

OXFORD IB DIPLOMA PROGRAMME



2014 EDITION

CHEMISTRY

COURSE COMPANION

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The atomic theory

A universally accepted axiom of science today is that all matter is composed of atoms. However, this has not always been so. During the seventeenth century the *phlogiston theory* was a widely held belief. To explain the process of combustion it was proposed that a fire-like element called **phlogiston**, said to be found within substances, was released during burning. Quantitative investigations of burning metals revealed that magnesium in fact gains rather than loses mass when it burns in oxygen, contradicting the phlogiston theory.

Scientists use a wide range of methodologies, instruments, and advanced computing power to obtain evidence through observation and experimentation. Much of the technology

commonly used today was not available to scientists in the past who often performed groundbreaking investigations in relatively primitive conditions to feed their appetite for knowledge and understanding. Over time, theories and hypotheses have been tested with renewed precision and understanding. Some theories do not stand the test of time. The best theories are those that are simple and account for all the facts.

The **atomic theory** states that all matter is composed of atoms. These atoms cannot be created or destroyed, and are rearranged during chemical reactions. Physical and chemical properties of matter are linked to the bonding and arrangement of these atoms.

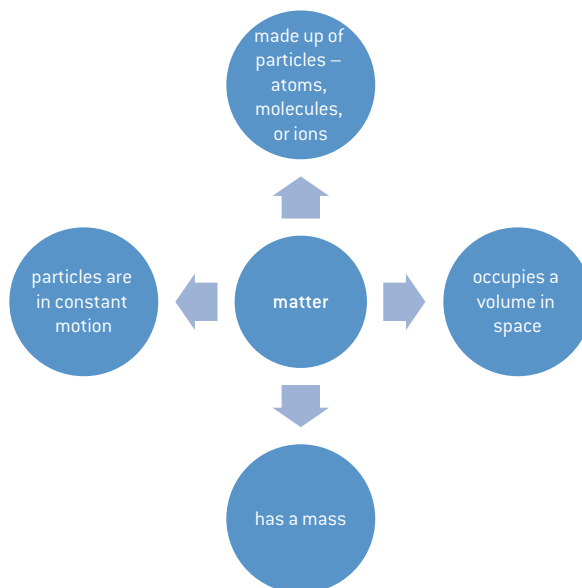
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Lavoisier is often referred to as the “father of modern chemistry”. His contribution to science is well documented. In 1772 Lavoisier discovered through experimentation that when sulfur and phosphorus were combusted they gained mass. These results contradicted the belief that mass would be lost during combustion as phlogiston was released. Could phlogiston have a negative mass? Empirical data derived from Lavoisier’s experiments was eventually accepted by the scientific community. Indeed Lavoisier’s work is considered some of the first examples of quantitative chemistry and the law of conservation of mass. His experiments may appear simple by present-day standards but they were ground-breaking in their day.

Lavoisier’s discovery of oxygen invalidated the phlogiston theory. This is an example of a paradigm shift. The dominant paradigm or belief is replaced by a new paradigm. Is this how scientific knowledge progresses?

States of matter

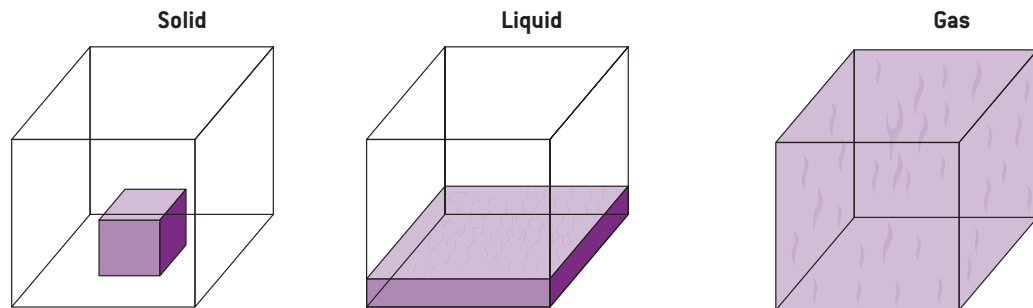
Matter is everywhere. We are made up of matter, we consume it, it surrounds us, and we can see and touch many forms of matter. Air is a form of matter which we know is there, though we cannot see or feel it. Our planet and the entire universe are made up of matter and chemistry seeks to expand our understanding of matter and its properties.



▲ Figure 1 The characteristics of matter



The properties of the three **states of matter** are summarized below.



- | | | |
|---|--|---|
| <ul style="list-style-type: none"> • fixed volume • fixed shape • cannot be compressed • attractive forces between particles hold the particles in a close-packed arrangement • particles vibrate in fixed positions | <ul style="list-style-type: none"> • fixed volume • no fixed shape – takes the shape of the container it occupies • cannot be compressed • forces between particles are weaker than in solids • particles vibrate, rotate and translate (move around) | <ul style="list-style-type: none"> • no fixed volume • no fixed shape – expands to occupy the space available • can be compressed • forces between particles are taken as zero • particles vibrate, rotate and translate faster than in a liquid |
|---|--|---|

The way the particles of matter move depends on the temperature. As the temperature increases the average kinetic energy of the particles increases – the particles in a solid vibrate more, and the particles in liquids and gases vibrate, rotate, and translate more.

Temperature

There are a number of different temperature scales. The most commonly used are the Fahrenheit, Celsius, and Kelvin scales. All three are named in honour of the scientist who developed them.

The SI unit for temperature is the **Kelvin** (K). The Kelvin scale is used in energetics calculations (see topic 5).

Absolute zero is zero on the Kelvin scale, 0 K (on the Celsius scale this is $-273\text{ }^{\circ}\text{C}$). It is the temperature at which all movement of particles stops. All particles at temperatures greater than absolute zero vibrate, even in solid matter.

You can convert temperatures from the Celsius scale to the the Kelvin scale using the algorithm:

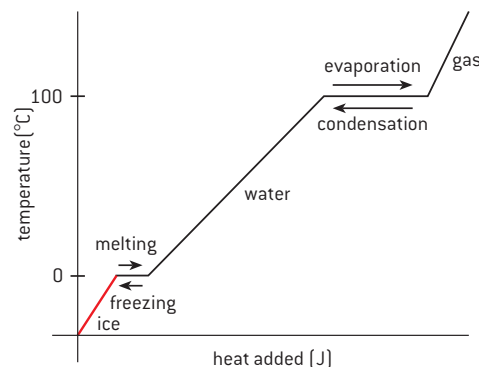
$$\text{temperature (K)} = \text{temperature (}^{\circ}\text{C)} + 273.15$$

Changes of state

If you heat a block of ice in a beaker it will melt to form liquid water. If you continue heating the water will boil to form water vapour. Figure 2 shows a heating curve for water – it shows how its temperature changes during these **changes of state**. We will look at the relationship between temperature and the kinetic energy of particles during these changes of state.

SI (Système International) units are a set of standard units that are used in science throughout the world. This will be discussed in great detail in sub-topic 1.2.

When describing room temperature, we might say '25 degrees Celsius [$25\text{ }^{\circ}\text{C}$]' or '298 Kelvin [298 K]' (to the nearest Kelvin). Note that we use just the word Kelvin, not degrees Kelvin. The boiling point of water is $100\text{ }^{\circ}\text{C}$ or 373 K , and the melting point of water is $0\text{ }^{\circ}\text{C}$ or 273 K .

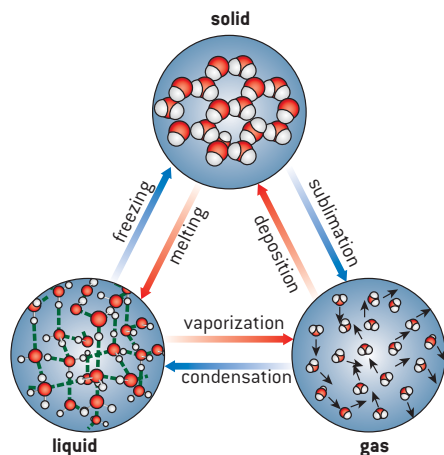


▲ Figure 2 The heating curve for water

Freeze-drying is a food preservation technique that uses the process of sublimation. Foods that require dehydration are first frozen and then subjected to a reduced pressure. The frozen water then sublimates directly to water vapour, effectively dehydrating the food. The process has widespread applications in areas outside the food industry such as pharmaceuticals (vaccines), document recovery from water-damaged books, and scientific research laboratories.

Activity

- 1 Explain why the temperature of a boiling liquid does not increase despite energy being constantly applied.
- 2 Which would be more painful, scalding your skin by water vapour or boiling water?
- 3 Explain why you might feel cold and shiver when you get out of the water at the beach on a very hot, windy day.



▲ Figure 3 Changes of state for water

What happens to the particles during changes of state

- As a sample of ice at $-10\text{ }^{\circ}\text{C}$ (263 K) is heated, the water molecules in the solid lattice begin to vibrate more. The temperature increases until it reaches the melting point of water at $0\text{ }^{\circ}\text{C}$ (273 K).
- The ice begins to **melt** and a solid–liquid equilibrium is set up. Figure 2 shows that there is no change in temperature while melting is occurring. All of the energy is being used to disrupt the lattice, breaking the attractive forces between the molecules and allowing the molecules to move more freely. The level of disorganization increases. (The nature of the forces between molecules is discussed in sub-topic 4.4.)
- Once all the ice has melted, further heating makes the water molecules vibrate more. The temperature rises until it reaches the boiling point of water at $100\text{ }^{\circ}\text{C}$ (373 K), and the water starts to **boil**.
- At $100\text{ }^{\circ}\text{C}$ a liquid–gas equilibrium is established as the water boils. Again the temperature does not change as energy is required to overcome the attractive forces between molecules in the liquid water and free water molecules from the liquid to form a gas. (equilibrium is covered in sub-topic x.x)
- The curve shows that while the water is boiling its temperature remains at $100\text{ }^{\circ}\text{C}$. Once all the liquid water has been converted to steam, the temperature will increase above $100\text{ }^{\circ}\text{C}$.
- Melting and boiling are **endothermic** processes. Energy must be transferred to the water from the surroundings to bring about these changes of state. The potential energy (stored energy) of the molecules increases – they vibrate more.
- Cooling brings about the reverse processes to heating – the **condensation** of water vapour to form liquid water, and the **freezing** of liquid water to form solid.
- Condensation and freezing are **exothermic** processes. Energy is transferred to the surroundings from the water during these changes of state. The potential energy of the molecules decreases – they vibrate less.
- **Vaporization** is the change of state from liquid to gas which may happen during boiling, or by **evaporation** at temperatures below the boiling point. In **sublimation** matter changes state directly from the solid to gas phase without becoming a liquid. **Deposition** is the reverse process of sublimation – changing directly from a gas to a solid.

Elements and compounds

An **element** contains atoms of only one type. Atoms of elements combine in a fixed ratio to form **compounds** composed of molecules or ions. These rearrangements of the particles of matter are the fundamental cornerstone of chemistry, represented in formulae and balanced chemical equations. (Atoms are covered in detail in sub-topic x.x)

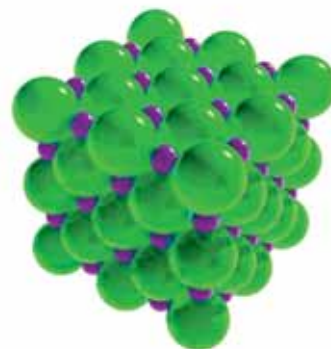


Chemists study how elements and compounds react with one another, the many different chemical and physical properties of the substances created in these reactions, and how they can be used by society for many important applications.

The compound sodium chloride, NaCl, is made up of the elements sodium and chlorine.

The group 1 alkali metal sodium is a soft metal that undergoes rapid oxidation in air and violent reactions with water, creating alkaline solutions. Sodium is stored under oil to prevent these reactions. It is the sixth most common element on the planet.

The halogen chlorine, is a gas at room temperature. Chlorine, Cl₂, is highly irritating to humans if it comes in contact with the eyes, skin, or upper respiratory tract.



▲ Figure 4 The structure of sodium chloride. It consists of a crystalline lattice of sodium ions (shown purple) and chloride ions (shown green)



▲ Figure 5 Elemental sodium is a reactive alkali metal

The highly reactive elements sodium and chlorine combine to form the ionic crystalline compound sodium chloride, commonly called table salt and consumed daily in the food we eat. The properties and uses of sodium chloride are very different from those of its constituent elements.

Mixtures

A **pure substance** is matter that has a constant composition. Its chemical and physical properties are distinct and consistent. Examples include the elements nitrogen, N₂ and argon, Ar and compounds such as water, H₂O, table salt, NaCl and glucose, C₆H₁₂O₆.

Pure substances can physically combine to form a **mixture**. For example, sea water is a combination of sodium chloride and water. The mixing process can be reversed and the pure substances separated by physical separation techniques such as filtration, fractional distillation,

CFCs and the impact of science and technology

The process of refrigeration involves the energy changes of a condensation–evaporation cycle using volatile liquids. Chlorofluorocarbons (CFCs) were traditionally used in refrigerators and air-conditioning units. They cause depletion of the ozone layer which protects us from the harmful effects of ultraviolet light in sunlight.

CFCs are now banned in many countries, and non-halogenated hydrocarbons such as propane are more commonly used instead. There is more about this later on page xx.