7 Model of Matter – The Particulate Nature of Matter

Water is precious to all of us. Water can exist in three different states of matter namely solid, liquid and gas.
Are the water molecules in each state arranged in the same manner?
Is the movement of the water particles the same in each state?
We can use the particulate nature of matter to understand both the arrangement and movement of water particles in these states of matter. The particulate nature of matter is a model representing matter that is made up of small discrete particles in constant and random motion.

- Matter (7.1)
- Particulate Nature of Matter (7.2)
- General Properties of Matter (7.3)
- Thermal Expansion and Thermal Contraction (7.4)
- Gas Pressure and Temperature (7.5)
- The Heating Curve and Cooling Curve (7.6)
- Conservation of Mass (7.7)
- Evidence for the Particulate Model of Matter (7.8)

7.1 Matter

There are actually more than the three main states of matter commonly known to us: solid, liquid and gas. Another state of matter is plasma, which was identified by William Crookes in 1879. Besides plasma, Bose-Einstein condensates is another state of matter discovered by scientists Cornell, Ketterie and Wieman who did extensive research on this and received a Nobel Prize in 2001 in recognition of their work. Another state of matter closely related to the Bose-Einstein condensates (BEC) is fermionic condensates.

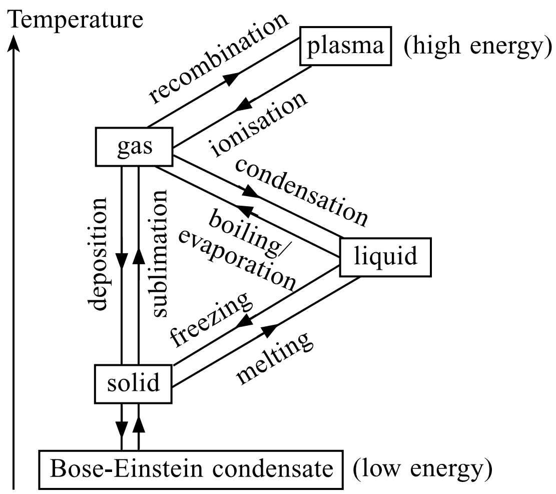


Fig 7.1 The five states of matter

Extra

At 30 000 K (29726.85 °C), a gas of atoms and molecules becomes a plasma, which is a gas of electrons and ions. Near 0 K (–273.15 °C), a gas of sodium atoms lumps to form a dense, super-particle called a BEC. Also, when cooled to 5×10^{-8} K, potassium-40 forms a superfluid phase called fermionic condensate.

1. Matter is anything that has mass and occupies space.
2. The states of matter can be described by their general physical properties.
3. Matter can change from one state to another when heat is supplied or removed. No new substances are formed in these changes.

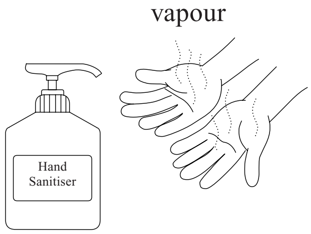


Fig 7.2 As hand sanitiser evaporates from your palms, you feel cool. This can be explained using the idea of the Particulate Model of Matter. (More energetic solvent particles escape into the air from the solvent surface leaving behind less energetic solvent particles.)

7.2 Particulate Nature of Matter

Scientists need to use a model to describe what we cannot see with our eyes. The Particulate Nature of Matter is a model that scientists came up with to explain the general physical properties of matter and changes in state.

1. Matter is made up of very small particles that are in constant, random motion.
2. The greater the temperature of matter, the faster these particles move.

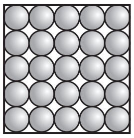
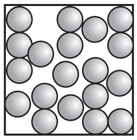
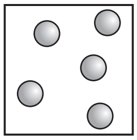
	Solid	Liquid	Gas
Diagram			
Are the particles closely packed?	Closely packed	Closely packed	Far apart
Arrangement of particles	Orderly (or regularly) arranged	Disorderly	Disorderly
Forces of attraction between particles	Very strong	Strong but weaker than in solids	Very weak
Motion of particles	The particles vibrate about fixed positions	The particles move about randomly by sliding past one another	The particles move about randomly and freely in all directions at high speeds

Table 7.1 Arrangement and motion of particles in the three states of matter

7.3 General Properties of Matter

The same substance can exist in different states depending on factors such as temperature and pressure. Often, the states of the substance are linked closely to its boiling point and melting point. For example, if the temperature of a substance is higher than its boiling point, the substance will exist as a gas. Similarly, at a temperature below its boiling point or above its melting point, the same substance will exist as a liquid.

> **Note**
> In this book, we use the term 'move freely' to refer to gas particles as they experience negligible forces of attraction with other gas particles.
> When drawing the particles in solids and liquids, make sure that the particles are touching one another. Notice that in liquids there are some empty spaces between clusters of particles.

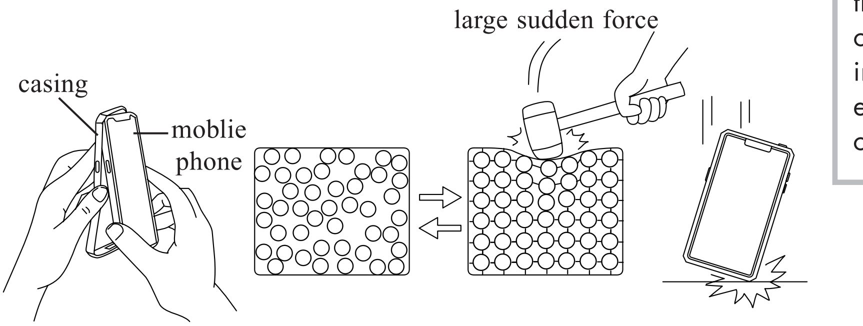


Fig 7.3 This new protective covering can change shape easily like a liquid but hardens up like a strong solid upon impact. It is an example of non-Newtonian fluid whereby viscosity changes when enough force is applied. When a slow force is applied, the polymer particles move and rearrange themselves. When a sudden large force is applied, the polymer particles do not have time to rearrange themselves and become entangled into a regular arrangement.

> **Note**
> The term 'macroscopic' denotes 'large enough to be seen with the naked eye'.

1. Solids have fixed shapes while liquids and gases do not. Why?

	Solid	Liquid	Gas
Macroscopic property: Shape	Fixed shape	No fixed shape	No fixed shape
Explanation using the Particulate Model	Particles are regularly arranged in fixed positions and cannot move freely	Particles are able to move and slide past one another	Particles are able to move freely at great speeds in all directions

2. Solids and liquids have fixed volumes while gases do not. Why?

	Solid	Liquid	Gas
Macroscopic property: Volume	Fixed volume	Fixed volume	No fixed volume
Macroscopic property: Compressibility	Cannot be compressed	Cannot be compressed	Can be compressed
Explanation using the Particulate Model	Particles are packed closely together such that there is no empty space between them	Particles are packed closely together such that there is very little empty space between them	Particles are far apart and there is a lot of empty space between them

3. Solids and liquids have high densities while gases have low densities. Why?

	Solid	Liquid	Gas
Macroscopic property: Density	High density	High density	Low density
Explanation using the Particulate Model	There is a large number of particles per unit volume	There is a large number of particles per unit volume	There is a smaller number of particles per unit volume

7.4 Thermal Expansion and Thermal Contraction

Rails contract at low temperatures and will experience tensile stress. At high temperatures, the rails will expand and compress under the stress. These natural occurrences can lead to heat kinks which could cause derailments. Rail networks all over the world spend millions of dollars each year on ways to counter the dangers posed by thermal expansion and contraction.

Note

Tensile stress is the maximum amount of pulling stress that a material can take before it breaks/fails.

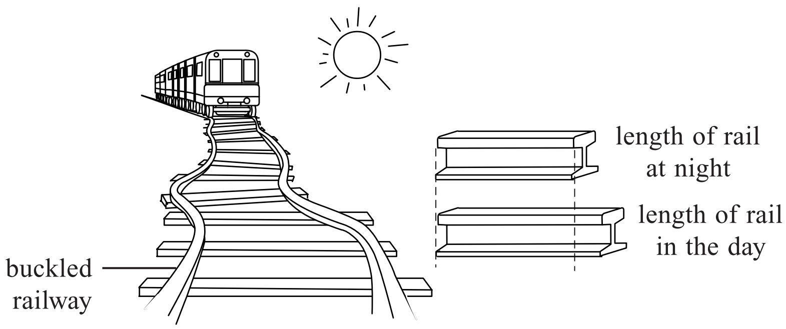


Fig 7.4 This train has stopped as the railroad ahead is buckled.

1. **Macroscopic observation**: Matter expands when heated and contracts when cooled.
2. **Explanation using the Particulate Model**: When heat energy is supplied to matter (solid, liquid or gas), particles move more vigorously and collide with one another more frequently and at greater force. The distance between particles increases.

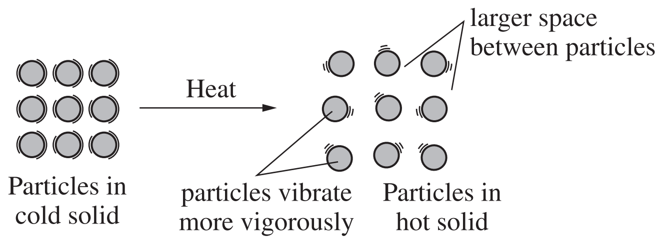


Fig 7.5 How the Particulate Model can be used to explain thermal expansion in solids

7.5 Gas Pressure and Temperature

The main industrial process to produce ammonia NH_3 from hydrogen, H_2 and nitrogen, N_2 is known as Haber process. Both the gas pressure and temperature are crucial conditions to ensure that an optimal yield of NH_3 can be obtained at a reasonable rate of formation.

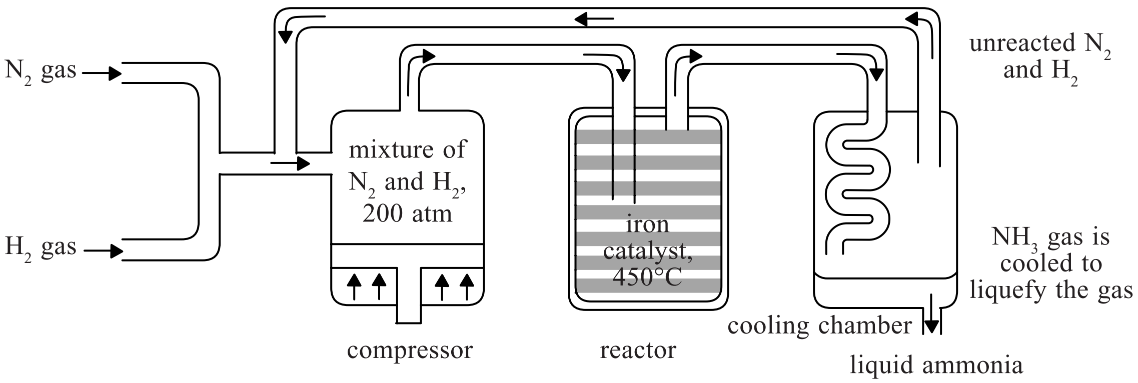


Fig 7.6 To make nitrogen and hydrogen react to form ammonia, the two gases need to be compressed to 200 atmospheres (200 times the normal pressure in our atmosphere).

1. **Macroscopic property**: A gas exerts a pressure on the inner wall of a cylinder.
2. **Explanation using Particulate Model**: Gas particles hit the inner wall of the cylinder. During each moment of collision, a gas particle exerts a force on the inner wall.
3. **Macroscopic observation**: A gas in a fixed-volume cylinder is heated. When the temperature of the gas is increased, the gas pressure increases.
4. **Explanation using Particulate Model**: When heat energy is supplied, the gas particles move at greater speeds. They collide with the inner wall more frequently and with greater force.

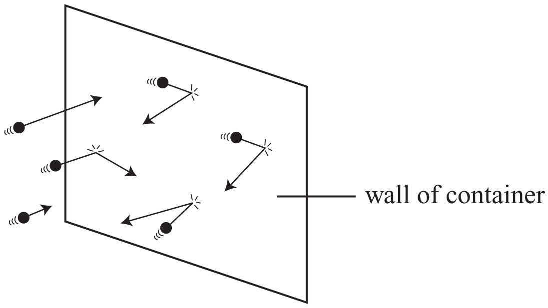
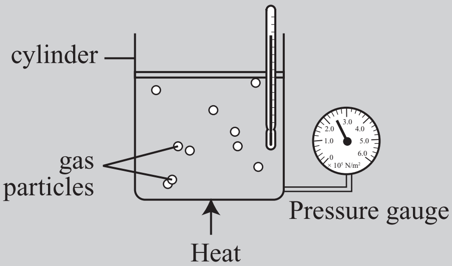


Fig 7.7 The bombardment of gas molecules on a surface gives rise to gas pressure.

Experiment

Temperature (°C)	Temperature (K)	Pressure ($\times 10^5$ N/m^2)
0	273	1.0
25	298	1.1
50	323	1.2
75	348	1.3
100	373	1.4



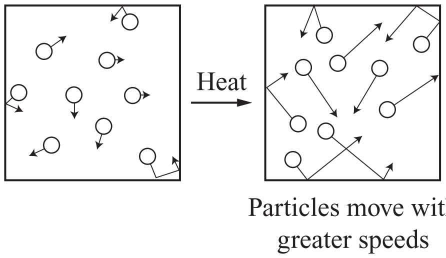


Fig 7.8 As the temperature of a fixed mass of gas at constant volume increases, the gas pressure increases.

Note

Try sketching the graph of pressure against temperature using the data shown in Fig 7.8.

Extra

The following are three gas laws that can be verified by using a cylinder with a movable piston containing a fixed mass of gas.

- Boyle's Law: At constant temperature, as pressure increases, volume decreases.
- Charles' Law: At constant pressure, as temperature increases, volume increases.
- Gay-Lussac's Law: At constant volume, as temperature increases, pressure increases.

7.6 The Heating Curve and Cooling Curve

The Heating Curve

As temperature increases, the energy supplied to the particles will cause them to move further apart from one another. The heating curve can help to explain why these changes take place.

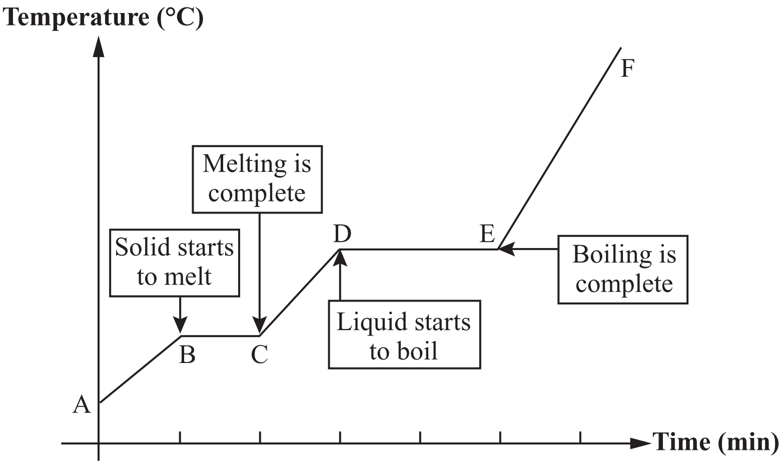


Fig 7.9 The heating curve

1. **Macroscopic observations**: When a solid substance is heated until it changes into a gas, its temperature increases but remains constant (or steady) during melting and boiling. The following heating curve in Fig 7.9 is obtained.

Note

There are some substances that change from solid to gas directly without changing to liquid. Examples include carbon dioxide, iodine and naphthalene (mothball).

2. **Explanation using Particulate Model**:

Part of heating curve	Macroscopic observations	Explanation using Particulate Model
AB	Temperature of solid increases.	Heat supplied makes the particles vibrate more vigorously.
BC	Temperature is constant. Solid is melting.	**Optional** for N(A) Heat supplied is used to overcome the strong attractive forces that hold the particles in an orderly, closely packed arrangement.
CD	Temperature of liquid increases.	Heat supplied makes the particles slide past one another with greater speeds.
DE	Temperature is constant. Liquid is boiling.	**Optional** for N(A) Heat supplied is used to overcome the attractive forces that hold the particles close together and pull them far apart.

3. The steady temperature at which the solid melts is known as the **melting point**.
4. The steady temperature at which the liquid boils is known as the **boiling point**.

The Cooling Curve

As temperature decreases, the energy taken away from the particles will cause them to move closer to one another. The cooling curve can help to explain these changes.

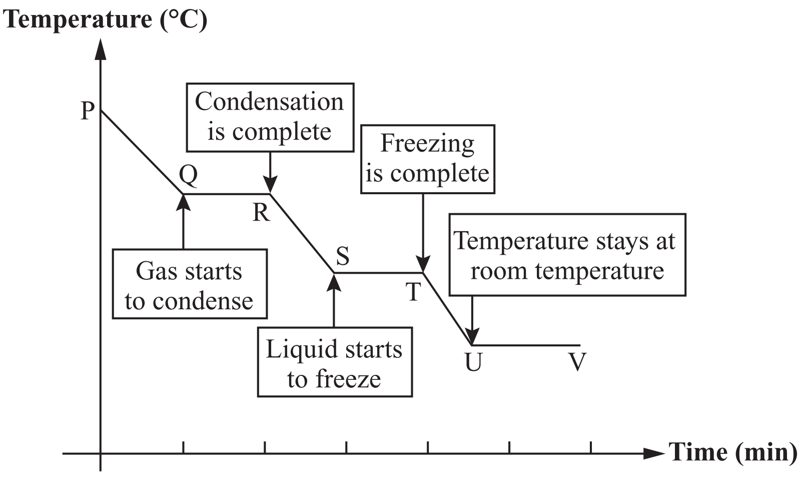


Fig 7.10 The cooling curve

Note

Indicate 'solid', 'solid and liquid', 'liquid and gas' and 'gas' in the different sections of the graph.

1. **Macroscopic observations**: When a gaseous substance is cooled until it becomes a solid, its temperature decreases but remains constant (or steady) during condensation and freezing. The cooling curve in Fig 7.10 is obtained.
2. **Explanation using Particulate Model**:

Part of heating curve	Macroscopic observations	Explanation using Particulate Model
PQ	Temperature decreases.	The removal of heat causes the gas particles to move with slower speeds.
QR	Temperature is constant. Gas is condensing.	**Optional** for N(A) When particles come closer together and form attractive forces between them, heat is released. This heat evolved is removed during cooling.
RS	Temperature decreases.	The removal of heat causes the liquid particles to slide past one another more slowly.
ST	Temperature is constant. Liquid is freezing.	**Optional** for N(A) When particles form stronger attractive forces between them and become orderly arranged, heat is released. This heat evolved is removed during cooling.

7.7 Conservation of Mass

In 1789, Antoine Lavoisier discovered the Law of Conservation of Mass which states that mass is neither created nor destroyed in chemical changes. Hence, the mass of any one element at the start of a reaction will be the same as the mass of that element at the end of the reaction.

1. When matter changes its state, it does not lose or gain mass.
2. This is because the number of particles will remain the same with no net gain or loss.
3. This is termed the **conservation of mass**.

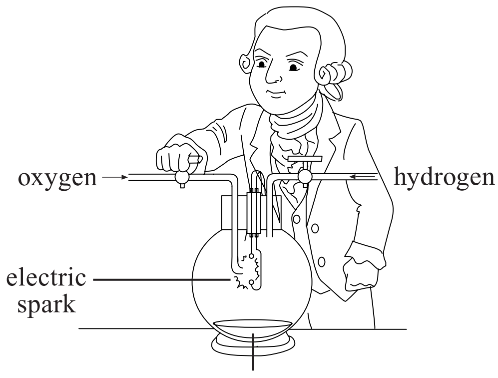


Fig 7.11 This illustration shows Antoine Lavoisier conducting an experiment to react hydrogen and oxygen to form water. After the experiment, he measured that the total mass of oxygen and hydrogen equals the mass of water produced.

7.8 Evidence for the Particulate Model of Matter

In order to prove that this model is sufficiently robust to be used, there must be clear scientific evidence to support this model. Evidence should give observable changes which are aligned to the ideas proposed by the model.

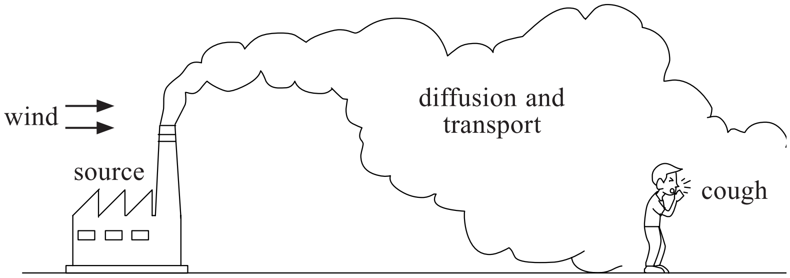


Fig 7.12 Once an air pollutant is given off from a source into the atmosphere (emission), it mixes with the surrounding air (diffusion) and travels long distances with the wind (transport).

1. One piece of evidence for the Particulate Model is diffusion where particles are moving randomly.
2. **Diffusion** is the net movement of particles from a region of higher concentration (i.e. more solute particles per unit volume of the solution) to a region of lower concentration (i.e. less solute particles per unit volume of the solution).

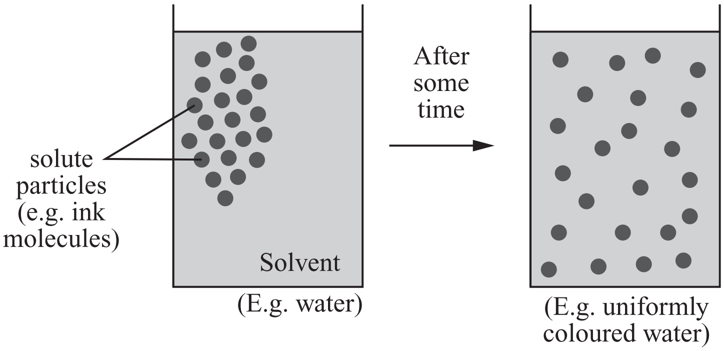


Fig 7.13 Without stirring, the solute molecules spread throughout the solvent by diffusion.

3. Another piece of evidence for the Particulate Model is Brownian motion.
4. **Brownian motion** refers to the random motion of particles (e.g. smoke particles and pollen grains) suspended in a fluid (e.g. air and water).

Note

Changes in state are physical changes as the substance (element or compound) does not change in chemical composition during the changes in state. In chemical reactions, however, substances are changed into new substances. Familiar examples of chemical reactions include combustion (burning) and rusting of iron.

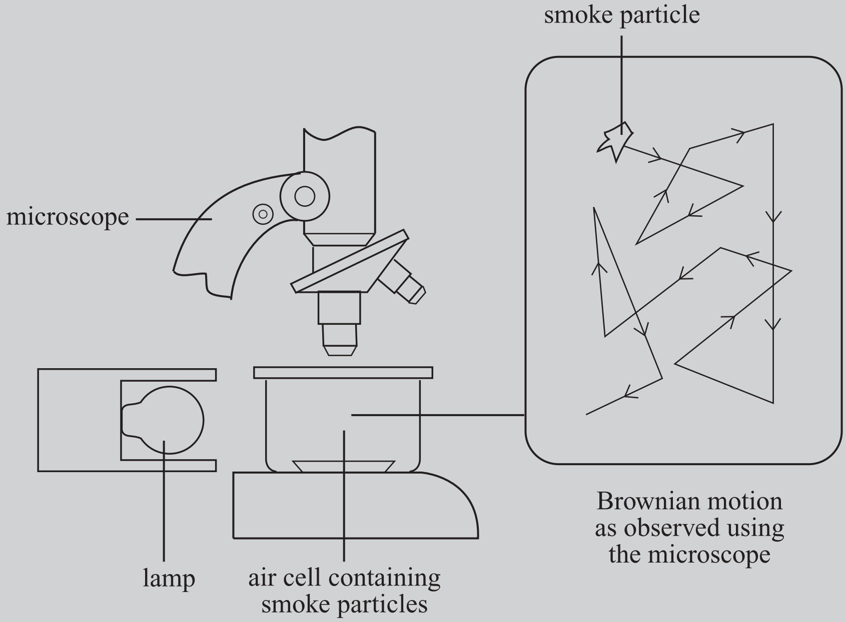
Note

Diffusion is a spontaneous process. No energy is needed to make it happen.

SCIENCE AROUND US

(a) Explain one everyday macroscopic observation that shows the Particulate Nature of Matter.

(b) Explain how the following set-up is used to demonstrate the Particulate Nature of Matter.



ANSWER

(a) Macroscopic observation: When the cap of a perfume bottle is opened, the fragrance spreads (diffuses) throughout a room even when there is no wind.
Explanation using Particulate Model: The air molecules which are in constant motion collide with (or bombard) the perfume molecules causing them to move from one place to another.

(b) Observation: A glass cell of smoke and air is observed under a microscope. The bright specks of smoke particles are seen to move randomly on their own.
Explanation using Particulate Model: The invisible air molecules which are in constant motion bombard the larger smoke particles causing them to move randomly.