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3. Kinetic Particle Theory

The picture above shows tear gas being used by the police for crowd control. It works by irritating the mucous membranes in your eyes, nose, mouth, throat and lungs, causing tremendous pain and discharge of fluids, e.g., tears and mucus. Hence, tear gas was also once known as a lachrymatory agent (from *lachrymal* meaning 'tear').

For riot control, tear gas is discharged from cartridges such as the ones below. To be effective, only a very small amount of gas is required to be packed inside the cartridges.

In training context, cartridges are sometimes not used. This is because there is no way to control the discharge once the cartridge is fired and begins discharging. To allow a controlled release of tear gas for training, tear gas tablets are used. They are placed on a small pan and heated gently with a flame (from a Bunsen burner). The tablet melts into a liquid which is vapourised upon further heating to release the tear gas. All this is done in a controlled fashion, and in an enclosed environment. Notice what happens to you once the gas hits you! You break out into an uncontrollable coughing and tearing fit!

What changes in state take place when the tear gas tablet is heated?

What happens at the atomic level?

How does the solid tear gas tablet get to the trainee?

Learning Outcomes

1. Describe the main properties of solids, liquids and gases.
2. Describe and explain the movement of particles in liquids and gases.
3. Explain the interconversion of states of matter in terms of the kinetic particle theory and the energy changes involved.
4. Explain everyday examples of diffusion in terms of particles.
5. State the qualitative effect of particle mass on the rate of diffusion and explain the effect of temperature on the rate of diffusion.

Accompanying Material

1. Tutorial

1. What is Matter and What are its Different States?

- ***Matter is anything that ____***

- There are three states of matter: solid, liquid, gas, and they have different properties.

Figure 1.1 Greenland's Birthday Canyon

Solids	Liquids	Gases
• Fixed volume • Fixed shape • Cannot be compressed • Do not flow	• Fixed volume • No fixed shape • Cannot be compressed • Flow easily	• No fixed volume • No fixed shape • Easily compressed • Flow in all directions

2. What is the Kinetic Particle Theory?

- The kinetic particle theory states that:
  - Particles are ____________ and are ______________________________________.
  - There are _____________ between particles of matter, and this space is different between solids, liquids and gases.
  - Particles are in ______________________________, and they move at different speeds in solids, liquids and gases.

3. Is there any Evidence for the Kinetic Particle Theory?

- ***Diffusion is the spreading and mixing of particles in liquids and gases from***
  ____
  ____

- Diffusion provides indirect evidence that matter comprises particles (which are too small to be seen with the naked eyes).

Science-in-Action

Can we 'see' atoms? Scientists have used the Scanning Tunnelling Microscope (STM) to take a 'picture' of the surface of a silicon crystal. The STM has a microprobe which generates a tiny current as the probe passes over the electron cloud of individual atoms. What is the electron cloud? You will learn more of this in the next chapter on atoms.

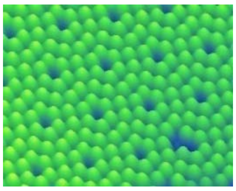


Figure 3.1 Silicon atoms

3.1 Diffusion in Gases

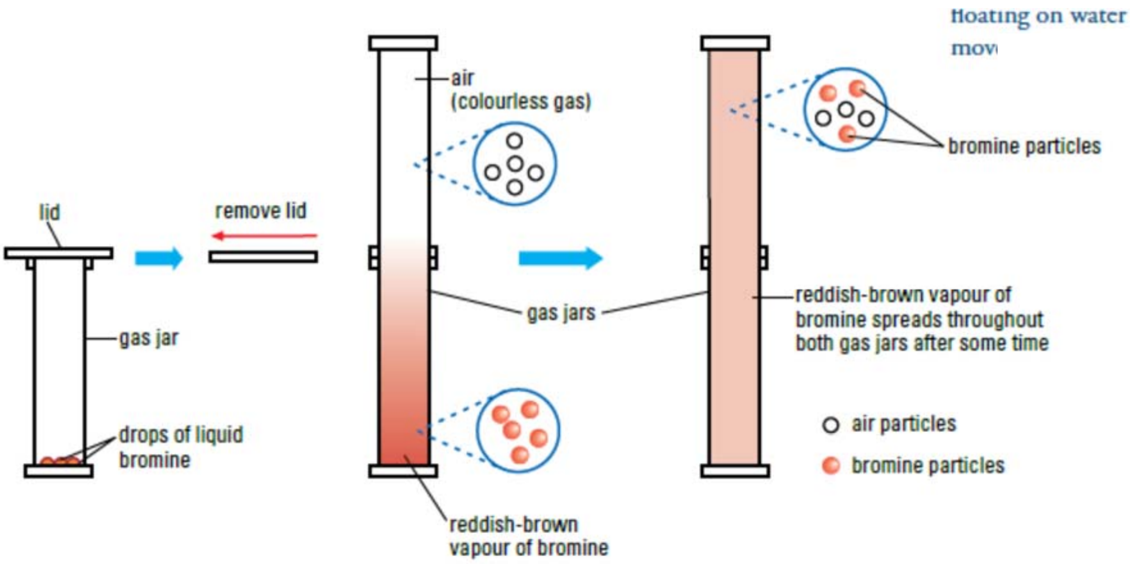


Figure 3.1.1 Diffusion of bromine

- Interpretation of Figure 3.1.1
  - A few drops of liquid bromine are placed in a gas jar.
  - The bromine evaporates to fill the gas jar with reddish-brown vapour.
  - An empty gas jar filled with air only is placed above the gas jar full of bromine vapour.
  - The reddish-brown vapour diffuses throughout the two gas jars after a period of time, even though bromine vapour is denser than air.
  - The bromine vapour moves upwards while the air particles move downwards and eventually they are completely mixed.

Singapore's Context

Figure 3.1.2 Aftermath of a gas explosion

There have been several incidences of gas explosions in HDB flats. One such flat in Bukit Merah was 'totalled' when a gas explosion ripped through the unit. A gas leak was suspected, and the gas which diffused throughout the unit was accidentally ignited, probably by an electric spark.

3.2 Diffusion in Liquids

Figure 3.2.1 Diffusion of potassium manganate(VII) in water

- Interpretation of Figure 3.2.1
  - A small crystal of potassium manganate(VII) is placed in water and dissolves to form a purple solution.
  - The purple colour diffuses throughout the water.

4. Factors Affecting the Rate of Diffusion

- Two factors affect the rate of diffusion:
  - Temperature
    - Particles move faster at higher temperatures as they absorb the heat energy.

- The faster the particles move, the faster the rate of diffusion, i.e., the higher the temperature, the faster the rate of diffusion.

- Mass of particle
  - The greater the (molecular) mass of a particle, the slower the rate of diffusion.

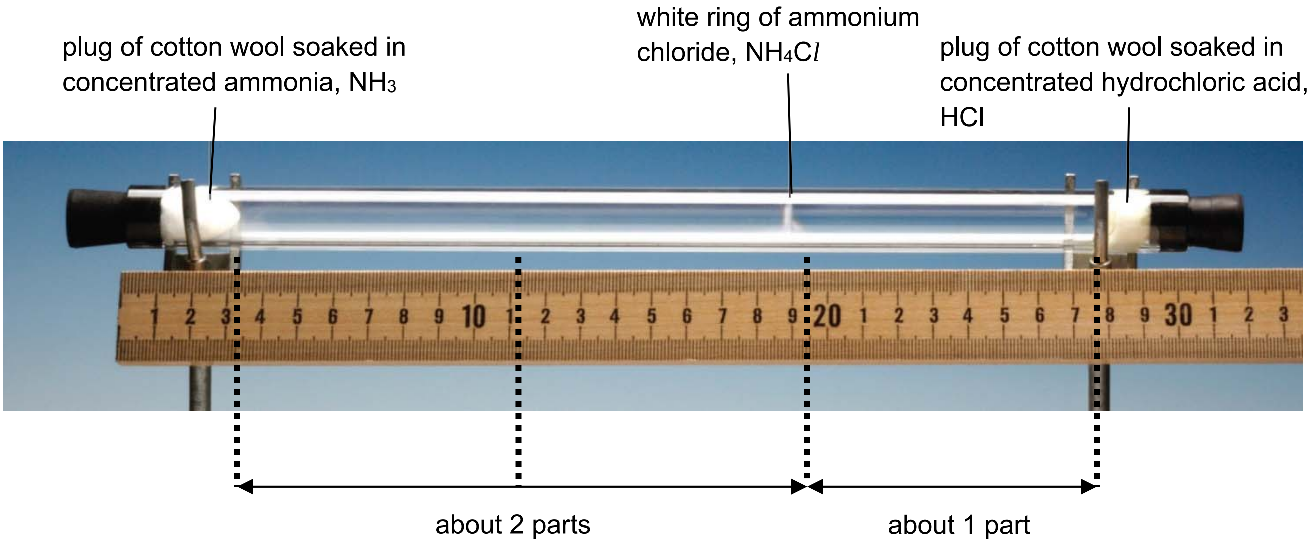
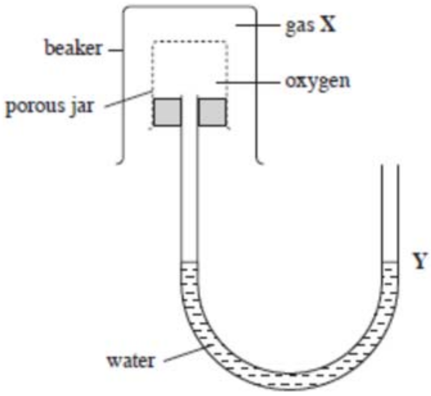


Figure 4.1 The rate of diffusion of ammonia and hydrochloric acid vapour determines the position of the white solid formed

- Interpretation of Figure 4.1
  - One plug of cotton wool is soaked in concentrated ammonia and placed at one end of the glass tube.
  - One plug of cotton wool is soaked in concentrated hydrochloric acid and placed at one end of the glass tube.
  - The glass tube is stoppered and observed.
  - A white ring is formed nearer the plug of cotton soaked in acid. Why?
    - The ammonia and hydrochloric acid vapourises, and the particles diffuse along the glass tube.
    - When they meet, they react to form ammonium chloride, the white solid.
    - ***Ammonia particles have a smaller relative molecular mass*** (NH_3 = ________) ***compared to hydrogen chloride particles*** (HC*l* = ___________).
    - As a result, ***ammonia particles diffuse _______________ than the hydrogen chloride particles.***
    - Hence, the white ring of ammonium chloride forms nearer the plug of cotton wool soaked in concentrated hydrochloric acid.
    - ***The relative molecular mass of hydrogen chloride is ________________ that of ammonia. Hence, the ammonia particles travel twice as much distance compared to the hydrogen chloride particles*** (Observe that if we divide the glass tube into 3 segments, the white ring forms at $^1/_3$ the length of the glass tube from the acid).

Checkpoint 1

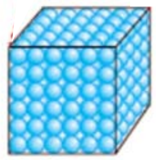
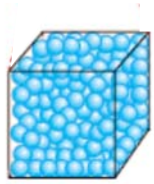
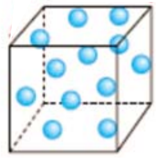
The following experiment is set up using oxygen inside the porous jar and a gas **X**.



In order to produce the greatest rise in the water level at **Y**, which of the following should be gas **X**?
A. Argon, Ar
B. Methane, CH_4
C. Carbon dioxide, CO_2
D. Carbon monoxide, CO

Give your reasons for the answer.

5. How Do Scientists Construct Models of Matter Based on Kinetic Particle Theory - Particulate Models of Matter?

Particles in a Solid	Particles in a Liquids	Particles in a Gases
• ______________________ ______________________ ______________________ • Very little empty space between them. • Cannot be compressed. • Vibrate but cannot move freely about their fixed positions.	• ______________________ ______________________ ______________________ • Very little empty space between them, although further apart than in solids. • Cannot be compressed. • Vibrate and can move freely throughout the liquid.	• ______________________ ______________________ ______________________ • Large spaces between them. • Can be compressed easily. • Vibrate and are free to move throughout the container.

- The particulate models above show the arrangement of particles in solids, liquids and gases. The arrangement also allows us to explain some properties of solids, liquids and gases, e.g., compressibility, rate of diffusion of substances in them.

Checkpoint 2

1. Sketch diagrams to show the changes in the arrangement of particles in a block of ice when heated until it forms vapour.

2. Using your diagrams above, explain (a) why ice cannot be compressed, and (b) why ice has a density of 0.92 g/cm^3 whereas water vapour has a density of 0.75 mg/cm^3.

6. Relating the Properties of Particles to the Macroscopic Properties of Matter

- The properties of matter must not be confused with the properties of particles.

- For example,

Matter	Particles
May be coloured, e.g., gold, iodine	Are not coloured
May be hot or cold	Do not get hot or cold
Expands when heated because the distance between the particles increase (as they vibrate more vigorously and move further apart)	Do not expand

7. Using the Kinetic Particle Theory to Explain Changes in State

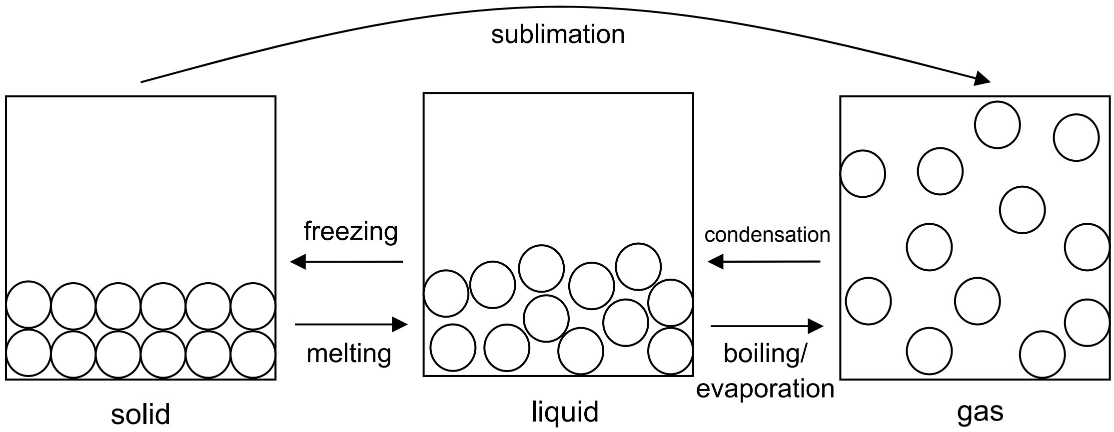


Figure 7.1 How the particulate model of matter represents changes in state

7.1 Melting

- Change in state from solid to liquid.

- Temperature at which the solid melts to become a liquid is known as the melting point.

- Process is as follows:
  (1) Particles in the solid absorb energy.
  (2) This energy causes the particles to vibrate faster about their fixed positions.
  (3) The vibrations of the particles overcome the forces of attraction between them.
  (4) The particles are no longer in fixed positions.
  (5) They can now move about freely, although still packed closely together.
  (6) The solid has now melted to form a liquid.

- Graphical interpretation of melting as follows:

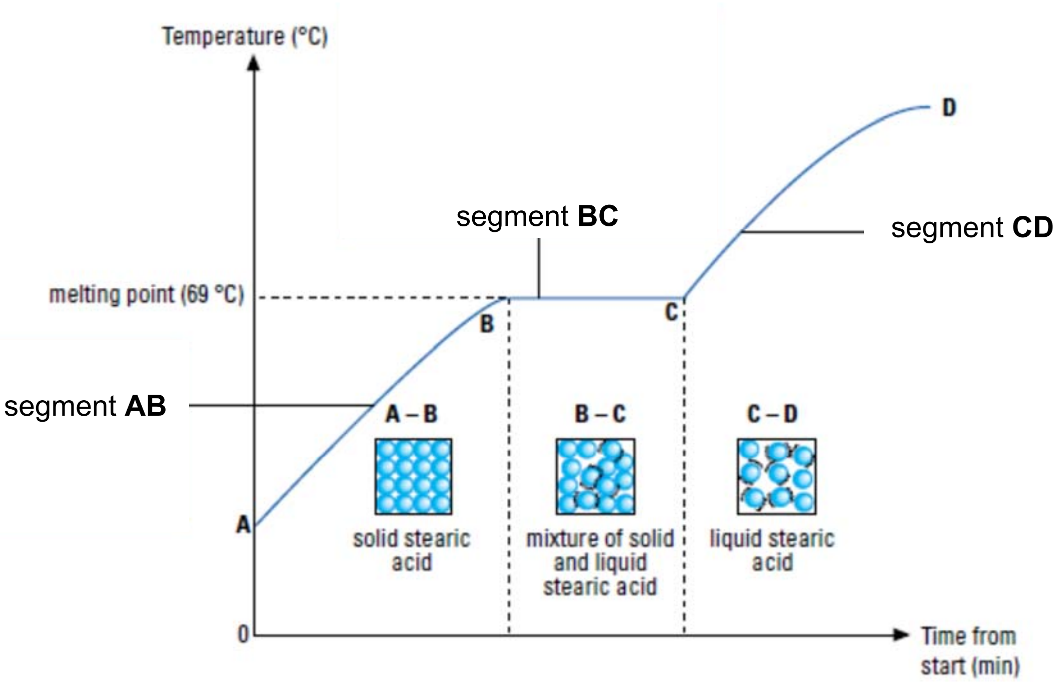


Figure 7.1.1 Temperature changes during melting

(1) Segment **AB**
- Temperature of the solid increases upon heating until ____________________________.
- The solid begins to melt at point B.

(2) Segment **BC**
- Heat energy absorbed by the particles is used to ____________________________ holding the particles together instead of being used to raise the temperature.
- Hence, the temperature ____ during melting.
- At this temperature, a solid-liquid mixture exists.

(1) Segment **CD**
- At point C, all the solid has ________________.
- The temperature of the liquid increases now as more heat is absorbed.

7.2 Freezing

- Change in state from liquid to solid.
- Temperature at which the liquid freezes to become a solid is known as the freezing point.
- Process is as follows:
  (1) Particles in the liquid lose energy.
  (2) The particles begin to move more slowly as the temperature decreases.
  (3) The particles are overcome by the forces of attraction and can no longer move freely.

(4) The particles settle into fixed positions.
(5) The liquid has now frozen to form a solid.

- Graphical interpretation of freezing as follows:

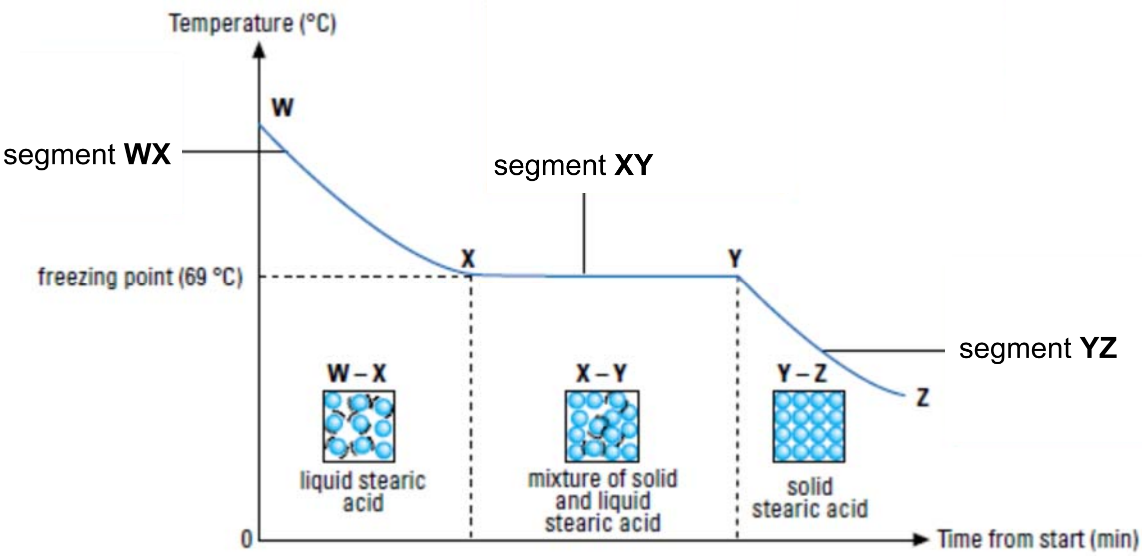


Figure 7.2.1 Temperature changes during freezing

(1) Segment **WX**
- Temperature of liquid decreases upon cooling until ______________________________
- The liquid begins to freeze at point X.

(2) Segment **XY**
- Heat energy is released from the liquid when the movement of the ________________
  ____
- The temperature does not decrease further and remains constant during freezing.
- At this temperature, a ___________________exists.

(3) Segment **YZ**
- At point Y, all the liquid has changed into a solid (frozen).
- The temperature of the solid decreases as cooling continues.

Beauty of Nature

Water when frozen slowly can produce water crystals with beautiful patterns:

7.3 Boiling

- Change in state from liquid to gas.

- Temperature at which a liquid boils to form a vapour is known as the boiling point.

- Process is as follows:
  (1) Particles in the liquid absorb energy.
  (2) The particles move faster as temperature increases
  (3) The particles gain enough energy to overcome the forces of attraction holding them together.
  (4) The particles move further apart and more freely.
  (5) When the particles gain enough energy to overcome both the forces of attraction and atmospheric pressure, the liquid changes into a gas.

- Graphical interpretation of boiling as follows:

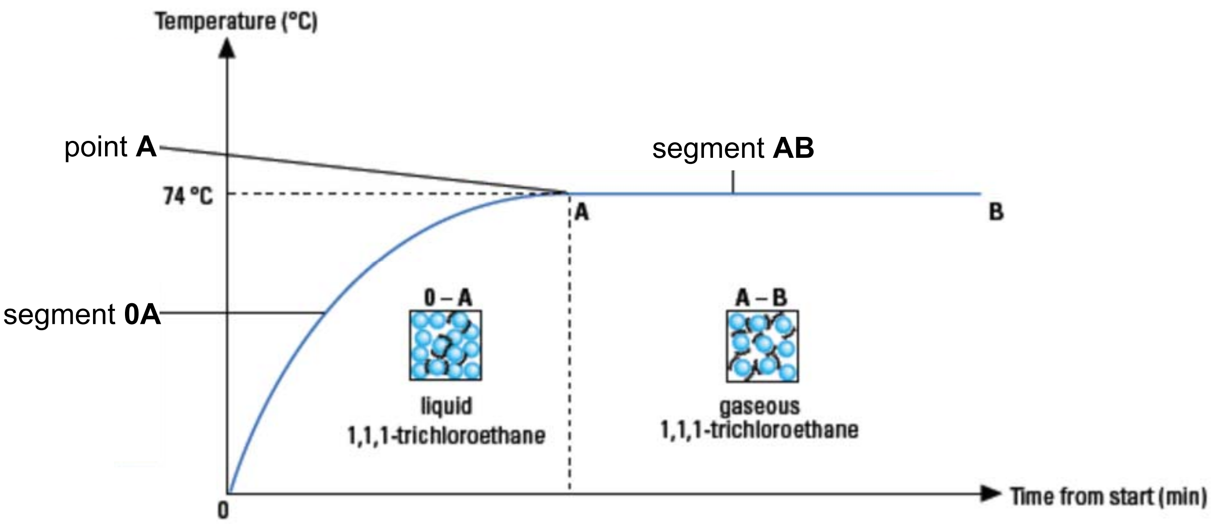


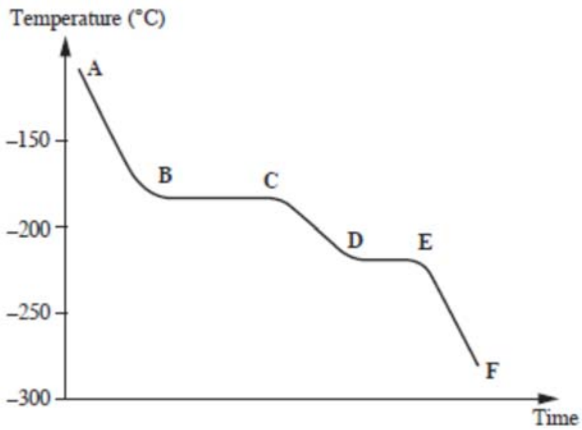
Figure 7.3.1 Temperature changes during boiling

(1) Segment **0A**
- Temperature of liquid increases until it ____.
- The liquid begins to _______ at point A.

(2) Segment **AB**
- Heat energy is absorbed by the particles of the liquid and used to __________________
  ____
- Hence, the temperature does not change but remain constant during boiling.
- The particles form a gas and move about freely.

<u>Checkpoint 3</u>

1. The graph below shows the temperature changes during the cooling of oxygen at atmospheric pressure.



a) Which of the segments in the graph indicates the following state(s) of oxygen:
- solid only:
- solid and liquid:
- liquid only:
- liquid and gas:
- gas only:

b) Which of the segments in the graph will the greatest decrease in volume of oxygen be observed?
A. AB → BC
B. BC → CD
C. CD → DE
D. DE → EF

c) Give your reason(s) for your answer in (b).

2. A substance has a boiling point of 80 °C and a melting point of 30 °C. Draw a cooling curve to

show the changes in temperature when a sample of this substance is cooled from 100 ^oC to 0 ^oC.

7.4 Condensation

- Change in state from ___________________________.
- Temperature at which a gas condenses to form a liquid is the same as the boiling point.

7.5 Evaporation

- Change in state from ___________________________________.
- Evaporation occurs ____________________________________, and the particles escape from the surface of the liquid to form a gas.

7.6 Sublimation

- Change in state from ___________________________ to form a liquid, e.g., sublimation of iodine.

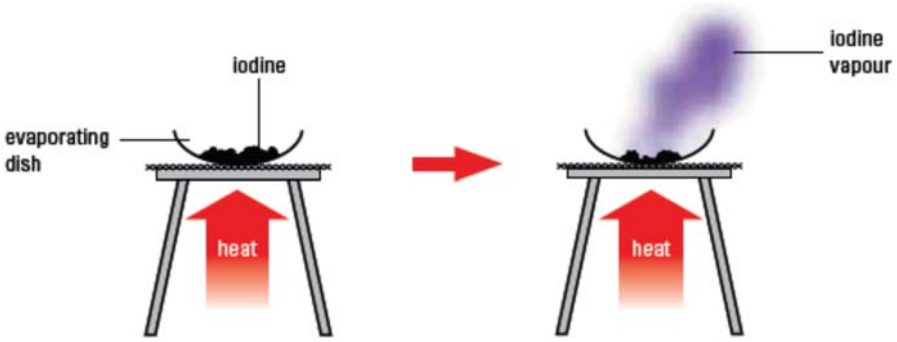


Figure 7.6.1 Sublimation of iodine

Checkpoint 4

1. State the difference between boiling and evaporation.

2. The change in state from a solid to a gas is known as sublimation. Suggest the term used to describe the reverse, i.e., a change in state from a gas to a solid.

3. The melting and boiling points of six substances are given below.

Substance	Melting point/ °C	Boiling point/ °C
A	-112	-108
B	-39	357
C	25	280
D	98	890
E	114	184
F	832	1330

a) Which substance(s) is a gas at room temperature?

b) Which substance(s) is a liquid at room temperature?

c) Which substance(s) will change its physical state when heated from 0 °C to 50 °C?

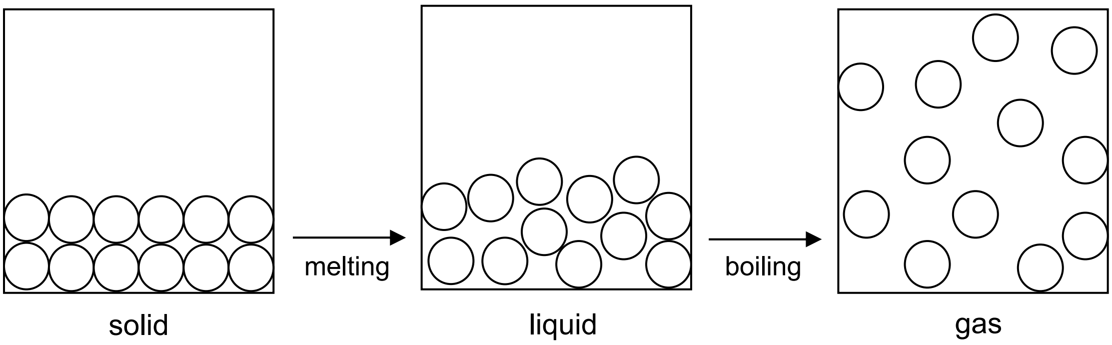
d) Which substance(s) exist in the liquid state over the widest range of temperature?

e) Which substance will have its particles furthest apart at 0 °C?

What changes in state take place when the tear gas tablet is heated?

The tear gas tablet melts to form a liquid, then vapourises to form a gas.

What happens at the atomic level?



The particles in the solid gain energy and vibrate faster. When they gain enough energy to overcome the forces of attraction that hold them together, they can now move freely and forms a liquid. The particles in the liquid continue to gain energy and move about faster. When they gain enough energy to overcome the forces of attraction that hold them together, they escape from the liquid into the surroundings, and can move about more freely, forming a gas.

How does the solid tear gas tablet get to the trainee?

The particles diffuse through the air to get to the trainee.

The Periodic Table of the Elements

Group

I	II											III	IV	V	VI	VII	0
						1 H hydrogen 1											4 He helium 2
7 Li lithium 3	9 Be beryllium 4											11 B boron 5	12 C carbon 6	14 N nitrogen 7	16 O oxygen 8	19 F fluorine 9	20 Ne neon 10
23 Na sodium 11	24 Mg magnesium 12											27 Al aluminium 13	28 Si silicon 14	31 P phosphorus 15	32 S sulfur 16	35.5 Cl chlorine 17	40 Ar argon 18
39 K potassium 19	40 Ca calcium 20	45 Sc scandium 21	48 Ti titanium 22	51 V vanadium 23	52 Cr chromium 24	55 Mn manganese 25	56 Fe iron 26	59 Co cobalt 27	59 Ni nickel 28	64 Cu copper 29	65 Zn zinc 30	70 Ga gallium 31	73 Ge germanium 32	75 As arsenic 33	79 Se selenium 34	80 Br bromine 35	84 Kr krypton 36
85 Rb rubidium 37	88 Sr strontium 38	89 Y yttrium 39	91 Zr zirconium 40	93 Nb niobium 41	96 Mo molybdenum 42	– Tc technetium 43	101 Ru ruthenium 44	103 Rh rhodium 45	106 Pd palladium 46	108 Ag silver 47	112 Cd cadmium 48	115 In indium 49	119 Sn tin 50	122 Sb antimony 51	128 Te tellurium 52	127 I iodine 53	131 Xe xenon 54
133 Cs caesium 55	137 Ba barium 56	139 La lanthanum 57 *	178 Hf hafnium 72	181 Ta tantalum 73	184 W tungsten 74	186 Re rhenium 75	190 Os osmium 76	192 Ir iridium 77	195 Pt platinum 78	197 Au gold 79	201 Hg mercury 80	204 Tl thallium 81	207 Pb lead 82	209 Bi bismuth 83	– Po polonium 84	– At astatine 85	– Rn radon 86
– Fr francium 87	– Ra radium 88	– Ac actinium 89 †															

*58-71 Lanthanoid series
†90-103 Actinoid series

140 Ce cerium 58	141 Pr praseodymium 59	144 Nd neodymium 60	– Pm promethium 61	150 Sm samarium 62	152 Eu europium 63	157 Gd gadolinium 64	159 Tb terbium 65	162 Dy dysprosium 66	165 Ho holmium 67	167 Er erbium 68	169 Tm thulium 69	173 Yb ytterbium 70	175 Lu lutetium 71
232 Th thorium 90	– Pa protactinium 91	238 U uranium 92	– Np neptunium 93	– Pu plutonium 94	– Am americium 95	– Cm curium 96	– Bk berkelium 97	– Cf californium 98	– Es einsteinium 99	– Fm fermium 100	– Md mendelevium 101	– No nobelium 102	– Lr lawrencium 103

Key

a X b	
	a = relative atomic mass X = atomic symbol b = proton (atomic) number