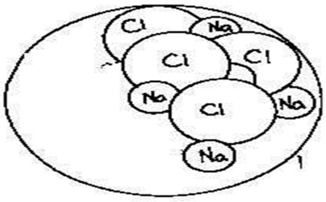
In this lesson we will look at how the atoms of elements combine to form the different substances we find on Earth and we will look at bonding using Lewis diagrams.

In this lesson you will:

- explain why atoms bond using a graph of energy changes
- describe bonding involving the equal sharing of electrons
- describe bonding involving the unequal sharing of electrons
- use Lewis diagrams and the pair concept of chemical bonding.

ACTIVITY 1

The figure below shows three substances and their sub-micro structures. See if you can name the substances and identify the relationship between the large amounts of the substances and the atoms, molecules and large network structures that make up these substances.

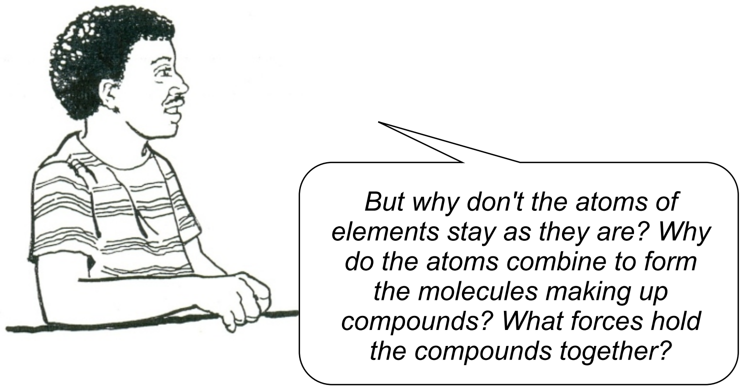
ANSWERS ON PAGE 135

Let's see if we can answer these questions.

How we know that bonds exist

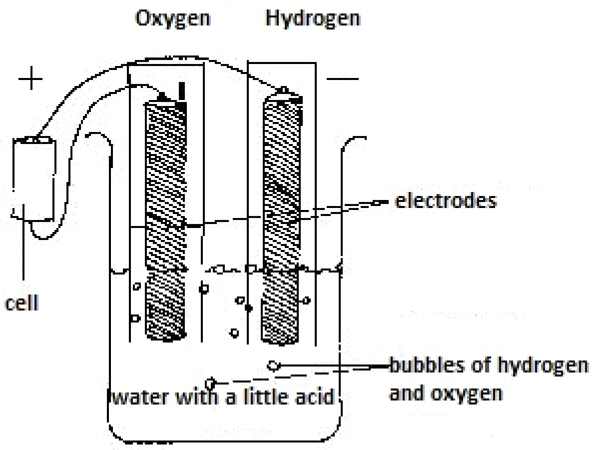
There are forces which hold the atoms together in a molecule.

But how can we show this?



Water (H_2O) is a compound that we use every day. If we can show that water can be broken into its elements, hydrogen and oxygen, by applying energy, this is evidence for the idea that forces hold atoms together. We can carry out a simple experiment to show that forces do exist between the atoms making up water molecules.

Look at the drawing below. Two carbon rods (electrodes) are placed in some water (with a little acid). The carbon rods are then connected to the opposite terminals of a battery. If you were to carry out this experiment you would see that bubbles of gas would come off at each electrode. Hydrogen is given off at one electrode and oxygen at the other.



Water breaks down according to the following reaction:

$$2\,H_2O\ > 2\,H_2\ +\ O_2$$

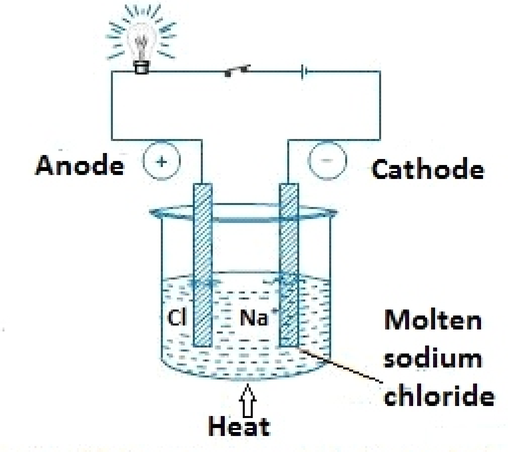
It is also evident that 2 volumes of H_2 are produced to 1 volume of O_2.

We used electrical energy from the cell to break the bonds holding the hydrogen and oxygen atoms together. The water is not boiling in this experiment. When we boil water we will not separate it into oxygen and hydrogen. In this experiment we are passing an electric current through the water and it is the current that causes water to separate into elements oxygen and hydrogen.

ACTIVITY 2

decomposition:
breaking up of a substance into simpler substances

Consider the following diagram in the **decomposition** of sodium chloride:



Electrolysis of molten sodium chloride

a. Give the energy conversion that takes place in the decomposition of sodium chloride.
b. Why does sodium chloride have to be molten?
c. What do you think are the products of this reaction?

ANSWERS ON PAGE 136

Forces and energy changes in bonding

From our previous discussion, we have seen that there are forces which hold the atoms of molecules together. To explain how these forces operate and how a molecule is formed, let's take a simple example – the combination of two hydrogen atoms to form a hydrogen molecule. This is a molecule of hydrogen gas, which is diatomic.

Atoms will bond only if the two atoms bonded together are at a lower energy state than each atom before bonding.

Let us look at what happens when two atoms of hydrogen bond. Each atom consists of a nucleus which has one proton and one electron.

When the atoms are far apart, there is little or no attraction or repulsion between them.

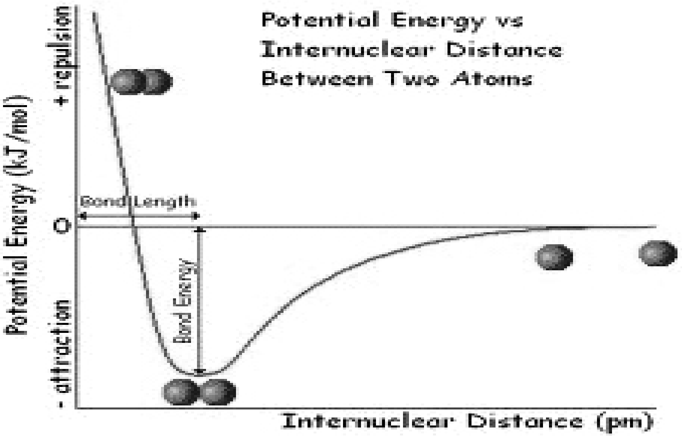
As the two atoms in the system move closer together, there will be some repulsion between the two electrons. But there is an equal probability of finding the electrons all around the nucleus. So there will also be times when the electron of one atom will be close to the nucleus of the other atom. The electron of one atom is then attracted to the nuclei of both atoms. The increased attraction leads to a lowering of energy of the system of the two atoms. Bonding can now take place. This is because the energy of the system is lower.

What happens if the atoms move very close to each other?

If the two positively charged protons in the nucleus get too close they will repel each other strongly. This strong repulsion leads to an increase in the energy of the two atoms and they will therefore not bond.

Chemists usually show the energy changes when atoms bond on a graph.

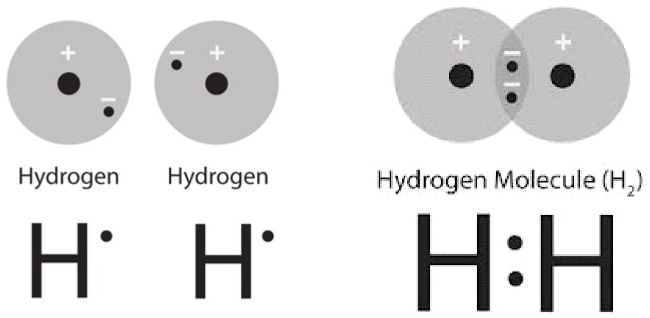
The figure shows the change in energy as the distance between two hydrogen atoms decreases. The right side of the graph shows the situation when 2 atoms are far apart. As we move from right to left the 2 atoms move closer to each other and finally bond.



What actually happens to the electrons when two atoms bond? Atoms form bonds by gaining, losing or sharing electrons to become stable like the noble gases (group 8 elements). Ionic bonds form when electrons are transferred between atoms to make positive and negative ions. Covalent bonds form when atoms share pairs of electrons. The bonded atoms form molecules.

Covalent bonding

Lewis diagram



Couper Notation

Single covalent bond

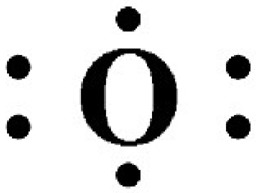
H-H (2 electrons represent a single bond)

When two atoms share electrons equally, we say they bond covalently. The figure above on the left shows the electrons of two hydrogen atoms. These are the outer electrons, because hydrogen atoms have only one electron each. The two atoms bond to form a molecule, H_2 and share the two electrons between them. The Lewis drawing always shows the two shared electrons in a pair, showing that there is a **bond**. We have drawn the single electron of the one H atom as a dot. When we use Lewis diagrams to show covalent bonding, we only use the electrons in the outer energy levels, i.e. the valence electrons. Only the valence electrons are involved in bonding.

Na•
The Lewis diagram for sodium

The Lewis diagram of any element in group I would look the same as that for hydrogen. For example, look at the Lewis diagram for sodium.

Lewis diagrams usually show electrons in pairs.



For example, the Lewis diagram for an oxygen atom (group 6) would show the six valence electrons.

If there is more than one electron, but less than eight, the rule is that you put the first 4 dots singly and then you start to pair off the electrons. It does not matter where you put the pairs,as long as there are two pairs and two single electrons shown.

You can also represent ions with Lewis diagrams. For example, the ion Ca^{2+} has no valence electrons, because both electrons have been lost. The ion F^+ would have six valence electrons because Fluorine has seven when it is neutral. So the F^+ ion would have its electrons arranged like the atom of oxygen.

Covalent bonding in chlorine

This figure shows the valence electrons for two Cl atoms. You know that Cl has 7 electrons in its outer energy level. So each atom has one unpaired electron to form a pair for bonding.

ACTIVITY 3

Show, using Lewis diagrams, the bonding which takes place:

a. between 2 oxygen atoms
b. in a water molecule
c. in NH_3
d. in CO_2
e. in Nitrogen gas (N_2)

ANSWERS ON PAGE 136

Unequal sharing of electrons in bonding

When 2 atoms of the same element bond to form molecules they share their electrons completely equally. This was the case for molecules formed from two identical atoms like H_2 and Cl_2. However bonding between atoms of different elements usually results in the unequal sharing of electrons.

Why do atoms share their electrons unequally?

We first need to look at the idea of **electronegativity**.

Electronegativity

The main reason why atoms share electrons unequally is because of the different atomic radii of atoms.

- There is number assigned to an element that indicates the extent to which the atom will attract the shared pair of electrons in a covalent bond.
- Elements with large electronegativities will tend to form negative ions and those with small values will form positive ions.
- Going across a period, electronegativity values increase. The attraction for electrons in the valence shell increases as protons are added to the nucleus.
- Going down a group, electronegativity values decrease. The valence shell is further from the nucleusand there are filled orbitals between the nucleus and the valence electrons.
- If atoms have different electronegativity values, they may share electrons unequally to form a molecule, or transfer electrons to form ions.
    - Equal sharing of electrons will result in a pure covalent bond
    - Unequal sharing of the electrons will result in a polar covalent bond
    - Transfer of electrons will result in an ionic bond.

We can tell whether a bond is pure covalent / polar covalent or ionic by looking at the electronegativity difference.

Increasing bond polarity	Pure covalent	Polar covalent	ionic
Electronegativity difference	0	0 to 1,9	>2

Example:

molecule	EN difference	Type of bond
H_2O	3,5 − 2,1 = 1,4	polar covalent
CS_2	2,5 − 2,5 = 0	pure covalent
NaCl	3 − 0,9 = 2,1	ionic

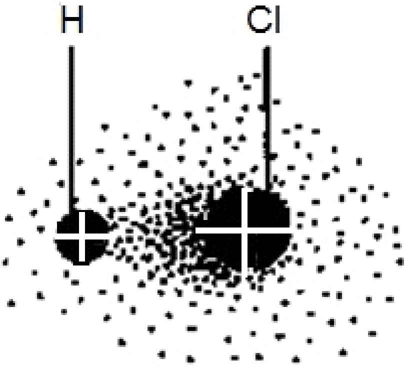
You can see the electronegativity table in the figure below.

		H 2,1						
Li 1,0	Be 1,5		B 2.0	C 2,5	N 3,0	O 3,5	F 4,0	Ne –
Na 0,9	Mg 1,2		Al 1,5	Si 1,8	P 2,1	S 2,5	Cl 3,0	Ar –
K 0,8	Ca 1,0		Ge 1,6	Ge 1,8	As 2,0	Se 2,4	Br 2,8	Kr –
Rb 0,8	Sr 1,0		In 1,7	Sn 1,8	Sb 1,9	Te 2,1	I 2,5	Xe –
Cs 0,7	Ba 0,9		Ti 1,8	Pb 1,8	Bi 1,9	Po 2,0	At 2,2	Rn –
Fr 0,7	Ra 0,9							

More values can be seen on the periodic table in a previous lesson.

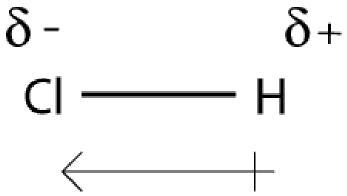
Some examples of molecules where electrons are shared unequally

Let us start with a molecule of hydrochloric acid, HCl.



Cl has a higher electronegativity than H and so the electrons are more attracted to the Cl atom.

The chloride end is more negative (δ^-) and the hydrogen end is more positive (δ^+).



ACTIVITY 4

1. If the following atoms join by sharing electrons, which atom would attract the shared electron pair more? Indicate this by using $(\delta-)$ and $(\delta+)$

   a. C and H
   b. F and O
   c. P and H
   d. N and H

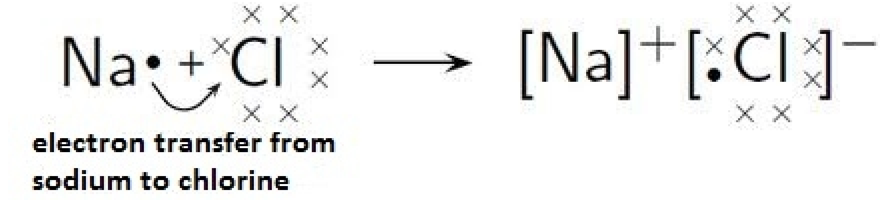
2. Use electronegativities to decide the type of bonding that occurs in the following compounds.

   a. LiI
   b. Cl_2
   c. AlF_3
   d. BeO
   e. H_2O
   f. Na_2O
   g. NaCl

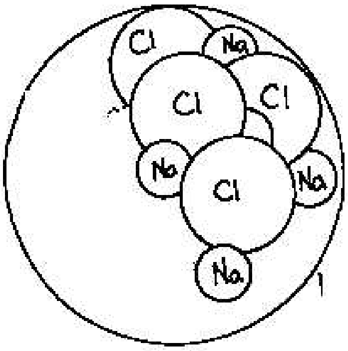
ANSWERS ON PAGE 136

Bonds between atoms with a big electronegativity difference: Ionic bonding

When the electronegativity difference between two atoms is large they often do not form the single molecules which we have come across so far. Rather, the atoms form lattices or networks. The most common example of this is NaCl.

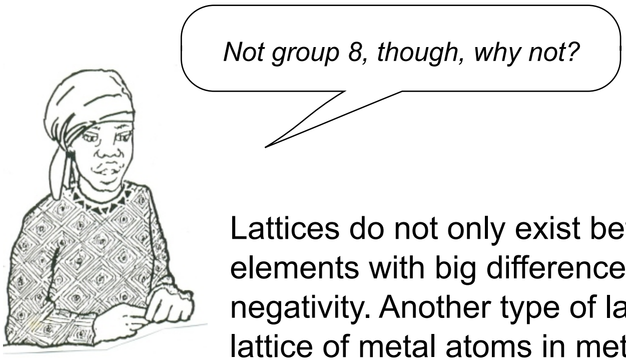


This goes on until a lattice or network structure is formed, as shown below.



In this Figure you can see that there is one structure, not individual molecules. A lattice is just one, huge molecule. We call the formula NaCl the formula unit rather than the molecular formula.

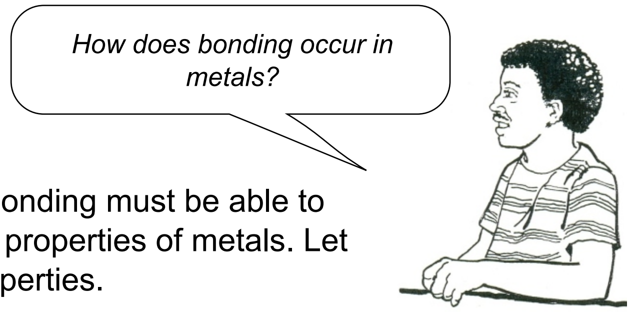
The NaCl type lattice is often called an ionic lattice. This is because when you melt NaCl the molten salt will conduct an electric current. This shows us that molten NaCl consists of charged atoms or ions. When the difference in electronegativity is very large the bond is often called ionic. Such bonds are likely to be formed between elements on the far left with elements on the far right of the table.



Lattices do not only exist between atoms of elements with big differences in electronegativity. Another type of lattice structure is the lattice of metal atoms in metallic bonding.

Metallic bonding

Metallic bonding refers to bonding between atoms of metals. For instance atoms of sodium can have metallic bonds with each other.



Any description of bonding must be able to explain the unusual properties of metals. Let us look at these properties.

Properties of metals

The activity shows you some of the properties of metals.

ACTIVITY 5

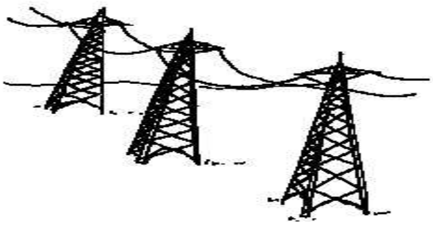
Take a metal coat hanger and carry out the following experiment.

1. Bend the hanger. Take a cloth and rub any part of the metal. Does it shine? Hold the hanger over the flame of candle for a while with your fingers a few centimetres from the flame. What do you feel?

ANSWERS ON PAGE 137

Talking about conducting electricity, look at the picture which shows a pylon holding copper wire which conducts electricity.

Why is copper able to conduct electricity?

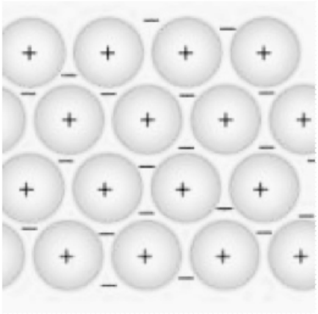


Look at the copper wire. It has the property of flexibility - it can bend without breaking.

Why should this be so? How can we explain these properties of metals in terms of metallic bonding?

Metallic bonding explains the properties of metals

The outermost energy levels in metals are nearly empty as they contain few electrons. For example the group I metals, Li, Na and K have only one electron in their outer energy level. So there is space for electrons from other metal atoms to move in these energy levels, which is exactly what they do.



Delocalised electrons in metallic bonds

In a metal the atoms are close together and the atoms build in orderly layers, like marbles in a box. As the electrons move from one atom to another, all the nearby positive cores attract them. So each atom is held in position by the attraction of electrons moving in and out of its outer energy levels. Because these electrons aren't forced together, we call these electrons delocalised. The Figure in the margin shows a model of the metallic bond. The signs represent the delocalised electrons which are attracted by the nearby positive cores.

The metallic bond explains the behaviour of metals in the following ways:

- The delocalised electrons can reflect light to give a shiny surface to metals.

- The delocalised electrons are free to move between the metal atoms. So they can move as an electric current in copper wire or their movement can conduct heat as you saw with the hangar.

- The metallic bonds don't have direction as in covalent bonds, so the positive cores of atoms can slide over one another. This allows the metal to bend and allows the metal to be flexible. Once again, think of the copper wire held up by the pylons. Also, remember the experiment you did with the metal coat hanger. In both cases the metal bends without breaking.

ACTIVITY 6

Describe the sharing of electrons and microscopic structures of a quantity of the following substances:

a. Nitrogen gas (N_2)

b. Potassium chloride (KCl)

c. Copper (Cu)

ANSWERS ON PAGE 137

CHECKLIST

Are you able to:

☐ explain why atoms bond using a graph of energy changes
☐ describe bonding involving the equal sharing of electrons
☐ describe bonding involving the unequal sharing of electrons
☐ use Lewis diagrams.
☐ explain the difference between a covalent bond, ionic and metallic bond, which are intra- molecular bonds. (bonds within a molecule between atoms).

NOTES

LESSON 7

Interaction between Molecules

About this lesson

In this lesson we will look at intermolecular forces. These occur between molecules and are forces of attraction. Intermolecular forces are quite different from chemical bonds,or intramolecular forces. For a start, they are much weaker.

Can you remember that these bonds were called covalent, ionic and metallic?

With chemical bonds there is a change in the arrangement of electrons in each of the bonding atoms. No such change occurs with intermolecular forces.

In this lesson we are most interested in the intermolecular forces between water molecules. However, we will look at some of the forces between other molecules as well.

Why are we so interested in water? What do you think the most important liquid on Earth is?

It's water! Water covers about 75% of the surface of our planet. All chemical reactions that support plant and animal life take place in a water solution.

In this lesson you will:

- describe intermolecular forces that occur between molecules
- predict the occurrence of hydrogen bonding
- explain the special properties of water in terms of hydrogen bonding.

Intermolecular Forces

Intermolecular forces occur when oppositely charged particles exert electrostatic forces of attraction between them. These forces depend on the type of particles involved, and we find that the strength of these forces depends on the size of the charges.

The particles may be:

- Positive and negative ions which are found in ionic compounds

- Polar molecules (dipoles) in which there is a partial separation of charge to give positive (δ+) and negative poles (δ-).

- Temporary or induced dipoles
  Non-polar molecules can form induced (temporary) dipoles when the electron cloud in one molecule is temporarily displaced to one side. The end of this molecule will carry small charges and this will cause the electron cloud in adjacent molecules to also become displaced.

- Ion-dipole and ion-induced dipole forces
  Ion-dipole: this is the attraction between the δ+ end of a polar molecule and a negative ion, or the δ- end of a polar molecule and a positive ion.

  For example, when NaCl is dissolved in water the Na+ ions and the Cl- ions are each surrounded by polar water molecules. Therefore you have an ion surrounded by polar water molecules.

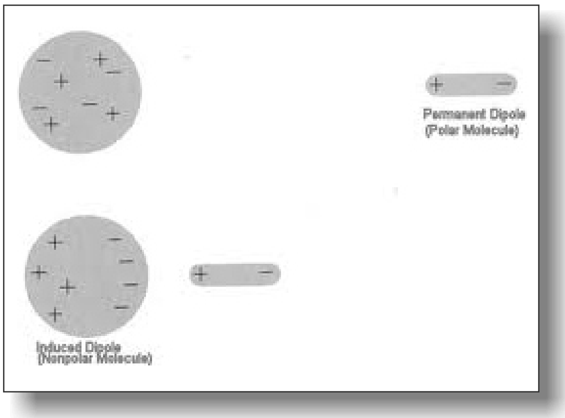
  Ion-induced dipole: an ion will cause the electron cloud of a non-polar molecule to become displaced. There will be an attractive force between the ion and the induced dipole.

Van der Waals forces

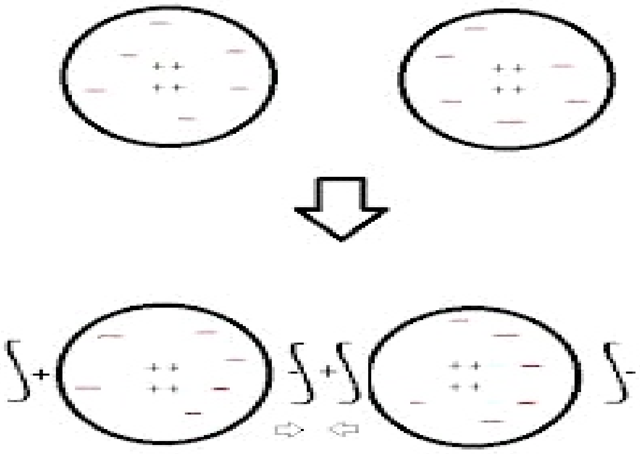
These forces exist between particles which carry small positive and negative charges. They are non-directional and act over long distances.

Dipole-dipole: attraction between the δ+ end of one polar molecule and the δ - end of another, for example the force between hydrogen chloride (HCl) molecules

Dipole- Induced dipole: a polar molecule will cause the electron cloud of a non- polar molecule to become displaced. There will be an attractive force between the permanent dipole and the induced dipole.

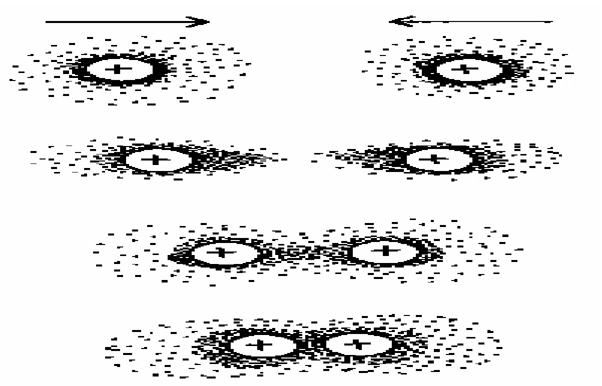


Induced dipole-induced dipole (London forces or Dispersive Forces): which are weak forces but they increase in strength with increasing size of the molecule. Larger molecules have larger electron clouds which become displaced more readily. The charges on the induced dipole are larger and the forces between induced dipoles are stronger. The halogens are a good example of this trend. F_2 and Cl_2 are both gases at room temperature but Br_2 is a liquid and I_2 is a solid.



The compounds called the hydrocarbons show the same trend. The simple hydrocarbons are gases, for example household gas (butane C_4H_{10}); larger molecules such as petrol (octane C_8H_{18}) are liquids, and very large molecules such as candle-wax ($C_{23}H_{48}$) are solids. The larger the molecule the greater surface area for the Van der Waals forces to act. Therefore this explains the nature and melting and boiling points of substances.

The noble gases do not make molecules but their atoms form induced dipoles which link together with very weak Van der Waals forces. The boiling point and melting point of Helium, the smallest of these atoms, is lower than any other substance.

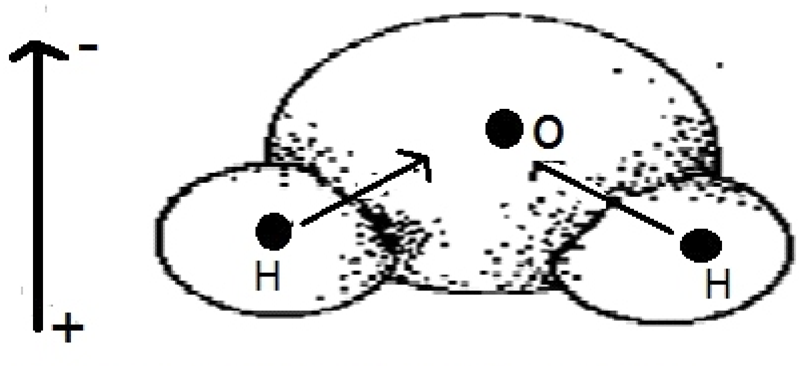


Two atoms with their electron clouds approach each other and bond by sharing electrons. The atoms have the same electronegativity, e.g. hydrogen.

Hydrogen Bonds

These are stronger than Van der Waals forces. They act over shorter distances and they are directional. Hydrogen bonds exist between molecules that contain hydrogen bonded to a small highly electronegative atom such as N; O; or F.

Because of the large difference in electronegativity the hydrogen atom acquires a significant positive charge. The δ+ H end of one molecule attracts the δ- end of another molecule. Because the hydrogen atom is so small the two molecules can approach each other very closely, forming a bond which is stronger than a normal dipole-dipole bond.



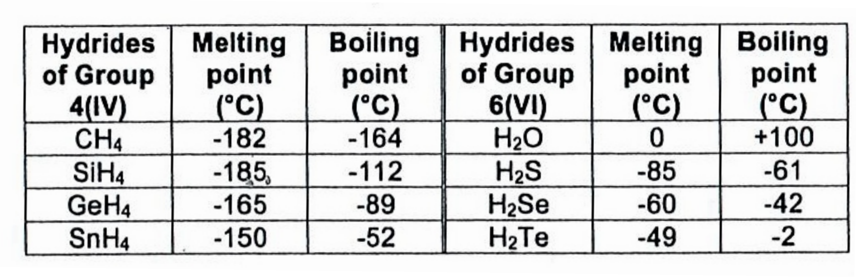
Oxygen is more electronegative than hydrogen. Oxygen pulls the bonding electrons towards itself.

Hydrogen bonding in water

Hydrogen bonds will not form between molecules that contain hydrogen bonded to atoms such as Cl, Br, I, P or S. These atoms are too large and the electronegativity difference is too small to give a molecule with the highly charged ends necessary for hydrogen bonding to take place.

ACTIVITY 1

1. Boiling points and melting points of substances are a measure of the strength of intermolecular forces. The table below shows the melting points and boiling points of the hydrides of Group 4 and 6.



Hydrides of Group 4(IV)	Melting point (°C)	Boiling point (°C)	Hydrides of Group 6(VI)	Melting point (°C)	Boiling point (°C)
CH_4	-182	-164	H_2O	0	+100
SiH_4	-185	-112	H_2S	-85	-61
GeH_4	-165	-89	H_2Se	-60	-42
SnH_4	-150	-52	H_2Te	-49	-2

   a. Refer to the boiling points of CH_4 and SiH_4. Which hydride has stronger intermolecular forces?
   b. Molecular size increases from top to bottom in a group. What is the relationship between boiling points and the size of molecules in Group 4?
   c. Do the boiling points of hydrides of Group 6 follow the same pattern as the boiling points of the hydrides of Group 4? Explain your answer.
   d. Write down the phase for each of the hydrides of Group 6 at room temperature (25°C).
   e. Water has a difference of 100°C between its melting point and boiling point. Explain how this property is useful in sustaining life on earth.

2. What type of intermolecular force is likely to occur between the atoms of a noble gas and molecules of a halogen.

ANSWERS ON PAGE 137

Cohesive and adhesive forces in water

You know that water molecules can slide over each other. This is because of the relatively weak intermolecular forces between them. However, these intermolecular forces are strong enough to cause two very important properties of water in biological systems: **adhesion** and **cohesion**.

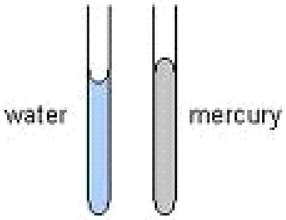
Cohesive and Adhesive forces

Cohesive and adhesive forces are two kinds of intermolecular forces. Cohesion simply means ‘sticking together’. **Cohesive forces** are the **forces between molecules of the same substance**.

Example of cohesive forces are the forces of attraction between two water molecules. Remember that these forces are hydrogen bonds.

Adhesive forces are the **forces between molecules of different substances**. Examples are the forces between water molecules and glass particles, water molecules and plastic, and water molecules and the 'tubes' in plants.

To illustrate adhesion and cohesion try these experiments.



meniscus:
liquid level

Adhesive forces are greater than cohesive forces in water, hence the **meniscus** is concave. In mercury cohesive forces are greater than adhesive forces, hence the convex meniscus.

ACTIVITY 2

a. Put a straw in a glass of water or cool drink. Look at the level of the liquid in the straw. What do you see?

b. Dip the bottom of a cloth in water and hold it for a few minutes. What do you see?

ANSWERS ON PAGE 138

Let us look at why the liquid rises up the cloth. Water molecules are **polar**. They are therefore attracted to the molecules of the cloth which are also slightly charged. This force of attraction is adhesion. But the water molecules are also attracted to each other by cohesive forces.

So, as the water molecules are attracted to the cloth, they also pull up more water molecules behind them. The result is that water moves up the cloth.

The same process happens with the straw. However, the straw has to be very narrow for the forces of adhesion to work well. If the straw is too large then the force of gravity overcomes the force of adhesion to the sides of the straw. The water therefore drops down to its normal level.

Plants have narrow tubes in their leaves, roots and stems. These tubes are called **xylem vessels**. These tubes stretch from the roots up the stem to the leaves. When plants absorb water in the roots the water moves up the stem partly because of the forces of adhesion and cohesion.

xylem vessels:
the tubes in a plant which transport water from the roots to the stems

With the exception of mercury, the particles in a liquid are molecules so intermolecular forces play a major role in the properties of liquids.

- **Surface Tension**: The surface of a liquid resists an increase in area. Particles in the body of the liquid are attracted equally in all directions so they experience no net force. Particles at the surface are attracted down and sideways and are pulled towards the interior of the liquid. This causes the surface of the liquid to act as though it is covered by a skin which resists being stretched. For example, falling drops of water are nearly spherical as the surface area has been reduced.

- **Viscosity**: Viscosity is the resistance to flow that is shown by all gases and liquids. Some liquids flow quickly (have a low viscosity) e.g. water, alcohol. Other liquids flow slowly (have a high viscosity) e.g. syrup, glycerine, oil.

  If the temperature of a liquid increases, the viscosity decreases. For small molecules a higher viscosity generally indicates stronger intermolecular forces. Longer molecules tend to tangle as they move, which increases the viscosity.

To compare the strengths of intermolecular forces we can compare how easily liquids will change to the gas phase. This change happens when liquids evaporate or boil.

- **Evaporation**: Evaporation occurs when high energy molecules escape from the surface of a liquid into the gas phase. This can happen at any temperature and it means that above the surface of any liquid there is a certain amount of vapour. If the liquid is in a closed container this vapour will exert a pressure on the surface of the liquid called the vapour pressure. Vapour pressure increases with increasing temperature. High values of vapour pressure indicate that the vapour forms easily and that intermolecular forces between the liquid particles are weak. We say that the liquid is volatile.

- **Boiling**. Liquids boil when bubbles of vapour appear within the body of the liquid and move to the surface.

For this to happen the pressure inside the bubble (vapour pressure) must be equal to the pressure of the atmosphere. A liquid will boil at a fixed temperature which is dependent on atmospheric pressure and the vapour pressure of the liquid. If a liquid has a high vapour pressure it will boil easily. i.e. have a low boling point. Low boiling points indicate that the intermolecular forces between liquid particles are weak.

COMMENT

For substances to boil, enough energy is needed to break the forces of attraction between the particles for them to change phase. The substance with the stronger forces will have the highest boiling point.

Hydrogen bonding in ice

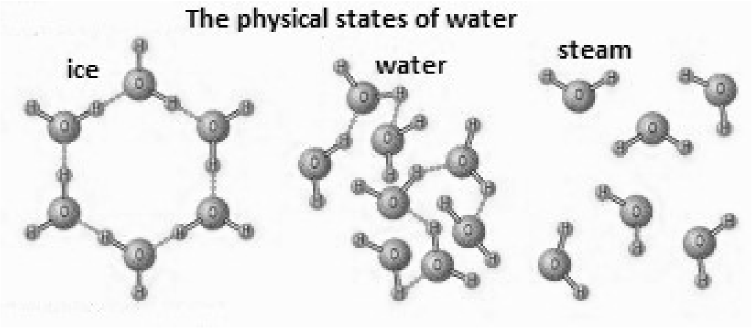
Does hydrogen bonding explain the strange behaviour of water?

Normally the density of substances increases as they cool because the molecules come closer together. **Water does not follow this rule.** The highest density of water is at 4ºC. Water is less dense at 0ºC. This can only be explained by the formation of hydrogen bonds between water molecules.

Hydrogen bonds do form when water is in the liquid phase. However, these bonds are not on all the molecules. The molecules in the liquid phase still have enough kinetic energy to break the hydrogen bonds. Hydrogen bonds are continually breaking and new hydrogen bonds form in the liquid phase.

The kinetic energy of molecules in the solid phase is less than the kinetic energy of molecules in the liquid phase. Therefore the hydrogen bonds are more permanent in the solid phase.

Look at the drawing on the next page showing the distances between the different molecules in the different phases. Ice has a crystalline structure whereas water does not.



The fact that ice is less dense than water is very important in lakes and rivers in cold climates. As the temperature drops, ice forms on the surface of the water, and the denser water sinks to the bottom and does not freeze solid. Fish can therefore still survive in the cold water below the ice.

ACTIVITY 3

The density of water decreases (becomes less dense) as it cools down from 4º C to 0º C. Normally the density of substances increases as it cools down because the molecules come closer together. Why is water different?

ANSWERS ON PAGE 138

COMMENT

Remember that oxygen is highly electronegative. Think about how this influences hydrogen bonding.

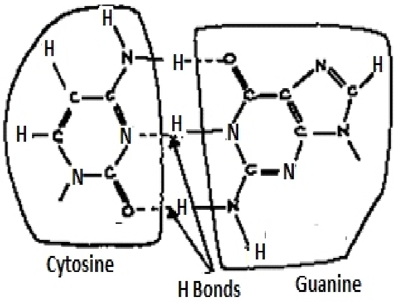
Hydrogen bonding is also important in the structure of organic molecules.

Hydrogen bonding in organic molecules

Hydrogen bonding plays an important part in many life processes. These bonds are the vital link that hold together the molecule that is the basis of life, the DNA molecule.

The DNA molecules are in the nucleus of each of our cells. These molecules carry the information which makes our cells function. Each molecule consists of thousands of bases in two matched rows. The matched rows of bases are joined by H bonds.

Look at the figure representing hydrogen bonds in DNA. You can see two bases from the parallel rows of thousands of bases. Find the H bonds between these two bases.



Hydrogen bonds between rows of bases in DNA

The H bonds are strong enough to hold the two rows of bases together but do not influence the chemical nature of the bases. H bonds are not as strong as the covalent bonds between the atoms of each base. The bonds can break and the two rows separate without any change in the structure of the bases. This ability is important for cell division and for forming proteins.

The effect of intermolecular forces on density and solubility

Let us look first at density. The more closely packed the particles of a substance are, the greater its density. Therefore the more strongly particles of a substance attract each other the denser that substance will be. Let us look at an example.

Pentane and 2,2-dimethylpropane have the same molecular formula, C_5H_{12}. But they are different. Pentane has longer, thinner molecules which wrap around each other like strands of spaghetti. 2,2-dimethylpropane has rounder molecules which only touch in a few places and do not wrap around each other. So the intermolecular forces in pentane are stronger than in 2,2-dimethylpropane. Pentane therefore has a higher density and boiling point than 2,2-dimethylpropane.

Let us look at solubility. The stronger the intermolecular forces between molecules of the solvent and particles of the solute, the more soluble the substance will be.

For example, methane (CH_4) hardly dissolves in water at all. But ammonia (NH_3) easily dissolves in water. Ammonia and water form strong hydrogen bonds when they are mixed together. This is why ammonia dissolves so easily in water. However, no such bonds can form between water and methane. So, methane is not as soluble as ammonia in water.

ACTIVITY 4

a. Two nitrogen atoms form a non-polar, covalent molecule of nitrogen gas (N_2). How is it possible for nitrogen gas to liquefy?

b. Explain why water boils at a much higher temperature than hydrogen sulphide, even though O and S are both in group VI. The boiling point of water is 100ºC and that of hydrogen sulphide -60ºC.

c. If you put a narrow tube in water the water rises up the tube. Why does this happen?

d. Mr Sithole has a problem. Every week he buys milk in plastic bags. He then places some of the bags in the freezer. When he takes them out of the freezer after a few days, he notices that the bags look fuller and some have even burst at the seams.

Explain to Mr Sithole why the bags sometimes burst.

ANSWERS ON PAGE 138

COMMENT

Intermolecular forces are forces of attraction or repulsion which act between neighbouring particles (atoms, molecules or ions). They are weak compared to the intramolecular forces, the forces which keep a molecule together. For example, the covalent bond present within HCl molecules is much stronger than the forces present between the neighbouring molecules, which exist when the molecules are sufficiently close to each other.

CHECKLIST

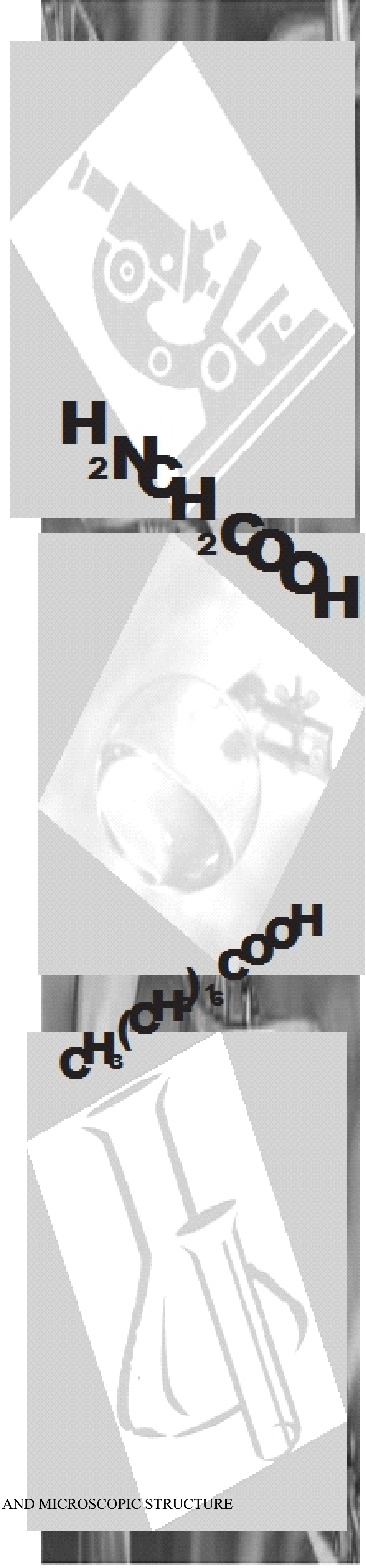
Are you able to:

❐ describe intermolecular forces that occur between molecules
❐ predict the occurrence of hydrogen bonding
❐ explain the special properties of water in terms of hydrogen bonding.

NOTES

LESSON 8

Relationship between macroscopic properties of materials and microscopic structure



About this lesson

In this lesson, we discuss what makes a substance exist as a solid and how some solids are made up of crystals while others are made up of long chains of molecules called 'polymers'. In addition, we learn how a solid can conduct heat as well as electricity. We explain the lustre of a solid and how we can hammer many solids into flat sheets without damaging them because of their 'malleability'.

We explain why there are solids that are soft and hard and why some solids break easily. Furthermore, we explain how some solids are good conductors of electricity and act as thermal conductors.

Some of these properties are macroscopic, while others are microscopic. We explain the difference between macroscopic and microscopic properties of solids and explain how both living and inanimate things exhibit these properties.

In this lesson you will:

- understand the nature of a substance based on its intermolecular forces
- find out how a solid can conduct heat and electricity
- learn about hard and soft solids
- explain some of the macroscopic and microscopic properties of solids
- learn about different kinds of materials.

Molecular and network substances

Carbon atoms can bond with each other to form giant crystal lattices such as diamond or graphite(C) which are called network structures. Sand is made up of millions of silica molecules (SiO_2) and forms molecular structures. Table salt (NaCl) is made of an ionic crystal lattice that contains millions of Na^+ and Cl^- ions, and copper (Cu) contains millions of copper atoms in a metal structure. Giant structures are represented by an empirical formula.

How does structure affect melting points of substances?

Solid substances can be classified as amorphous or crystalline. In an amorphous solid, the atoms are arranged randomly and there is no regular repeating pattern. Examples are glass and plastic. In a crystalline solid the atoms are arranged in a three-dimensional pattern, called a lattice, that repeats in an orderly way. If the pattern is repeated throughout the entire solid, it is called a single crystal. Examples are ice, sodium chloride and all metals. Single crystals do occur on their own, for example diamond. However, many combine to form larger molecules.

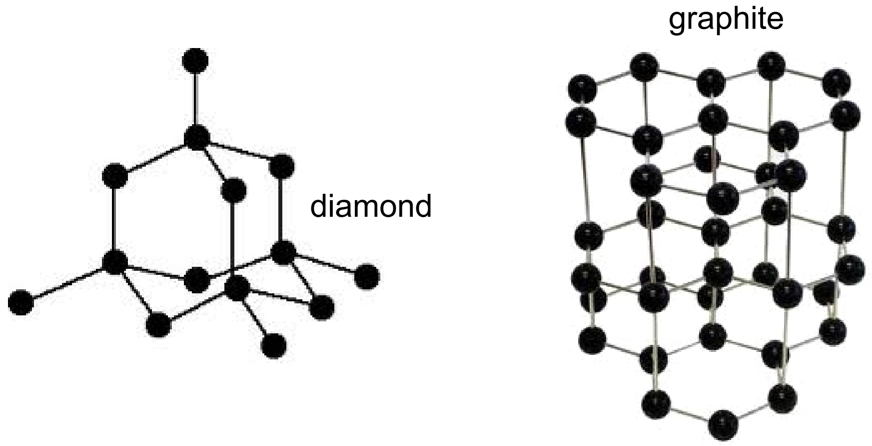
Covalent solids can be composed of atoms or molecules. Depending on these different types of particles that solids are made of, we can distinguish between the different types of crystal lattices. The boiling points of some covalent solids are presented in the following table. Their atoms are kept together by covalent bonds. What do you observe?

Substance	Melting point(^{0}C)
ice	0
phosphorus	44
sulphur	115
silicon dioxide(silica)	1710
carbon(as diamond)	3550

The particles that make up the crystals of the first three substances are molecules. They are molecular solids (have a molecular lattice made up of molecules). As a result of these weak intermolecular forces, these three substances have low melting points.

Diamond and silica are however, different. Their crystals are not made up of molecules, but atoms that are bonded together with very strong covalent bonds in a lattice.

They are made up of giant covalent structures or **macro molecules** (each crystal can be seen as a molecule of infinite size). Because covalent bonds are very strong, substances such as diamond and silica have very high melting points.



Diamond - a giant covalent lattice structure

Diamond has the following properties:

- It is a colourless transparent crystal that sparkles when light falls on it.
- It is very hard, because each carbon atom is kept in its position by four strong covalent bonds. It is the hardest substance on earth.
- For that reason it has a high melting point (3550°C) and boiling point (4530°C) .
- It cannot conduct electricity, because there are no free electrons that can act as charge carriers.

Graphite

Graphite is very similar to carbon. It is made up of carbon atoms that are bonded covalently in an atomic lattice. Diamond and graphite are allotropes of carbon. Although diamond is hard, graphite is one of the softest elements on earth. This is because of their crystalline structures.

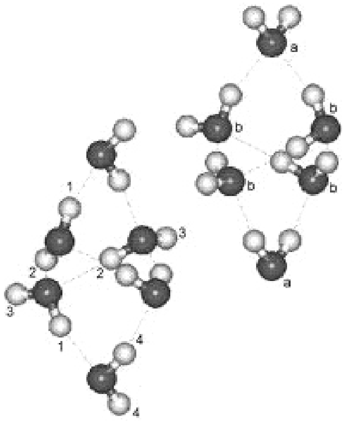
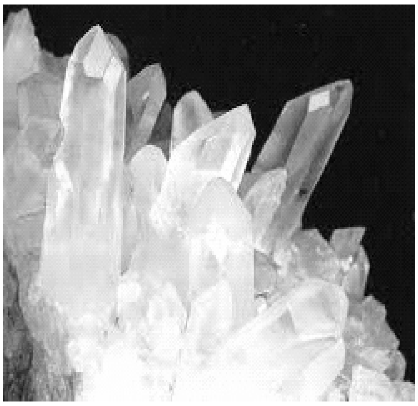
Allotropes are a phenomena where the same element can occur in different crystalline forms (i.e more than one crystalline form of the same element).

In graphite the carbon atoms are in layers. The atoms in each layer are covalently bonded to three other carbon atoms so that regular hexagons are formed in the same layer. The layers are held together by weak intermolecular forces. This causes the layers to glide over each other and gives graphite its gliding property. Because of this, graphite is used as a lubricant. The lead in pencil is actually a mixture of graphite and clay. When writing with it, layers are peeled of onto the paper.

Carbon has four valence electrons, of which three are bonded covalently in the graphite and one is ‘free’. This electron can move freely in graphite. As a result of these free-moving electrons in graphite, they can act as charge carriers and therefore graphite can conduct an electric current.

Silica

Silica or silicon dioxide (SiO_2) is similar to diamond. It occurs as quartz, the mineral in sand. Like diamond, it forms a large giant covalent structure or macromolecule.

Silicon dioxide	Quartz crystal
	

Each silicon atom bonds covalently to four oxygen atoms, and each oxygen atom bonds covalently to two silicon atoms. The result is a very hard substance with a melting point of 1710°C. There are also no free electrons in the structure, so that silicon dioxide does not conduct electricity.

ACTIVITY 1

1. Match properties, A, B, C and D, with the numbers 1– 4 in the sentences.

    A hard
    B resistant to corrosion
    C easily shaped
    D brittle

Iron from the blast furnace has few uses because it is . . . 1 . . .
A low carbon steel is used to make wire because it is . . . 2 . . . .
A high carbon steel is used to make hammers and chisels because it is . . . 3 . . . .
Stainless steel is used to make cutlery because it is . . . 4 . . . .

ANSWERS ON PAGE 139

Properties of metals; metalloids and non-metals

Metals are shiny solids which are good conductors of heat and electricity. They can be hammered into shape (malleable) and they can be drawn into long threads (ductile). Some are magnetic.

Metalloids have properties of both metals and non-metals. They are solids at room temperature but are neither malleable nor ductile.

Non-metals are dull (lack lustre), brittle and are good insulators.

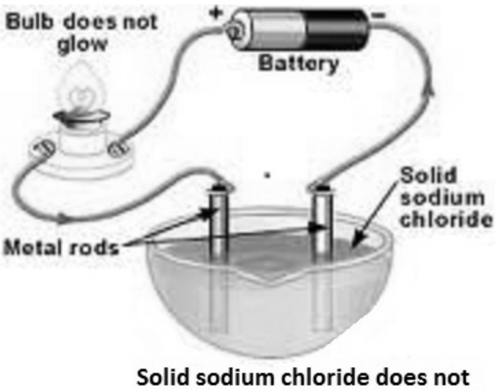
A few physical properties can be summarised in the following table:

Physical properties	Definitions
strength	how it resists transformat ion
thermal conductivity	if it is a conductor of heat or not
electrical conductivity	if it is a conductor of an electric current
water resistance	can it absorb water or not
brittle	how easily it breaks (splinters)
malleable	how easily it can be hammered into different shapes
ductile	how easily it can be stretched into long wires
magnetic	if it attracts certain metals or not

The following table indicates the reason why metals demonstrates the properties above:

Properties	**Reason**
metallic glow	The sea of delocalised electrons (free moving valence electrons) can reflect light and thus causes a shiny surface
conductors of electricity when solid and melted	The sea of delocalised electrons can move freely and act as charge carriers in solid or melted phases
good conductors of heat	The sea of delocalised electrons act as carriers of heat.
malleable	The atoms, even though tightly bonded together, can glide across each other, which allows the metal to bend or stretch.
high density	The atoms of metals in the soild phase are densely packed in the metal lattice.

Electrical conductivity of materials



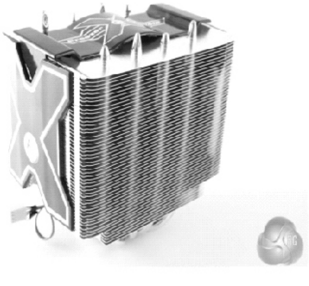
Solid sodium chloride does not conduct electricity

Materials which conduct an electric current when they are placed in a circuit are called electrical conductors. In the circuit above, NaCl must be molten in order to conduct and electric current. The reason for this is that electrons are 'free' to move. Materials can be tested for their electrical conductivity by setting up a circuit consisting of an ammeter (or torch bulb) connected to a battery and the substance you are testing.

All metals are good conductors of electricity. Non-metals do not conduct electricity. Carbon is the only non-metal that conducts an electric current. We say that non-metals are insulators.

Thermal conductivity

'Heat' is a form of the internal energy of substance due to the kinetic energy of motion of its molecules or atoms. If a slower moving particle, A, bumps into a faster moving particle, B, A will lose some kinetic energy and B will gain that energy. 'Heat' is the energy that is transferred from one particle to another because the two particles have different kinetic energies.

	A heat sink is an essential component for cooling high-power integrated circuits. This heat sink is a combination of aluminium fins and copper heat pipes for cooling high-heat-dissipation processors.

A heat sink is used in a computer to allow heat energy to transfer from heated circuits through metals (aluminium and copper). Metals are good conductors of heat and electricity.

In thermal conduction, there is a transport of thermal energy from one region of a hot body to another region of the same body that is at a lower temperature. This means that thermal conduction takes place in the direction in which the temperature decreases. It therefore tends to equalise the temperature within the body.

Engineers apply knowledge of thermal conductivity in designing a number of items, including cooking utensils, heating systems, buildings, bridges, plastics, mechanical devices, food processing technologies, and so on.

ACTIVITY 2

Testing materials for their thermal conductivity.

Suggested materials: Wood; ceramic; porcelain; plastic; aluminium; copper

Method: Place a wax blob at the end of each rod made of the above materials. Each material should be heated at the other end. The time and temperature should be recorded and compared. The test can show the rate at which the wax blob melted on different metals. The metal with the shortest duration of melting the wax blob qualifies as the best conductor.

Results:

1. Rank the materials in order of best conductor of heat to worst conductor of heat.

ANSWERS ON PAGE 139

ACTIVITY 3

A technician tests the properties of different materials used for making kitchen equipment.

The table shows the properties of some materials she tested.

Material	*Hard*	*Malleable*	*Brittle*
A	yes	no	yes
B	no	no	no
C	yes	yes	no
D	no	yes	no

1. Which material, A, B, C or D, is likely to be a ceramic? Give **one** reason for your answer.

2. Which material, A, B, C or D, is likely to be a metal? Give **one** reason for your answer.

3. The technician finds that copper is the best metal for making electrical wiring and saucepans. Give a reason why.

composite material : *natural material with separate layers in final product*

4. Other materials tested by the technician include: aluminium, glass, plywood, polyvinyl chloride (PVC), marble.

   a. Which of these materials can be used straight from the ground?
   b. Which of these materials is a composite?
   c. Which of these materials is a polymer?

ANSWERS ON PAGE 139

Other types of materials

Ceramics

When ceramics are hit by a hammer, they will shatter and break. People use ceramics to make pots, ornaments and tiles. Ceramic objects are made of clay and they hardened by heating them.

Today, ceramics play an important role in the search for materials that can resist thermal shock or act as abrasives. They are used for nose cones in missile and rocket nozzles, and ceramic tiles are used for to protect the Space Shuttle on re-entry through the Earth's atmosphere.

Ceramics made from uranium dioxide are being used as the fuel elements for nuclear power plants and are also used as laser materials and in permanent magnets and computer memory.

Concrete

Concrete is referred to as a composite material. It shatters when hit by a hammer. It is made out of sand, gravel, cement and water. When water is added to the sand, gravel and cement, crystals in the cement will start to form.

These crystals lock together. This makes concrete very strong and hard. But since concrete is made out of crystals, it is quite easy to break. The crystals are strongest if the concrete is allowed to dry out slowly. That is why it is a good idea to wet concrete with water for several days after it has been made.

Polymers

Plastic is an example of a polymer. Polymers are formed from long chains of carbon atoms. Plastic will not shatter when hit by a hammer. The atoms are held together by strong covalent bonds. Generally polymers are bonded in such a way that their bonds can stretch or bend and do not break easily.

Wetsuits are made from a thin type of polymer, called neoprene. People participating in water sports, such as scuba diving, surfing and windsurfing, use wetsuits for thermal protection. The garment forms a barrier that prevents body sweat from evaporating and taking the body's heat with it. Neoprene is a synthetic rubber containing bubbles of nitrogen gas. Nitrogen gas has a low thermal conductivity, which helps further to prevent heat loss.

ACTIVITY 4

Four classes of materials are listed below:

METALS	CERAMICS	GLASS	PLASTIC

Choose the class from the list above, to which the following belong.

1. _____________ can be bent, melts easily, can be shaped and does not conduct electricity.

2. _____________ is strong, hard, can be bent and is a good conductor of both heat and electricity.

3. _____________ is hard, opaque, strong when pressed together, but weak when stretched out. It is brittle.

opaque:
cannot see through

ANSWERS ON PAGE 140

ACTIVITY 5

Learning the skills necessary for an investigation

Scientists ask questions: Why? Where? When? Who? What? Which?

Scientists use **scientific methods** to understand the things happening around them. They have ideas which they want to test. They have predications about what they think will happen. It is the process of thinking through the possible solutions to a problem and testing each possibility to find the best solution.

The scientific process involves the following steps:

- research
- problem
- hypothesis or aim
- project experimentation
- project conclusion

Throughout the process you are also continually redoing, improving, reassessing and researching.

Hypothesis

An hypothesis is an idea about the solution to a problem, based on knowledge and research.

It is a single statement that you think is correct, but need to test. A hypothesis is an educated guess. It attempts to suggest an answer to a problem. A hypothesis is more than an inference because it **predicts** a result and suggests a way of testing it. The hypothesis should make a claim about how two or more factors relate.

All your experimenting will be performed to test the hypothesis.

Example: To test factors influencing temperature.

You will need:

- two cups of hot tea
- a teaspoon
- stopwatch
- thermometer

You suspect that a cup of tea gets colder more quickly if you leave the teaspoon in the cup. Set up the experiment and then answer these questions.

1. What is the hypothesis that you are testing?

   A cup of tea gets colder more quickly if you leave a teaspoon in it.

dependent variable: *variable that is measured*

independent variable: *variable that is changed*

2. If you were to do a risk assessment for the experiment, identify anything that could be dangerous and what you would do to reduce the risk.

   The water may be too hot, therefore maybe test water with a thermometer before putting your finger in it.

3. What is the dependent variable?

   temperature (which is measured every two minutes)

4. What is the independent variable?

   time

A control is an experiment set up exactly as the other experiment without changing any of the variables.

5. Which of the cups is the control?

   The cup without a teaspoon.

6. Justify whether or not you think the experiment is a fair test.

   The experiment is fair as type of cups are the same as well as initial temperature of water and time interval for taking measurements.

A fair test means that only the two variables will be changing and all other variables will be kept constant.

COMMENT

Some solids are made up of crystals while others are made up of long chains of molecules called polymers. Some solids can conduct heat as well as electricity; some solids are soft and hard; and some break easily. Some of these properties are macroscopic, while others are microscopic.

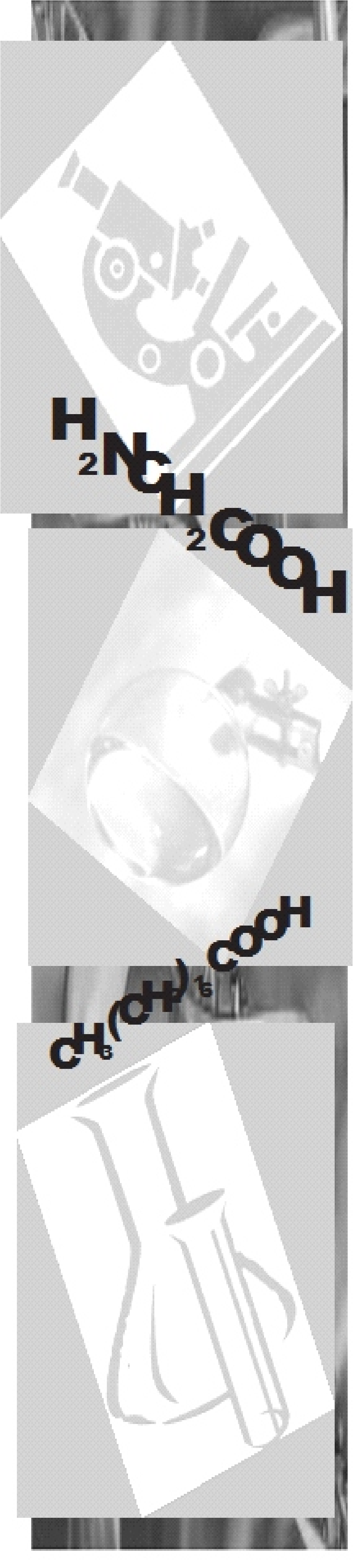
CHECKLIST

Are you able to:

☐ differentiate between different kinds of solids
☐ explain how solids can conduct heat and electricity
☐ discuss hard and soft solids
☐ explain some of the macroscopic and microscopic properties of solids
☐ identify different kinds of materials.

LESSON 9

Designer materials



About this lesson

Over the years, materials have been designed to improve the way we live, our performance in sport and our achievements in technology. With these advancements in material design we understand the need to research the properties of many different types of materials and to achieve stronger and more durable material which will suit the needs of many sectors of society.

In this lesson you will:

- find out the meaning of 'nano’
- find out how humans mimic nature to develop materials of different strengths
- learn how the flexibility and strength of a material affects its use
- discover how nanomaterials are used
- find out about 'energy bands' and how they are formed
- understand how energy bands explain conduction of electricity in semi-conductors.

This lesson involves the relationship between different elements and their reactivity and extended use in industry, technology and medicine to name a few. Their uses rely largely on the properties of the element and its reactivity.

Metal corrosion in the human body, and replacements:

The majority of medical implant devices are made of metal alloys. These are derived from three material systems: stainless steel, cobalt-chromium based alloys, and titanium alloys.

Concerns arise owing to the following factors:

1. Corrosion of the metal: because of the high temperature of the body and the salt content of body, electrochemical reactions occur, where metals which are reactive, corrode easily.
2. Strength of the metal.
3. Weight of the metal.

In order to ensure the functioning of the alloy, it is treated beforehand and coated, to minimise corrosion. The material is also tested for strength and durability.

Corrosion is one of the major issues resulting in the failure of biomedical implant devices. In clinical terms, the biggest improvements could be made by better material selection, design, and quality control to reduce, or possibly eliminate, corrosion in implant devices.

ACTIVITY 1

1. Metals are a very useful type of material because they are malleable and good conductors. The chemical industry uses metals to make many types of alloys. Some alloys of steel are shown in the table on the next page.

Alloy	*Made from*	*Properties*
mild steel	99.8% Fe, 0.2% C	easily pressed into shape
high carbon steel	98% Fe, 1.7% C, 0,3% Mn	hard but brittle
manganese steel	85% Fe, 1.2% C, 13.8% Mn	very hard
stainless steel	74% Fe, 0.3% C, 18% Cr, 7.7% Ni	rust resistant

a. Choose, giving a reason, the alloy you would use to make
   i. car bodies.
   ii. hip replacement joints.

Steel workers are also very familiar with the different types of steel.

b. Write down the symbols for the elements in mild steel.
   Iron
   Carbon

c. Which two elements are present in all types of steel?

d. Name an element that helps to make steel rust resistant.

e. Name the only non-metal in the table.

f. State two properties of non-metals.

g. The steel workers are asked to make steel for kitchen sinks. State which alloy of steel they will produce. Give one reason for your answer.

ANSWERS ON PAGE 140

Lightweight materials for bicycles, airplanes and sport equipment:

Carbon fibre and aluminium are newer and increasingly popular substitutes for the original bicycle frame material, steel. In the early 21st century, carbon fibre gained a reputation for being lightweight and the latest frame technology, but advancements in aluminium alloys and frame construction make the two frame materials equal contenders for best material.

Yield Strength, Ultimate Strength, and Elasticity Activity

When a bicycle maker chooses a material to make a bicycle frame, he or she usually considers the following properties of the material.

Elasticity: When an object responds to bending or stretching by returning to its original shape, it is said to have a high level of elasticity.

A material which bends and then holds the bent shape has very little elasticity.

Yield Strength: This is the amount of the force needed to bend a material to a point where it cannot return to its original shape.

Ultimate Strength: This is the amount of force needed to break a material. This is the point at which a bicycle frame breaks apart, usually with dangerous consequences for the rider.

ACTIVITY 2

What You'll Need:

- a plastic comb
- a rubber band
- a Bic ballpoint pen
- a pencil
- a paper clip

A wooden pencil can be surprisingly flexible.

Do you have a broad, thick pencil? You'll find it's much harder to bend or break than an ordinary pencil.

Method:

Try bending and stretching the various objects.

a. Which material do you think has the greatest elasticity?
b. Which has the least?
c. Which has the greatest yield strength?
d. Which has the least?
e. How about ultimate strength?

Decide which material would be good for a bicycle frame, based on strength and elasticity.

What's Going On?

This folding bicycle has a very large diameter top tube, which helps give the bicycle strength.

The various materials used for bicycle frames are in many ways similar to the materials you've used here. Steel, like the paper clip, has good ultimate strength, with much lower yield strength. This is good, since it means that a steel frame will bend well before it breaks, lessening the chance of a disastrous crash. Unlike the paper clip, steel used for bicycles has pretty good elasticity. This combination of properties has made steel a long-time favourite of frame builders. Steel's only drawback is its relatively high weight.

Aluminium has recently become a choice material for frames, because of its very light weight. However, aluminum has yield strength very close to its ultimate strength. In other words, it is quite brittle, and prone to breaking. This has many dangerous consequences for the rider of an aluminum bike, so frame makers have responded by over-building aluminum bikes with very large tubes and thick welds, to lessen the chance of frame breakage and make the frame stronger.

The wooden pencil has properties similar to aluminum: light weight, high strength, and brittleness. Wood, like aluminum, will only bend slightly before breaking.

Other materials, like carbon fibre and titanium, are similar in qualities to the plastic comb and pen: light weight, high elasticity, high ultimate strength, relatively low yield strength. This means that frames made of these materials need to be designed well, in order to be stiff enough to resist pedalling forces. It also means that such frames are extremely light and resilient.

However, these materials are extremely expensive, putting carbon-fibre or titanium frames out of reach for all but the wealthy or the professional racer.

ACTIVITY 3

1. Over time the design of badminton racquets has changed so top players can improve their performance. Read about how badminton racquets have changed over time.

Badminton racquets are lightweight, with top quality carbon fibre racquets having a mass of 90 g. Earlier racquets were made of wood. Wooden racquets are no longer made because of their larger mass (240 g). Also, unlike wooden racquets, which warped, cracked and dried out with age, carbon fibre racquets can last for many years. Carbon fibre racquets transfer more kinetic energy to the shuttlecock than wooden racquets.

Use the information above to answer the questions that follow.

a. State three ways in which carbon fibre racquets are different from wooden racquets.

b. Complete the sentence by underlining the correct word in the brackets.

Carbon fibre reinforced plastic is a
(ceramic / polymer / composite)

c. Find the density of carbon fibre if the volume of the racquet is 60 cm^3, using the following equation:

$$\text{density} = \frac{\text{mass}}{\text{volume}}$$

2. Manufacturers of sporting equipment use different types of materials.

The soles of high performance athletic trainers are made from polymers.

Write down, from the list below, three properties of polymers.

- low density
- high tensile strength
- flexible
- hard
- poor conductor
- high density

3. The modern pole used in pole vaulting is made from fibreglass. They used to be made of solid wood.
   Give two advantages of using fibreglass instead of wood.

4. The diagram shows a golf club which has three parts, a head, a shaft and a grip.

Some of the materials, and their properties, used in making golf clubs are shown in the table below. Sales people in a golf shop know about these properties so they can advise golfers about which clubs are suitable.

Material	Density g/cm^3	Strength N/m^2	Hardness	Flexible
wood	0.7	240	soft	snaps
steel	7.9	600	very hard	stiff
rubber		17	soft	
titanium	4.5	620	medium hardness	stiff

The original golf clubs were made from wood but modern ones are made from metal. Use the information in the table to:

a. Give one advantage and one disadvantage of wooden golf clubs.
b. Explain why titanium is a good material for the shaft but not for the head.
c. The rubber used to make the grips is supplied in pieces of mass 1800 g and volume 2000 cm3.
   Use the equation

$$\text{density} = \frac{\text{mass}}{\text{volume}}$$

to calculate the density of the rubber.

5. Two types of materials are metals and polymers. They have different properties. Draw lines to join the types of material to their properties.

Metal

Polymer

High strength

Low density

Hard

Poor conductors

6. Designers of some sporting equipment have to consider the effects of friction. One sport in the winter Olympics is the skeleton bob.

At the start of the race, the competitor must sprint on ice.

a. Give one reason why the competitor wears spiked shoes.

b. Why is the helmet streamlined?

c. Why is making the bodysuit from Lycra an advantage?

7. Designers decided to make the base of the skeleton bob from fibreglass instead of steel. State one advantage of using fibreglass.

ANSWERS ON PAGE 140

Spider webs

We call any material that is made from chemicals, synthetic material. Since the 1900s, more and more of the materials that we use everyday are synthetic.

In modern times, the manufacturers who produce synthetic fibres use the word ‘spinneret’ for the machine that forms filaments of synthetic fibre. ‘Post-spin’ is a step where silk molecules are stretched by a mechanical actuator to increase fibre strength. These mechanical improvements produce uniform spider silk and remove human error from the spinning process. As a result, the synthetic silk is much closer to the natural fibres produced by the female black widow spider than what was previously possible, and the procedure provides a scalable ground work to utilize spider silk in material manufacturing.

Owing to their mechanical properties, synthetic spider silks have numerous manufacturing and industrial applications. Of particular interest is the high tensile strength of black widow silk, which is comparable to **Kevlar** in strength, but is lighter and of a lower density. If scientists could reproduce the mechanical properties of spider spun silk in the laboratory, the material could be used to replace Kevlar, carbon fibre and steel. Increased production of this new biomaterial will have an impact on a wide variety of products where spider silk's properties are valuable, ranging from bulletproof vests and aircraft bodies to bridge cables and medical sutures.

Kevlar is a material formed by combining para-phenylenediamine and terephthaloyl chloride. Aromatic polyamide (aramid) threads are the result. They are further refined, by dissolving the threads and spinning them into regular fibres. When woven, Kevlar forms a strong and flexible material. If layers of the woven Kevlar are combined with layers of resin, the resulting material is light and has twenty times the strength of steel. It is also superior to specialist metal.

Other materials that are designed for a specific purpose

Many materials are manufactured today from a long chain of organic molecules. These are referred to as polymers. Nylon is an example of a polymer. It does not occur in nature, but has to be synthesised in a laboratory. It is the first synthesised fibre. Nylon is made from petroleum, the crude oil that we use to make petrol, natural gas, air and water.

In the 1930s, it was the fashion for women to wear very short dresses, so women always wore silk stockings. But silk stockings were very expensive. Chemists tried to find a substitute for silk. A chemist, Wallace Carothers, did much research and experimentation in an effort to design a material that could behave like silk, but would cost much less. He succeeded, and called his designer material 'nylon'. Nylon is also used to make parachutes, which is significant because of the strength and durability of the material.

You have probably had the experience of cooking food in a pot and finding that the food sticks to the pot. It is then a big nuisance as the pot is difficult to clean! This problem was solved by the manufacture of 'Teflon'.

'Teflon' is the trade name for polytetrafluoroethene, an organic compound and also a polymer. It is a tough, wax-like heat-resistant material. Manufacturers use it to coat pots and pans because it prevents food from sticking to these items of cookware. Teflon is also used to coat the gaskets and bearings of a motor car. When you buy a pot that is advertised as 'non-stick', you can be sure that the pot is coated in Teflon.

ACTIVITY 4

The table below shows some of the properties of six important plastics:

plastic	relative strength	flexibility	max temp for use (°C)	resistance to dilute acids	resistance to oils	cost (R per kg)
high density polythene	4	fairly stiff	150	excellent	good	12
low density polythene	1	very floppy	70	good	good	10
perspex	9	stiff	90	good	good	23
polycarbonate	9	stiff	140	excellent	excellent	45
PTFE	30	fairly flexible	250	excellent	excellent	900
urea formaldehyde resin	9	very stiff	75	poor	good	13

For each of the following, decide which of the above plastics would be best suited for the task and explain your choice

a. wrapping cheese
b. coating frying pans
c. handles of screwdrivers

ANSWERS ON PAGE 141

Nano-materials

The meaning of 'nano'

'Nano' comes from Mathematics. If a measurement is, for example, 8 X 10^{-9} m, then we can say that this number is 8 nanometres'. (Nano means X 10^{-9}.)

'Nano technology' is the science of the building of devices that are almost as small as molecules. An example is a 'nano-robot' that is so small that it can travel through the bloodstream of a human into the organs of the body. This little robot can then inspect and also remove diseased tissue from the body.

It is possible that these little robots may one day be able to correct most diseases and even repair aging cells!

Nanoscience involves the study of very small particles.

ACTIVITY 5

1. Nano-sized silver particles have antibacterial, antiviral and antifungal properties, so they are used:
   a. to coat self-cleaning windows,
   b. to coat the inner surface of refrigerators,
   c. in suncreams,
   d. in sterilizing sprays to clean operating theatres in hospitals,
   e. to wash test tubes in a chemistry laboratory.

2. Read this passage about metals.

   Metals are crystalline materials. The metal crystals are normally about 20 000 nm(nanometres) in diameter. The atoms inside these crystals are arranged in layers. A new nanoscience process produces nanocrystalline metals. Nanocrystalline metals are stronger and harder than normal metals. It is hoped that nanocrystalline metals can be used in hip replacements.

The use of nanocrystalline metals should give people better hip replacements which last longer.

a. State why metals can be bent and hammered into different shapes.
b. How is the size of the crystals in nanocrystalline metals different from the size of the crystals in normal metals?
c. Hip joints are constantly moving when people walk. Suggest and explain why the hip replacement made of nanocrystalline metal should last longer than one made of normal metals.

ANSWERS ON PAGE 141

3. Read the article and then answer the questions that follow.

Nanotennis!

Tennis balls contain air under pressure, which gives them their bounce. Normal tennis balls are changed at regular intervals during tennis matches because they slowly lose some of the air. This means that a large number of balls are needed for a tennis tournament, using up a lot of materials.

'Nanocoated' tennis balls have a 'nanosize' layer of butyl rubber. This layer slows down the escape of air so that the ball does not lose its pressure as quickly. The 'nanocoated' tennis balls last much longer and do not need to be replaced as often.

a. How does the 'nanosize' layer make the tennis balls last longer?
b. Suggest why using 'nanocoated' tennis balls would be good for the environment.

Semiconductors

Semiconductors are crystalline materials with an electrical conductivity that is between that of metals (good) and insulators (poor). Semiconductors are useful because we can improve their conductivity by adding minute amounts of different substances to the crystalline material. One of the most important semiconductors is silicon.

Silicon has a poor conductivity at low temperatures, but if we increase the temperature, apply light, or increase the voltage, its conductivity improves.

Silicon is useful because we can use it in transistors and computer chips. One of the most useful applications of a semiconductor is in a cell phone.

We explain how a semiconductor works by using a theory called the 'band theory'.

Silicon is neither a good conductor of electricity nor a bad one. Its conducting ability is somewhere between that of a good conductor, like copper, and that of an insulator, like glass, wood, plastic and porcelain.

Semiconductors do not conduct electricity in the same way that ordinary conductors do, for example copper.

Semiconductor materials

Semiconductors are special because it is easy to control how current passes through them. They are made up of a limited number of free and mobile charged particles. The best known semiconductor is silicon. We use silicon to make a 'silicon chip'. Germanium is also a good semiconductor.

A semiconductor has a natural conduction, like that of an ordinary metal, which we call 'intrinsic conduction'. It also has an artificial extra conduction ability that is due to impurities that the manufacturer adds. We call this conduction 'impurity conduction' or '**extrinsic** conduction.'

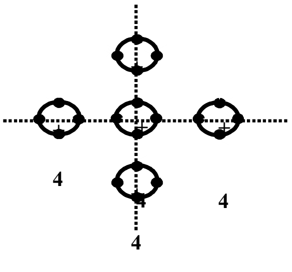
extrinsic:
does not belong to

We call this material the '**n**-type' conducting material because the main contribution to its conductivity comes from the mobile electro**n**s.

n-type semiconductors

In the solid phase, silicon forms a three-dimensional crystalline structure in which each atom has four near 'neighbours'. The diagram below shows you this plan in two dimensions.

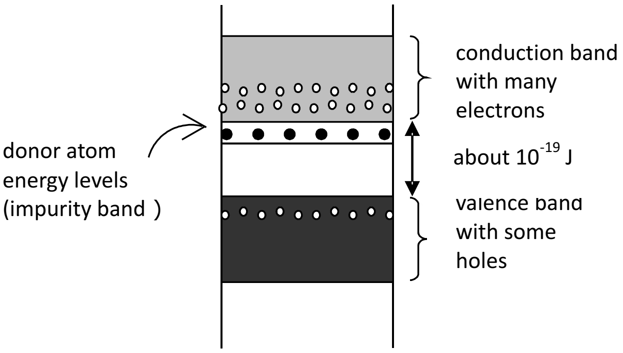
All of the silicon valence electrons are involved in forming covalent bonds.



Any one positive core shares its four valence electrons, one with each of four near neighbours.

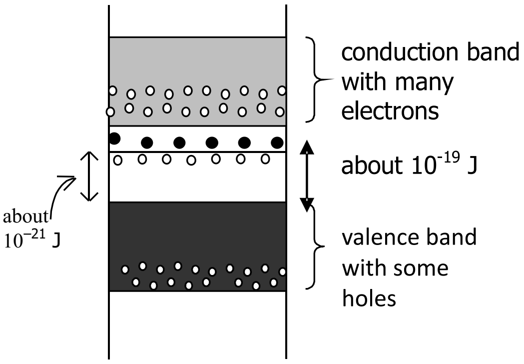
The band theory of semiconductors

n-type: Study the diagram below:



n-type impurity conductor

p-type: Study the diagram below:



p-type impurity semiconductor

One of the main reasons that silicon is so popular as a semiconductor is that we can heat it to high temperatures without it losing its material properties. This means that engineers can be sure that it will perform according to their plans, even under extreme conditions.

ACTIVITY 6

1. Choose the correct answers:

   i. In a semiconductor, conduction takes place by:
      a. the motion of free electrons;
      b. electrons and positive holes;
      c. electrons and negative holes;
      d. electrons jumping into higher energy levels.

   ii. A semiconductor is a crystalline material with an electrical conductivity between that of metals and insulators. Its conductivity is improved by:
      a. cooling;
      b. heating;
      c. adding a computer chip;
      d. compressing it.

A 'pentavalent' atom has a valency of 5, i.e. it can share 5 electrons with another atom or atoms.

The technician then adds in 'donor impurities'. These are pentavalent atoms, such as those of antimony, arsenic and phosphorous. Only four of the valence electrons are needed to bond with a silicon atom. The fifth valence electron then bonds weakly to the parent silicon atom. This bonding is so weak that this electron becomes mobile very easily. And it is this 'spare' valence electron that is responsible for the conductivity of silicon.

p-type semiconductors

Trivalent atoms, for example those of aluminium, boron and indium, have **three** valence electrons. However, **four** valence electrons are needed to complete the covalent bonding with a silicon atom.

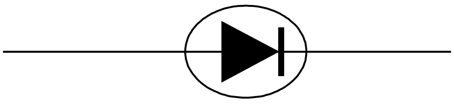
If the technician uses these elements to make a semiconductor, there will be a vacancy at each point of the crystal lattice. This acts a positive hole. Less energy is needed for this hole to capture an electron from an adjacent silicon atom that is required for an electron to break out from a location at which there is a positive charge.

We call this kind of conducting material, the '**p**-type'. This is because the main contribution to its conductivity comes form the mobile **p**ositive holes.

We call the trivalent material an 'acceptor' impurity, since it accepts electrons from the lattice atoms to fill the vacancies it creates. We call the 'holes' the 'majority' carriers because there will always be some electron conduction in them. In a p-type material, we call the electrons the 'minority' carriers'.

When an n-type and a p-type semiconductor are combined we obtain a diode. A diode is an electronic device that restricts current flow chiefly to one direction.

A light-emitting diode (LED) is a semiconductor light source. LEDs are used as indicator lamps in many devices and are increasingly used for other lighting.



Corresponding symbol for this diode

2. Light-emitting diodes (LED's) are used in applications as diverse as replacements for aviation or automotive lighting.
   a. Name one other use of LEDs.
   b. In spite of LEDs being currently more expensive on an initial capital cost basis than most conventional lighting technologies they are still preferred to incandescent light bulbs. Give two reasons for this.

3.

> When we think of electronics, we think of semiconductors. Essential electronic devices, such as diodes and transistors, are combinations of n-type and p-type semiconductors. You might have wondered why we use semiconductors, since metals appear to be by far better conductors.
>
> [Extract adapted from Radmaste 2007]

Give **one** reason why semiconductors, and not metals, are used as conductors in electronic components such as diodes.

ANSWERS ON PAGE 142

COMMENT

Humans strive to mimic nature in their quest to develop useful materials of varying strength and flexibility. Of particular significance is the use of semiconductors to exploit the potential of energy bands.

CHECKLIST

Are you able to:

☐ explain the meaning of the prefix 'nano'
☐ discuss some of the ways in which humans copy nature to develop materials
☐ explain how the flexibility and strength of a material affects its use
☐ describe energy bands and explain how they are formed
☐ discuss the function of energy bands in semiconductors.

Answer section

Lesson 1

Activity 1

1. Total mass before reaction = 40 g + 36 g = 76 g
   Total mass after reaction =72 g calcium sulphide + 4 g (sulphur left over) = 76 g
   The total mass after the reaction = the total mass before the reaction.
   Thus the total mass is conserved and this illustrates the Law of Conservation of Mass

2. Total mass before reaction = 40 g + 16 g.
   $\therefore$ mass of calcium oxide = 56 g

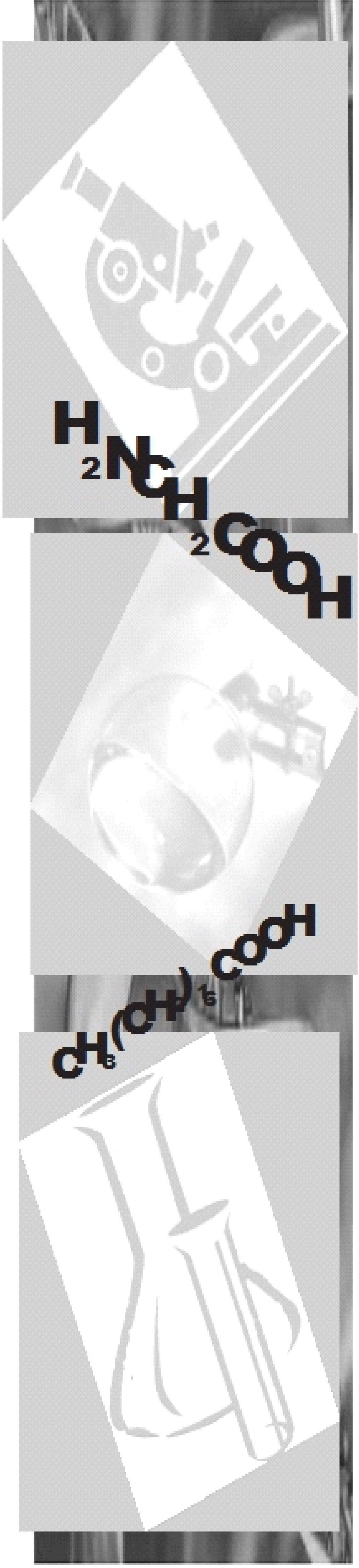
3. Mass before reaction = mass of magnesium + 32 g of sulphur = 56 g of magnesium oxide.
   $\therefore$ mass of magnesium used up = 56 g − 32 g = 24 g

4. Total mass of product = 40 g
   Total mass of reactants = 24 g magnesium + mass of oxygen
   = 40 g magnesium oxide
   $\therefore$ mass of oxygen = 40 g − 24 g = 16 g

5. Mass ratio H:O = 1:8. Therefore $\frac{1}{9}$ of total mass of product is hydrogen and $\frac{8}{9}$ is mass of oxygen.
   $\therefore$ mass of hydrogen used up = $\frac{1}{9} \times 36$ g = 4 g
   $\therefore$ mass of oxygen used up is $\frac{8}{9} \times 36$ g = 32 g.
   (or you could simply subtract 4 g from 36 g)

6. Chemical (A new substance is formed).

7. Physical. It involves a phase change (solid to liquid) without a chemical reaction. The end product remains as water.



Activity 2

a. i. A macroscopic diagram shows us what we see with our own two eyes. A microscopic diagram shows us what we would see if we had a **very** powerful microscope that could make what we are looking at very many times bigger.

ii. Atoms are singular. Molecules are two or more atoms combined. Atoms are not bonded. Molecules are atoms bonded to each other.

b. Molecules are not all the same size. This is because they are made of atoms, and the sizes of atoms are different.

c. 'Dioxide' means that a sand molecule is made up of two ('di') atoms of oxygen (and another atom).

d.

Mixture	Compound
1. substances mixed in any ratio	1. atoms combined in fixed ratio. FeS
2. substances do not combine chemically	2. atoms are chemically combined to each other
3. substances can be separated by physical means	3. substances can not be separated by physical means

e.
- pure honey-mixture
- pure tomato juice-mixture
- iron ore-mixture
- magnesium sulphide-pure (compound)

Lesson 2

Activity 1

a. Opposite charges attract each other.

b. An electron is a very tiny, negatively charged particle that is part of an atom. A cathode is a negatively charged electrode. It is usually a metal connected to the negative terminal of a battery.

c. Positive and negative charges attract each other. So the positively charged anode could attract and so pull loose, electrons from the cathode.

d. We call it the cathode. Cathode rays are made of electrons.

e. Dalton's atom is that of a solid sphere. His theory could not explain why atoms combine with each other in fixed ratios or why their chemical and physical properties differ.

Activity 2

Dalton's model was referred to as the ‘Billiard ball’ model. Thomson's was called ‘plum pudding’ or ‘current bun/raisin bun’ model. Dalton considered the atom as a solid. Thomson considered it as a sphere with positively and negatively charged particles. Dalton's model contained no sub-atomic particles. Thomson's model contained particles evenly present (positive and negative).

Activity 3

a. Evidence 1: alpha particles, which are positively charged, were repelled by the nucleus. Thus the nucleus has a positive electrical charge.
   Evidence 2: electrons, which are negatively charged, move around the nucleus.
   Evidence 3: rutherford knocked positively charged particles out of nitrogen nuclei.

b. Rutherford knocked small positively charged particles (protons) out of atoms in 1919.

c. In the ‘Scattering experiment’, a few of the alpha particles bounced back in the direction they had come from. So something small, with a positive charge, was repelling them. Also, only a few alpha particles bounced back. Thus there had to be a small region of positive charge, that Rutherford then called the nucleus.

Activity 4

1. b. negatively charged

2. a. 6
   b. nucleus
   c. number of protons are equal to the number of electrons.
   d. carbon with 6 protons; 6 electrons and 7 neutrons
   e. 12 (protons +neutrons)

3. a. 11
   b. around the nucleus
   c. neutrons

4. If the electrons were to spiral into the nucleus, then all atoms would become smaller and smaller. We would then see all objects becoming smaller and smaller. This does not happen!

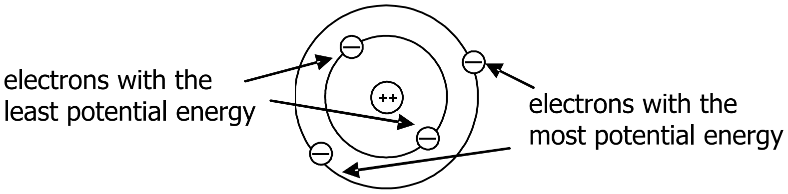
Lesson 3

Activity 1

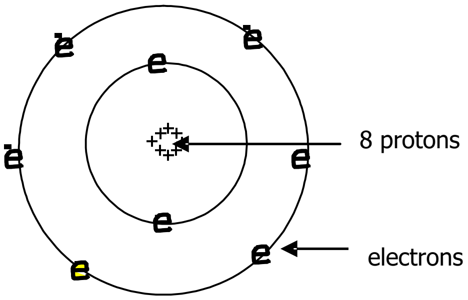
1. The nucleus is positively charged. So the electrons would be attracted to it and so fall into the nucleus.

2. Democritus' uncuttable atom; Dalton's solid sphere; Thomson's Raisin Bun model (1897); Rutherford's Nuclear model of 1911; Rutherford's model with protons (1911) and Bohr's planetary model (1918).

3.



4.



Activity 2

1. The potential energy of an election increases as its distance from the nucleus increases.

2. a. An electron has the most potential energy at the place where it is furthest from the nucleus, and
   b. the least amount of energy when it is nearest the nucleus.

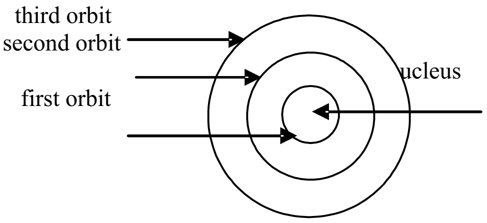
3. From the left to the right: Dalton (early in 1800); Rutherford (1911); Bohr (circa. 1918).

Activity 3

1. Number is 2 + 8 + 18 = 28

2. Ca - 2e lost; Li Li+1 ; Mg 2e lost

3. The correct missing words are:
   a. two; pair;
   b. eight; four
   c. 2(3)2 = 18



Activity 4

1. The missing words are:
   a. proton number;
   b. attracted; negatively; positively

2. a. Atomic number = 88;
   b. An atom of radium is made up of 88 protons.
   c. Its mass number is 226.
   d. The nucleon number is 226.
   e. There are 226 −88 neutrons in one atom of radium = 138.
   f. The number of electrons that make up on atom of radium is 88.
   g. No.

Activity 5

a. Lithium and sodium
b. One. It has a lower first ionisation energy so less energy is required to remove the first electron. Therefore it loses one electron only to react.
c. Two
d. Beryllium
e. Magnesium. As it has lower first and second ionisation energy. Therefore it will be more reactive as less energy is required for it to lose electrons.
f. $Mg - 2e\ Mg^{2+}$

Lesson 4

Activity 1

If two electrons are removed, calcium would have 20 protons and 18 electrons and would form an ion with a double positive charge, written as Ca^{2+}.

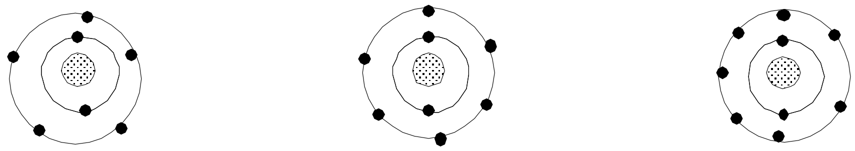
Activity 2

1. Look at Table 1 on page 42. The first ionisation energy of sodium is 494 and the second ionisation energy is 4563. If you divide 4563 by 494, you get 9.2. In other words, the second ionisation energy is more than 9 times bigger than the first ionisation energy.

So the second electron is 9 times more difficult to remove. This is a big jump. Similarly for potassium. The second electron is 7 times more difficult to remove, another big jump (check this calculation yourself). So for both Na and K there is a big jump for the second electron. This shows a change in energy level. So both sodium and potassium have one electron in the outer energy level.

2. Look at Table 1. The fifth ionisation energy of nitrogen is 9442 and the sixth ionisation energy is 53253. If you divide 53253 by 9442, you get 5.6. In other words, the sixth ionisation energy is more than 5 times bigger than the fifth ionisation energy. So the second electron is 5 times more difficult to remove. This is a big jump. Similarly for phosphorus. The sixth electron is 3.4 times more difficult to remove, another big jump (Check this calculation yourself). So for both N and P there is a big jump for the sixth electron. This shows a change in energy level. So both nitrogen and phosphorus have five electrons in the outer energy level.

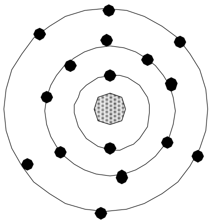
Activity 3



nitrogen oxygen fluorine

Figure 2

Activity 4



sulphur

Figure 3

1. Sulphur has an atomic number of 16. So it has 16 electrons. (See Figure 3.)

2. The electron configuration is 2,8,6.

3. The elements are K (potassium) and Ca (calcium).

4. The atomic number for K is 19 and Ca is 20.

5. Four energy levels contain electrons.

Activity 5

1. Boron (B), aluminium (Al) both belong to group III. They each have three valence electrons.

2. Oxygen needs two electrons.

3. They belong to group VII, the halogens. Examples are fluorine (F), chlorine (Cl), bromine (Br) and iodine (I).

Activity 6

For each of the elements you first need to work out how many valence electrons there are. Check the Periodic Table to see which group the elements are in. aluminium (Al) is in group III and has three valence electrons, chlorine (Cl) is in group VII and has seven, and calcium (Ca) is in group II and has two. An atom of carbon (C) is in group IV and has four valence electrons, so C+ will have one less electron. Notice that we show the + charge in the Lewis diagram.

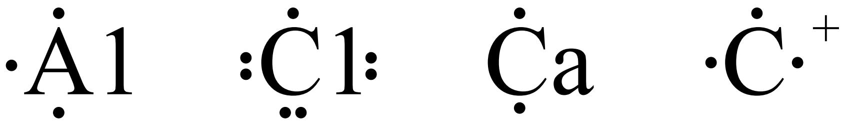


Figure 4

Activity 7

C is in group IV, so it has a valency of 4. F is in group VII, so it has a valency of 8 -7=1. P is in group V, so it has a valency of 8 5 = 3.

Activity 8

1.

Element		Al	S	K
a.	Lewis diagram	2,8,3	2,8,6	2,8,1
b.	See Figure 5.			
c.	No. valence electrons	3	6	1
d.	Valency	3	2 (8 – 6)	1

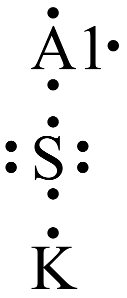


Figure 5

Lesson 5

Activity 1

1. The first figure is 126 C or carbon -12 (atomic number 6 and mass number 12). The second figure is 146 C or carbon –14 (atomic number 6 and mass number 14).

2. a. Atom (a) and atom (i) are isotopes. Atom (c) and atom (l) and (g) are isotopes. Atom (d) and atom (h) are isotopes and atom (e) and atom (j) are isotopes.
   b. (a) and (i) are atoms of the element carbon. (c), (g) and (l) are atoms of the element hydrogen. (d) and (h) are atoms of the element chlorine. (e) and (j) are atoms of the element uranium.
   c. The table shows that some of the atoms are isotopes because they have the same number of protons but different numbers of neutrons and different mass numbers.

Activity 2

1. An α particle consists of 2 protons and 2 neutrons. Every time 2 protons leave the nucleus the atomic number changes and the atom therefore changes into an atom of a different element.

3. β particles and γ radiation, since both these forms of radiation are capable of penetrating skin.

Activity 3

1. A radioactive-isotope of an element is the same as the normal version of the same element, but its atoms have more neutron particles in their atomic nuclei, which can make them radioactive. An example of a useful radioactive-isotope would be Carbon 14, which is commonly used to 'carbon-date' fossils and dead bodies, since that particular isotope of carbon decays in a very simple and predictable manner that can be used to 'date' materials.

2. If a person swallowed or inhaled (breathed in) a substance which was undergoing radioactive decay α and β particles could be emitted inside their body.

$$\frac{232}{90}Th \rightarrow \frac{228}{88}Ra + \frac{4}{2}He$$

3. Here you have to work out what the daughter element will be. You also have to look at the Periodic Table to find the atomic number for radon. Radon has atomic number 88, so the daughter element will have atomic number 86, which is two less than radon (remember, an alpha particle is given off). If you look at a Periodic Table, you will see that this is the atomic number for polonium (Po). You are now able to write the equation because you know that the alpha particle will be a helium ion.

$$\frac{222}{86}Rn \rightarrow \frac{218}{84}Po + \frac{4}{2}He$$

4. $\frac{32}{15}p \rightarrow \frac{32}{16}S + \frac{0}{-1}e + y$

Activity 4

1. Iodine-131 is less stable because it has a shorter half-life. The shorter the half-life, the quicker the atom decays and the less stable it is.

2. a. 23h00 (11pm). (sodium-24 has a half-life of 15 hours so it takes 15 hours for 100g to decay to 50g pure sodium-24. 08h00 + 15 = 23h00).
   b. The atoms of the rest of the block have decayed into atoms of different elements.

3. 125mg. (The half-life of cobalt-60 is 5,3years. So after 5,3years we have 500mg left; after 10,6years we have 250mg left and after 15,9 years we have 125mg left).

4. Cobalt 60. Cobalt has a half-life of 5.27 years and would be intensely radioactive at the same time. Sodium-24 is more radioactive but it would decay faster.

Activity 5

1. Nuclear fission means splitting the atomic nucleus.

2. When an unstable nucleus is hit with a fast moving neutron it splits into nuclei of other atoms (fission products). Neutrons are also released and these hit other nuclei which then split, and so on.

3. The energy comes from the breaking of strong nuclear forces and the conversion of matter into energy.

4. Radiation breaks DNA molecules in the nuclei of cells in the person's body. The DNA molecule's genetic code can be scrambled causing it to reproduce abnormally and form cancer cells.

Lesson 6

Activity 1

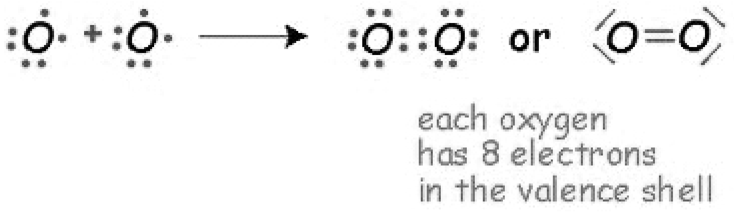
The three substances that you have been asked to identify are water (H_20), quartz (SiO_2) and sodium chloride (NaCl) which is also common table salt. You can see that the substances are actually made up of tiny atoms which have combined to form molecules and larger network structures.

Activity 2

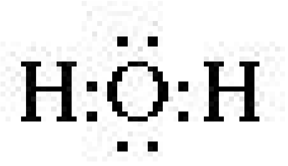
a. Electrical to chemical.
b. There are no free ions in the solid phase. When sodium chloride is molten, the ions can move freely.
c. Sodium and chlorine gas.

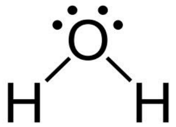
Activity 3

a.



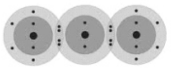
b.





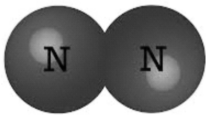
c.

d.



Carbon Dioxide Molecule (CO_2)

e.



Activity 4

1. a. C(δ-) (δ+) H
   b. F(δ-) (δ+) O
   c. no difference
   d. N(δ-) (δ+) H

2.

a) LiI	**polar covalent**
b) Cl_2	**pure covalent**
c) AlF_3	**ionic**
d) BeO	**ionic**
e) H_2O	**polar covalent**
f) Na_2O	**ionic**
g) NaCl	**ionic**

Activity 5

The hanger can easily be bent, so the metal is flexible. The metal also shines when you polish it with a cloth. When you hold the hanger under a candle flame, it gets warm, so the metal is a good conductor of heat. It is also a conductor of electricity.

Activity 6

a. N_2 gas: equal electronegativity of the two N atoms share electrons to form a covalent bond and molecules of N_2.
b. KCl: very unequal sharing of electrons because of strong electronegativity differences resulting in strong attraction between the units and a lattice structure.
c. Cu: electrons delocalised and move around many atoms rather than just their own atom. Form a lattice of metal atoms.

Lesson 7

Activity 1

1. a. SiH_4

   b. The greater the size of the molecule, the higher the boiling point.

   c. No. Oxygen which is in period 2 is bonded to H to form water and it has the highest boiling point.

   d. H_20 liquid; rest are gases as they melt before room temperature and also boil before 25 degrees Celsius.

   e. Water remains liquid for consumption and many other uses. It is also cheaper to find water in this form instead of converting it from any other phase.

2. London forces. London forces are relatively weak forces of attraction that exist between nonpolar molecules and noble gas atoms.

Activity 2

In both cases the liquid rises up the straw or the cloth.

Activity 3

Hydrogen bonding occurs in water because oxygen is highly electronegative (3,5), because it has lone pairs of electrons, and because the molecules of water are highly polar. When water is in the liquid phase, existing hydrogen bonds break as new bonds are being formed. As the water cools down, more and more permanent hydrogen bonds are formed. When permanent hydrogen bonds form, the water molecules are kept further apart so the water actually expands as it cools.

Activity 4

a. You should remember that electrons are not static, they are continuously moving around. At one instant the electrons of the covalent bond in the N_2 molecule may be on one side of the molecule. This leads to a temporary dipole. This temporary dipole can then attract other temporary dipoles and so the molecules bond with temporary London forces. If these forces act on enough of the molecules then N_2 can form a liquid. This only happens at very low temperatures.

b. The key to answering this question is to understand how hydrogen bonds form. In your answer you should speak of the difference in the electronegativity of oxygen and sulphur. You should mention that a strong polar molecule is formed when hydrogen and oxygen bond, but a weaker polar molecule is formed when hydrogen and sulphur bond. You should further mention that the hydrogen atom is very small compared to oxygen. You should also mention the lone pair of the O atom.

c. Water molecules are attracted toward each other. These forces are called cohesive forces. Water is also attracted towards the surface of the tube. This kind of attraction is called adhesion. So the attraction between the walls of the tube and the water molecules pulls them up the tube. Because of the cohesive forces, more water molecules are pulled up in a column.

d. Milk consists mainly of H_2O. Water is one of the few substances that is less dense as a solid than it is as a liquid. Hydrogen bonding between water molecules is the cause of this behaviour. When water is in the liquid phase, the water molecules are constantly moving. Because of the movement of the water molecules new hydrogen bonds are formed as other hydrogen bonds break. Water begins to freeze when water molecules are no longer moving vigorously enough to break the hydrogen bonds. Each water molecule will now bond to a maximum of four other water molecules. In the solid phase, hydrogen bonds keep the water molecules far apart, thus increasing the volume of the liquid. The increased volume of the water can burst the bag (most milk bags today have space in them to let the water expand without bursting the bag.)

Lesson 8

Activity 1

A - 3

B - 4

C - 2

D - 1

Activity 2

copper; aluminium; iron; porcelain; ceramic and plastic and wood

Activity 3

1. A. It is hard but when bent, it is very brittle , it will break

2. C. It is hard and malleable

3. Good electrical conductivity
   Good thermal conductivity

4. a. aluminium
   b. marble; plywood; glass
   c. PVC

Activity 4

1. plastic
2. metal
3. ceramic

Lesson 9

Activity 1

1. a. i mild steel: easy to mold into shapes of cars and features
      ii stainless steel so that there is no corrosion in the body

   b. Fe ; C

   c. Fe and C

   d. Cr

   e. C

   f. do not conduct electricity; brittle

   g. stainless steel. Crockery is constantly washed in water which leads to rusting.

Activity 3

1. a. lightweight and durable, does not warp, crack easily firm surface and shuttlecock moves faster

   b. composite

   c. density = 90/60= 1,5 g.cm^{-3}

2. low density, flexible and a poor conductor

3. flexible, durable and lighter than wood

4. a. lightweight
   not very flexible

b. for the shaft you would need a strong substance for strength. For the head, you would need a more flexible substance to mould into shape.

c. d= 7800/2000 = 0,9 g.cm^{-3}

5. metal: high strength and hard Polymer: low density,poor conductor

6. a. Very smooth surface. Shoes are spiked so that he can get a good grip on the ice.

   b. decrease air resistance

   c. lycra acts as an insulating material against the cold

7. Lightweight and aerodynamic to handle high speeds.

Activity 4

a. LDPE: cheap, floppy like clingwrap

b. PTFE: teflon used for non-stick surfaces: must be able to withstand high temperatures, resistance to oils, very strong

c. HDPE: hard and stiff, but also cheap

Activity 5

1. d

2. a. The atoms even though tightly bonded together, can glide across each other, which allows the metal to bend or stretch

   b. x10^{-9} …so particles are this many times smaller. Microparticles.

   c. nanocrystalline particles are flexible, non corrosive and light.

3. a. Particles are fine and close and keeps air locked inside the ball.

   b. material does not have to be replaced as often. Rubber is a polymer which is derived from Crude oil.

Activity 6

1. i. b
   ii. b

2. a. filament light bulbs; tiny lights in computers and remotes

   b. saves energy (sustainable); long term use is more cheaper

3. metals are good conductors and lose heat easily. Therefore energy is lost and wasted.