Cambridge

OL

Chemistry

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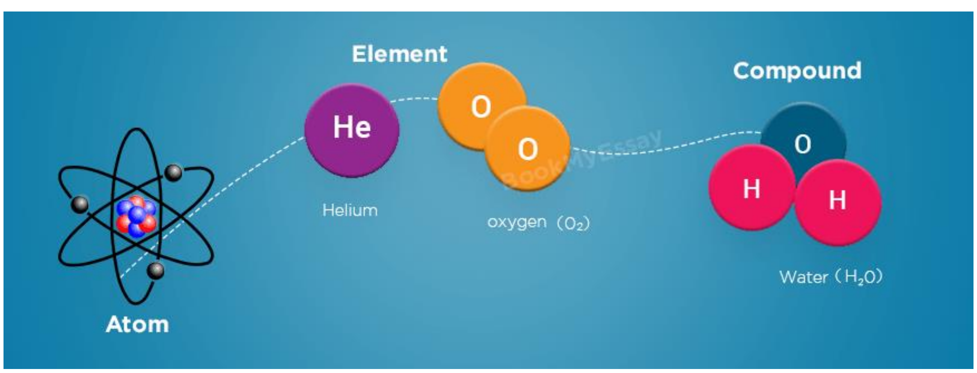
Chapter 02

Atoms, elements and compounds



2.1 Elements

Each element is composed of only one kind of atom, with the word atom coming from the Greek word atomos meaning 'unsplittable'. 118 elements have been identified, with 20 not occurring naturally and 88 naturally occurring. Physical properties of elements can be measured and classified as **metals** or **non-metals**. Metals have high densities, high melting points, and high boiling points, while non-metals have low densities, low melting points, and low boiling points. Combining elements like aluminium creates complex substances like aluminium oxide, nitrate, and sulfate.

a Gold is very decorative

b Aluminium has many uses in the aerospace industry

c These coins contain nickel

▲ **Figure 2.2** Some metals

▼ **Table 2.1** Physical data for some metallic and non-metallic elements at room temperature and pressure

Element	Metal or non-metal	Density/ g cm^{-3}	Melting point/°C	Boiling point/°C
Aluminium	Metal	2.70	660	2580
Copper	Metal	8.92	1083	2567
Gold	Metal	19.29	1065	2807
Iron	Metal	7.87	1535	2750
Lead	Metal	11.34	328	1740
Magnesium	Metal	1.74	649	1107
Nickel	Metal	8.90	1453	2732
Silver	Metal	10.50	962	2212
Zinc	Metal	7.14	420	907
Carbon	Non-metal	2.25	Sublimes at 3642	
Hydrogen	Non-metal	0.07^{a}	−259	−253
Nitrogen	Non-metal	0.88^{b}	−210	−196
Oxygen	Non-metal	1.15^{c}	−218	−183
Sulfur	Non-metal	2.07	113	445

Source: Earl B., Wilford L.D.R. Chemistry data book. Nelson Blackie, 1991 a: at −254°C; b: at −197°C; c: at −184°C.

Property	Metal	Non-metal
Physical state at room temperature	Usually solid (occasionally liquid)	Solid, liquid or gas
Malleability	Good	Poor – usually soft or brittle
Ductility	Good	
Appearance (solids)	Shiny (lustrous)	Dull
Melting point	Usually high	Usually low
Boiling point	Usually high	Usually low
Density	Usually high	Usually low
Electrical conductivity and **thermal conductivity**	Good	Very poor

The elements also have chemical properties, which are characteristics or behaviours that may be observed when the substance undergoes a chemical change or reaction. A discussion of the chemical properties of some metals and non-metals is given in Chapters 9 and 10.

Everything is composed of billions of extremely small atoms, with the smallest being hydrogen. Atoms of different elements have different diameters and masses. Chemists use symbols to label elements and their atoms, often consisting of one, two, or three letters. Some symbols have no relation to the element's name, like Na for sodium and Pb for lead, which come from their Latin names.

c Neon is used in advertising signs

▲ **Figure 2.3** Some non-metals

Molecules

The atoms of some elements are joined together in small groups. These small groups of atoms are called **molecules**.

The atoms of some elements are always joined in pairs, for example, hydrogen, oxygen, nitrogen, fluorine, chlorine, bromine and iodine. They are known as **diatomic molecules.**

The complete list of the elements with their corresponding symbols is shown in the **Periodic Table** on p. 130.

Monatomic molecules, composed of separate atoms, are used to describe gases like helium, neon, argon, krypton, xenon, and radon at 0°C and atmospheric pressure.

▼ **Table 2.3** Sizes of atoms

Atom	Diameter of atom/mm	Masses/g
Hydrogen	7×10^{-8}	1.67×10^{-24}
Oxygen	12×10^{-8}	2.66×10^{-23}
Sulfur	20.8×10^{-8}	5.32×10^{-23}

a A premature baby needs oxygen

b Artists often use charcoal (carbon) to produce an initial sketch

Cl —— Cl

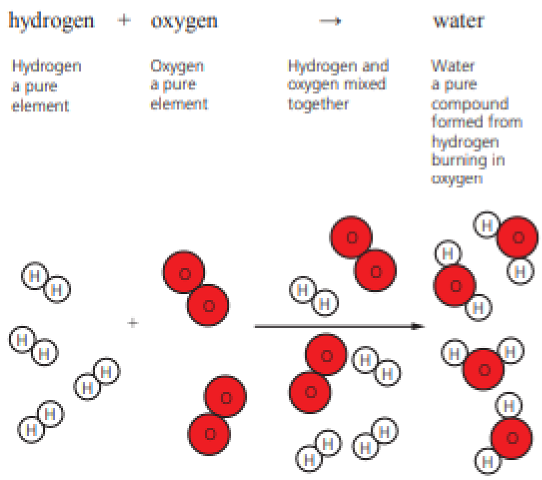
a Represented by a letter-and-stick model

b Represented by a space-filling model

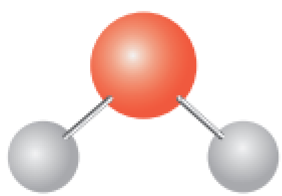
▲ **Figure 2.4** A chlorine molecule

2.2 Compounds

Pure substances, such as compounds, are homogeneous materials with consistent properties due to chemical combination of elements, as demonstrated by water.



a The element hydrogen reacts with the element oxygen to produce the compound water



b A model of water showing 2 H atoms and one O atom. Models such as this can be built to show what a compound looks like

The formula for water molecules, consisting of two hydrogen atoms and one oxygen atom, is H2O, where the symbol represents the element's atomic number.

When a new substance is formed during a chemical reaction, a **chemical change** has taken place.

magnesium + oxygen → magnesium oxide

When substances such as hydrogen and magnesium combine with oxygen in this way they are said to have been oxidised, and this process is known as **oxidation**.

▼ **Table 2.4** Some common elements and their symbols. The Latin names of some of the elements are given in brackets

Element	Symbol	Physical state at room temperature and pressure
Aluminium	Al	Solid
Argon	Ar	Gas
Barium	Ba	Solid
Boron	B	Solid
Bromine	Br	Liquid
Calcium	Ca	Solid
Carbon	C	Solid
Chlorine	Cl	Gas
Chromium	Cr	Solid
Copper (Cuprum)	Cu	Solid
Fluorine	F	Gas
Germanium	Ge	Solid
Gold (Aurum)	Au	Solid
Helium	He	Gas
Hydrogen	H	Gas
Iodine	I	Solid
Iron (Ferrum)	Fe	Solid
Lead (Plumbum)	Pb	Solid
Magnesium	Mg	Solid
Mercury (Hydragyrum)	Hg	Liquid
Neon	Ne	Gas
Nitrogen	N	Gas
Oxygen	O	Gas
Phosphorus	P	Solid
Potassium (Kalium)	K	Solid
Silicon	Si	Solid
Silver (Argentum)	Ag	Solid
Sodium (Natrium)	Na	Solid
Sulfur	S	Solid
Tin (Stannum)	Sn	Solid
Zinc	Zn	Solid

Key definition

The **molecular formula** of a compound is defined as the number and type of different atoms in one molecule.

Key definitions

Oxidation is gain of oxygen.

Reduction is loss of oxygen.

Reduction is the opposite of oxidation. In this process oxygen is removed rather than added.

A **redox reaction** involves reduction and oxidation, with a reducing agent like carbon monoxide playing a crucial role in this process. Oxygen is removed from iron (III) oxide, reducing it to iron, and the **oxidizing agent**, iron (III) oxide, is used as the **reducing agent.**

We can write the redox reaction as:

iron(III) oxide + carbon monoxide → iron + carbon dioxide

Key definitions

Redox reactions involve simultaneous oxidation and reduction.

An **oxidising agent** is a substance that oxidises another substance and is itself reduced.

A **reducing agent** is a substance that reduces another substance and is itself oxidised.

Formulae

The formula of a compound consists of symbols and numbers representing the ratio of elements. For example, carbon dioxide has the formula CO2, indicating one carbon atom for two oxygen atoms.

The ratio of atoms within a chemical compound is usually constant. Compounds are made up of fixed proportions of elements: they have a fixed composition. Chemists call this the **Law of constant composition.**

Balancing chemical equations

Word equations are useful for representing chemical reactions, but a balanced chemical equation provides more detailed information on reactants, products, and particle numbers, as well as the resulting substances.
Balanced equations often include symbols that show the physical state of each of the reactants and products:

» (s) = solid
» (l) = liquid » (g) = gas
» (aq) = aqueous (water) solution

We can use the reaction between iron and sulfur as an example. The word equation to represent this reaction is;

$$\text{iron} + \text{sulfur} \xrightarrow{\text{heat}} \text{iron(II) sulfide}$$

When we replace the words with symbols for the reactants and the products, and include their physical state symbols, we get:

$$Fe(s) + S(s) \xrightarrow{\text{heat}} FeS(s)$$

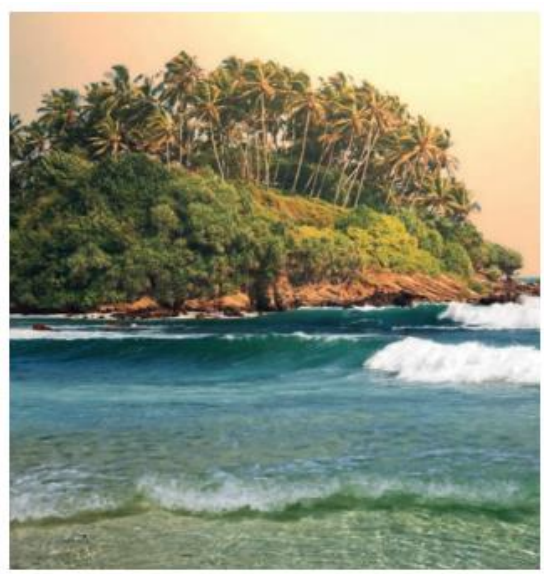
2.3 Mixtures

Many everyday things are not pure substances, they are mixtures. A mixture contains more than one substance, which could be elements and/or compounds.

The difference between mixtures and compounds

The reaction between iron filings and sulfur reveals differences between compounds and mixtures. A mixture of iron filings and sulfur has properties of both elements, allowing separation with a magnet. When heated, a chemical reaction occurs, forming iron(II) sulfide, with the reaction equation being:

$$\text{iron} + \text{sulfur} \xrightarrow{\text{heat}} \text{iron(II) sulfide}$$



▲ **Figure 2.7** Sea water is a common mixture. It is a water solution of substances such as sodium chloride as well as gases such as oxygen and carbon dioxide

▲ **Figure 2.8** The elements sulfur and iron at the top of the photograph, and (below) black iron(II) sulfide on the left and a mixture of the two elements on the right

▲ **Figure 2.9** A magnet will separate the iron from the mixture

During the **reaction** heat energy is released as new chemical bonds are formed. This is called an **exothermic reaction** and accompanies a chemical change (Chapter 6, p. 87).

An **endothermic reaction** occurs when a chemical reaction takes in heat, resulting in a product with unique properties, such as iron (II) sulfide's inability to attract a magnet.

▼ **Table 2.6** Different properties of iron, sulfur, an iron/sulfur mixture and iron(II) sulfide

Substance	Appearance	Effect of a magnet	Effect of dilute hydrochloric acid
Iron	Dark grey powder	Attracted to it	Very little action when cold. When warm, a gas is produced with a lot of bubbling (effervescence)
Sulfur	Yellow powder	None	No effect when hot or cold
Iron/sulfur mixture	Dirty yellow powder	Iron powder attracted to it	Iron powder reacts as above
Iron(II) sulfide	Black solid	No effect	A foul-smelling gas is produced with some effervescence

In iron(II) sulfide, FeS, one atom of iron has combined with one atom of sulfur. In a mixture of iron and sulfur no such ratio exists, as the atoms have not chemically combined. Table 2.7 compares mixtures and compounds. Some common mixtures are discussed in Chapter 10 (p. 159) and Chapter 11 (p. 171).

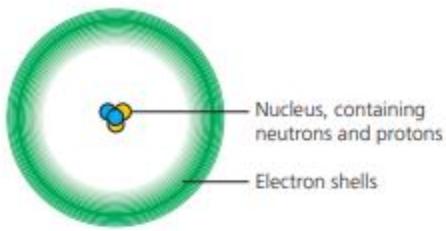
▼ **Table 2.7** The major differences between mixtures and compounds

Mixture	Compound
It contains two or more substances	It is a single substance
The composition can vary	The composition is always the same
No chemical change occurs when a mixture is formed	When the new substance is formed it involves chemical change
The properties are those of the individual elements/ compounds	The properties are very different to those of the component elements
The components may be separated quite easily by physical means	The components can only be separated by one or more chemical reactions

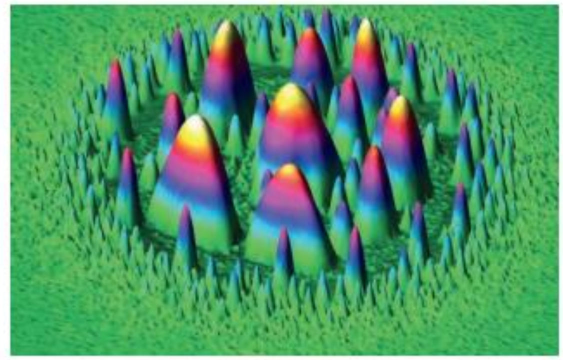
2.4 Inside atoms

Atoms, tiny particles, were initially believed to be solid particles like marbles. However, scientists like Niels Bohr, Albert Einstein, and James Chadwick have proven that atoms are made up of smaller sub-atomic particles, including **electrons, protons, and neutrons**. This discovery has led to a more accurate understanding of atomic structure.

Atoms consist of three sub-atomic particles: protons and neutrons in the nucleus, which is dense and has no charge, and electrons in **electron shells**. Electrons move around the nucleus quickly, held in these shells by an **electrostatic force attraction**, with each shell having a fixed number of electrons.



▲ **Figure 2.13** Diagram of an atom



▲ **Figure 2.12** An electron micrograph of atoms taken using a very powerful microscope called an electron microscope

In Table 2.8. You will notice that the masses of all these particles are measured in atomic mass units (amu). This is because they are so light that their masses cannot be measured usefully in grams.

▼ **Table 2.8** Characteristics of a proton, a neutron and an electron

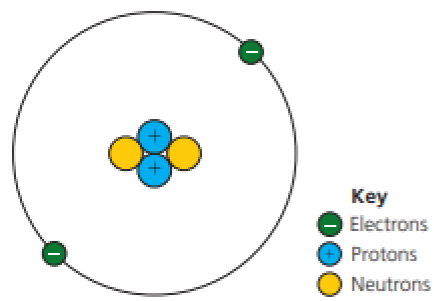
Particle	Symbol	Relative mass/ amu	Relative charge
Proton	p	1	+1
Neutron	n	1	0
Electron	e	1/1837	−1

Proton number and mass number

The mass number of an atom is determined by the proton number, which represents the number of protons in its nucleus. Each element has its own proton number, and the mass of an atom depends on the total number of protons and neutrons in its nucleus, represented by the symbol A.

> **Key definitions**
> **Proton number** or atomic number is the number of protons in the nucleus of an atom.
> **Mass number** or nucleon number is the total number of protons and neutrons in the nucleus of an atom.

$$\underset{(A)}{\text{mass number}} = \underset{(Z)}{\text{proton number}} + \text{number of neutrons}$$



▲ **Figure 2.14** An atom of helium has two protons, two electrons and two neutrons

The mass number of an element, such as helium or lithium, is determined by its nucleus's protons and neutrons, with helium having a mass number of 4.

Mass number (A) → $^{4}_{2}He$ ← Symbol of the element
Proton number (Z) →

The number of neutrons present can be calculated by rearranging the relationship between the proton number, mass number and number of neutrons to give:

$$\text{number of neutrons} = \underset{(A)}{\text{mass number}} - \underset{(Z)}{\text{proton number}}$$

Table 2.9 Number of protons, neutrons and electrons in some elements

Element	Symbol	Proton number	Number of electrons	Number of protons	Number of neutrons	Mass number
Hydrogen	H	1	1	1	0	1
Helium	He	2	2	2	2	4
Carbon	C	6	6	6	6	12
Nitrogen	N	7	7	7	7	14
Oxygen	O	8	8	8	8	16
Fluorine	F	9	9	9	10	19
Neon	Ne	10	10	10	10	20
Sodium	Na	11	11	11	12	23
Magnesium	Mg	12	12	12	12	24
Sulfur	S	16	16	16	16	32
Potassium	K	19	19	19	20	39
Calcium	Ca	20	20	20	20	40
Iron	Fe	26	26	26	30	56
Zinc	Zn	30	30	30	35	65

Ions

An **ion** is an electrically charged particle. When an atom loses one or more electrons it is no longer electrically neutral and becomes a positively charged ion. This is called a cation.

When an atom gains one or more electrons it becomes a negatively charged ion. This is called an anion.

The process of gaining or losing electrons is known as **ionization.**

Table 2.10 shows some common ions. You will notice that:

- some ions contain more than one type of atom, for example NO_3^-
- an ion may possess more than one unit of charge (either negative or positive), for example Al^{3+}, O^{2-} and SO_4^{2-}.

Table 2.10 Some common ions

Name	Formula
Lithium ion	Li^+
Sodium ion	Na^+
Potassium ion	K^+
Magnesium ion	Mg^{2+}
Calcium ion	Ca^{2+}
Aluminium ion	Al^{3+}
Zinc ion	Zn^{2+}
Ammonium ion	NH_4^+
Fluoride ion	F^-
Chloride ion	Cl^-
Bromide ion	Br^-
Hydroxide ion	OH^-
Oxide ion	O^{2-}
Sulfide ion	S^{2-}
Carbonate ion	CO_3^{2-}
Nitrate ion	NO_3^-
Sulfate ion	SO_4^{2-}

Isotopes

Isotopes are atoms of the same element with different neutron numbers, resulting in different mass numbers, as illustrated in Figure 2.15 for chlorine.

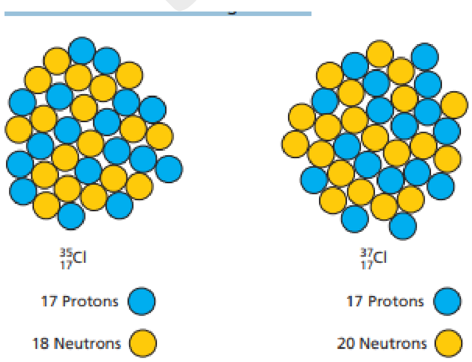


Figure 2.15 The nuclei of two isotopes of chlorine

Radioisotopes, unstable isotopes resulting from extra neutrons in nuclei, are **radioactive** and release large amounts of energy and dangerous radiations. These atoms, such as uranium-235 and cobalt-60, are used in nuclear reactors and radiotherapy treatment, respectively, and can be useful to society in certain cases.

Key definition

Isotopes are different atoms of the same element that have the same number of protons but different numbers of neutrons.

Isotopes of the same element have the same chemical properties because they have the same number of electrons and therefore the same electronic configuration (p. 26).

▲ **Figure 2.16** Cobalt-60 is used in radiotherapy treatment. A beam of gamma rays produced by the radioactive isotope is directed into the patient's body to kill tumour tissue.

▼ **Table 2.11** Some atoms and their isotopes

Element	Symbol	Particles present
Hydrogen	${}^{1}_{1}H$	1e, 1p, 0n
(Deuterium)	${}^{2}_{1}H$	1e, 1p, 1n
(Tritium)	${}^{3}_{1}H$	1e, 1p, 2n
Carbon	${}^{12}_{6}C$	6e, 6p, 6n
	${}^{13}_{6}C$	6e, 6p, 7n
	${}^{14}_{6}C$	6e, 6p, 8n
Oxygen	${}^{16}_{8}O$	8e, 8p, 8n
	${}^{17}_{8}O$	8e, 8p, 9n
	${}^{18}_{8}O$	8e, 8p, 10n
Strontium	${}^{86}_{38}Sr$	38e, 38p, 48n
	${}^{88}_{38}Sr$	38e, 38p, 50n
	${}^{90}_{38}Sr$	38e, 38p, 52n
Uranium	${}^{235}_{92}U$	92e, 92p, 143n
	${}^{238}_{92}U$	92e, 92p, 146n

Relative atomic mass

The average mass of a large number of atoms of an element is called its relative atomic mass (Ar). This quantity considers the percentage abundance of all the isotopes of an element which exist.

Key definition

Relative atomic mass, A_r, is the average mass of the isotopes of an element compared to 1/12th of the mass of an atom of ${}^{12}C$.

$$A_r = \frac{\text{average mass of isotopes of the element}}{\frac{1}{12} \times \text{mass of one atom of carbon-12}}$$

Note: $\frac{1}{12}$ of the mass of one carbon-12 atom = 1 amu.

The arrangement of electrons in atoms

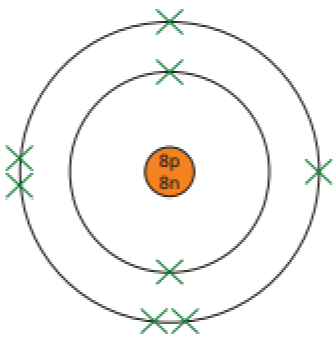
Atoms have a nucleus with heavier sub-atomic particles, protons and neutrons. Electrons, the lightest, move around the nucleus in electron shells, moving fast and occupying specific, definite shells, unlike planets orbiting the Sun.

Also, as mentioned earlier, each of the electron shells can hold only a certain number of electrons.

» First shell holds up to two electrons.

» Second shell holds up to eight electrons.
» Third shell holds up to 18 electrons. There are further shells which contain increasing numbers of electrons

The **electronic configuration** refers to the arrangement of electrons in an atom, starting from the lowest energy shell to the most energetic. For example, a 16-8O atom has eight electrons, with two entering the first shell and six occupying the second. The electronic structure of 118 elements is illustrated in Figure 2.20, illustrating the distribution of electrons in the first 20 elements.

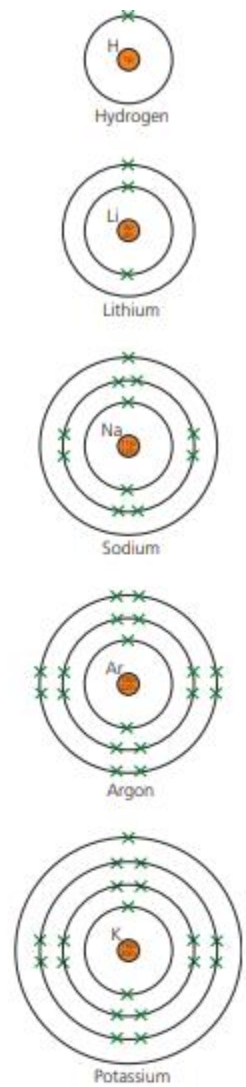


▲ **Figure 2.19** Arrangement of electrons in an oxygen atom

From Table 2.12 you can see helium has a full outer shell of two electrons, and neon has a full outer shell of eight electrons.

▼ **Table 2.12** Electronic configuration of the first 20 elements

Element	Symbol	Proton number	Number of electrons	Electronic configuration
Hydrogen	H	1	1	1
Helium	He	2	2	2
Lithium	Li	3	3	2,1
Beryllium	Be	4	4	2,2
Boron	B	5	5	2,3
Carbon	C	6	6	2,4
Nitrogen	N	7	7	2,5
Oxygen	O	8	8	2,6
Fluorine	F	9	9	2,7
Neon	Ne	10	10	2,8
Sodium	Na	11	11	2,8,1
Magnesium	Mg	12	12	2,8,2
Aluminium	Al	13	13	2,8,3
Silicon	Si	14	14	2,8,4
Phosphorus	P	15	15	2,8,5
Sulfur	S	16	16	2,8,6
Chlorine	Cl	17	17	2,8,7
Argon	Ar	18	18	2,8,8
Potassium	K	19	19	2,8,8,1
Calcium	Ca	20	20	2,8,8,2



▲ **Figure 2.20** Electronic configurations of hydrogen, lithium, sodium, argon and potassium

Revision questions

1)The table gives the composition of three particles.

particle	number of protons	number of electrons	number of neutrons
A	15		16
B	15		16
C	15		17

(a) What is the evidence in the table for each of the following? (i) Particle A is an atom. [1]

(ii) A, B and C are all particles of the same element. [1]

(iii) Particles A and C are isotopes of the same element. [2]

(b) (i) What is the electronic structure of particle A? [1]

(ii) Is element A, a metal or a non-metal? Give a reason for your choice

2) Protons, neutrons and electrons are subatomic particles.

(a) Complete the table to show the relative mass and relative charge of a proton, a neutron and an electron

particle	relative mass	relative charge
proton		
neutron		
electron	$\frac{1}{1840}$	

(b) Bromine has two isotopes.

(i) Define the term isotope. [2]

(ii) Explain why the two isotopes of bromine have the same chemical properties. [2]

(c) The table shows the number of protons, neutrons and electrons in some atoms and ions. Complete the table.

particle	number of protons	number of neutrons	number of electrons
$^{7}_{3}Li$			
$^{34}_{16}S^{2-}$			
	19	22	18

[5]

3) (a) (i) Define the term atomic number. [1]

(ii) Define the term nucleon number. [2]

(b) The table shows the number of protons, neutrons and electrons in some atoms or ions. Complete the table. The first line is given as an example.

particle	number of protons	number of electrons	number of neutrons	symbol or formula
A	6	6	6	$^{12}_{6}C$
B	12	12	12	
C	8			$^{16}_{8}O^{2-}$
D	11	10	13	

[6]

4) (a) The table below gives information about particles. Complete the table. The first line has been done for you.
(b) Gallium is a Group III element. Define the term element.
(c) The following are gallium atoms.

$^{69}_{31}Ga$ $^{71}_{31}Ga$

Complete the following table.

atom	number of protons	number of neutrons	number of electrons
$^{69}_{31}Ga$			
$^{71}_{31}Ga$			

[3]

5) (a)Define the term isotope. [2]
(b) The table gives information about four particles, A, B, C and D. Complete the table. The first line has been done for you.

particle	number of protons	number of electrons	number of neutrons	nucleon number	symbol or formula
A	6	6		12	C
B	11	10	12		
C	8		8		O^{2-}
D		10		28	Al^{3+}

[7]

6) The table below gives the composition of six particles which are either atoms or ions

particle	number of protons	number of neutrons	number of electrons
A	33	40	33
B	19	20	18
C	34	45	36
D	33	42	33
E	13	14	13
F	24	28	21

(a) Which particles are atoms? Explain your choice. [2]
(b) Which particle is a negative ion and why has this particle got a negative charge? [2]
(c) Which particles are positive ions? [1]
(d) Explain why particle A and particle D are isotopes

7) The following table gives information about six substances.

substance	melting point / °C	boiling point / °C	electrical conductivity as a solid	electrical conductivity as a liquid
A	839	1	good	good
B	–18		poor	poor
C	776	1	poor	good
D	–11		poor	poor
E	1607		poor	poor
F	–5	1	poor	good

(a) Which substance could be a metal? [1]
(b) State all the substances that are liquid at room temperature? [1]
(c) Which substance could have a macromolecular structure similar to that of silicon(IV) oxide? [1]
(d) Which substance could be propane? [1]
(e) Which substance could be sodium chloride?

8) (a) Potassium iodide is an ionic compound.
(i) Describe what happens, in terms of electron loss and gain, when a potassium atom reacts with an iodine atom. [2]
(ii) Describe the structure of solid potassium iodide. You may draw a diagram. [2]
(iii) Explain why potassium iodide has a high melting point
(b) Potassium iodide and lead nitrate are both soluble. Lead iodide is insoluble.
(i) Describe how a pure dry sample of lead iodide could be made from solid potassium iodide and solid lead nitrate. [4]

(ii) Write an ionic equation for the formation of lead iodide, PbI2, when potassium iodide and lead nitrate react with each other. State symbols are not required.

9) Carbon dioxide and silicon(IV) oxide are oxides of Group IV elements.
(a) Complete the following table

	carbon dioxide	silicon(IV) oxide
formula		SiO_2
melting point/°C	–56	1610
physical state at 25°C	gas	
conduction of electricity	non-conductor	
structure		macromolecular

(b) (i) Name the type of bonds that exist between the atoms in silicon (IV) oxide. [1]
(ii) Explain why silicon (IV) oxide has a very high melting point. [1]
(iii) Explain, in terms of attractive forces between particles, why carbon dioxide has a very low melting point. [1]
(iv) Explain, in terms of particles, why carbon dioxide is a non-conductor of electricity. [1]
(c) Suggest a chemical equation for the reaction between sodium hydroxide solution and carbon dioxide.
(d) (i) Name the type of chemical reaction in which carbon dioxide is produced from fossil fuels. [1]
(ii) Name the chemical process in which green plants convert carbon dioxide into carbohydrates. [1]
(iii) Name the chemical process in which living things produce carbon dioxide