Thermal Physics and the Particulate Nature of Matter

IB SL Study Guide

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Aligned to IB Physics 2025 syllabus — Theme B: The Particulate Nature of Matter (first assessment 2025)

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Section 1: Thermal Energy and Temperature

Internal Energy

Internal energy is the total random kinetic energy and potential energy of all the particles in a substance. It is NOT the same as temperature.

MEMORISE THIS

Internal energy = sum of random kinetic energy + intermolecular potential energy of all particles

- **Kinetic energy component**: energy of random translational, rotational, and vibrational motion of molecules
- **Potential energy component**: energy stored in intermolecular bonds (relevant in liquids and solids)
- In an **ideal gas**, the potential energy component is zero — molecules do not interact except during collisions

EXAM ALERT

Temperature vs thermal energy — a source of Paper 1 marks every year. Temperature is a measure of the **average** random kinetic energy per particle. Thermal energy (heat) is a **total** quantity for the whole system. A large cold lake contains more internal energy than a small hot cup of tea, even though the tea is at a higher temperature. Never write "temperature = thermal energy."

The Kelvin Scale and Absolute Zero

The **Kelvin scale** is the SI temperature scale used in all physics equations.

MEMORISE THIS

$$T(\mathrm{K}) = T(^{\circ}\mathrm{C}) + 273.15 \approx T(^{\circ}\mathrm{C}) + 273$$

- **Absolute zero (0 K = −273.15 °C)** is the temperature at which particles have minimum possible kinetic energy (zero in the classical model).
- You cannot have a temperature below 0 K.
- **Always convert to Kelvin** before using any gas law or kinetic theory equation.

EXAM ALERT

Forgetting to convert to Kelvin is the single most common error in thermal physics. A temperature of 27 °C must be entered as 300 K in every equation. The IB mark scheme deducts the mark if you use Celsius in a gas law calculation.

Specific Heat Capacity

Specific heat capacity (c) is the energy required to raise the temperature of 1 kg of a substance by 1 K (or 1 °C).

MEMORISE THIS

$$Q = mc\Delta T$$

Symbol	Meaning	SI Unit
Q	heat energy transferred	J
m	mass	kg
c	specific heat capacity	$\mathrm{J\ kg^{-1}K^{-1}}$
ΔT	temperature change	K or °C

WORKED EXAMPLE

Worked Example B1 — Heating water:

A kettle contains 1.5 kg of water initially at $18\ ^{\circ}\mathrm{C}$. The specific heat capacity of water is $4200\ \mathrm{J\ kg^{-1}K^{-1}}$. Calculate the energy needed to bring the water to boiling point (100 °C).

Given: $m = 1.5\ \mathrm{kg}$, $c = 4200\ \mathrm{J\ kg^{-1}K^{-1}}$, $\Delta T = 100 - 18 = 82\ \mathrm{K}$

$Q = mc\Delta T = 1.5 \times 4200 \times 82 = 517{,}000\ \mathrm{J} = 517\ \mathrm{kJ}$

Examiner tip: Units for c are always $\mathrm{J\ kg^{-1}K^{-1}}$ — do not write $\mathrm{J/kg/K}$ in an IB paper; use the $^{-1}$ superscript notation. Note ΔT in K equals ΔT in °C, so converting to Kelvin does not change ΔT — only the absolute temperature T needs converting (e.g., for gas laws).

Specific Latent Heat

Specific latent heat (L) is the energy required to change the phase of 1 kg of a substance at constant temperature.

MEMORISE THIS

$Q = mL$

- **Specific latent heat of fusion** (L_f): solid ↔ liquid (melting/freezing)
- **Specific latent heat of vaporisation** (L_v): liquid ↔ gas (boiling/condensing)
- For water: $L_f \approx 3.34 \times 10^5$ J kg^{-1}; $L_v \approx 2.26 \times 10^6$ J kg^{-1}
- During a phase change, temperature is **constant** — energy goes into breaking/forming intermolecular bonds, not increasing kinetic energy.

WORKED EXAMPLE

Worked Example B2 — Melting ice:

Calculate the total energy needed to convert 0.50 kg of ice at $-10\ ^\circ$C to liquid water at 20 $^\circ$C.

Use $c_{\text{ice}} = 2100$ J kg^{-1}K^{-1}, $L_f = 3.34 \times 10^5$ J kg^{-1}, $c_{\text{water}} = 4200$ J kg^{-1}K^{-1}.

Step 1 — heat ice from −10 °C to 0 °C:

$Q_1 = 0.50 \times 2100 \times 10 = 10{,}500$ J

Step 2 — melt ice at 0 °C:

$Q_2 = 0.50 \times 3.34 \times 10^5 = 167{,}000$ J

Step 3 — heat water from 0 °C to 20 °C:

$Q_3 = 0.50 \times 4200 \times 20 = 42{,}000$ J

Total: $Q = 10{,}500 + 167{,}000 + 42{,}000 = 219{,}500$ J ≈ 220 kJ

Phase Change Diagram

A **heating curve** shows temperature vs. energy supplied for a pure substance. Its characteristic shape has two flat regions (phase changes) and three sloping regions (temperature increases in each phase).

- **Slope 1 (solid region):** gradient $= 1/(mc_{\text{solid}})$. Steeper slope = smaller specific heat capacity.
- **Flat region 1 (melting):** temperature is constant at the melting point. Length $\propto mL_f$.
- **Slope 2 (liquid region):** gradient $= 1/(mc_{\text{liquid}})$.

- **Flat region 2 (boiling):** temperature is constant at the boiling point. Length $\propto mL_v$.
- **Slope 3 (gas region):** steepest, since gases typically have lower specific heat capacities per kg than liquids.

⚠ EXAM ALERT

The boiling plateau is always longer than the melting plateau for water (and most substances), because $L_v \gg L_f$. Examiners often ask students to sketch heating curves — if you draw the plateaus the same length, you lose marks.

Section 2: Ideal Gas Laws

The Three Empirical Gas Laws

An **ideal gas** is a theoretical model in which molecules are treated as point masses with no intermolecular forces.

MEMORISE THIS

Boyle's Law (constant T, fixed amount of gas):

$$pV = \text{constant} \qquad \Rightarrow \qquad p_1V_1 = p_2V_2$$

Charles's Law (constant p, fixed amount of gas):

$$\frac{V}{T} = \text{constant} \qquad \Rightarrow \qquad \frac{V_1}{T_1} = \frac{V_2}{T_2}$$

Gay-Lussac's Law (constant V, fixed amount of gas):

$$\frac{p}{T} = \text{constant} \qquad \Rightarrow \qquad \frac{p_1}{T_1} = \frac{p_2}{T_2}$$

All three combine to give the **combined gas law:**

$$\frac{p_1V_1}{T_1} = \frac{p_2V_2}{T_2}$$

The Ideal Gas Equation

Adding Avogadro's law (equal volumes of ideal gases at the same T and p contain equal numbers of molecules) to the combined gas law gives the **ideal gas equation**:

MEMORISE THIS

$$pV = nRT$$

Symbol	Meaning	Value / Unit
p	pressure	Pa (N m^{-2})
V	volume	m^3
n	amount of substance	mol
R	universal gas constant	8.31 J $\text{mol}^{-1}\text{K}^{-1}$
T	absolute temperature	K

R and the equation are given in the **IB data booklet**. You need to know what each symbol means and be able to rearrange.

IB TIP

Avogadro's number: $N_A = 6.02 \times 10^{23}\ \text{mol}^{-1}$. The number of molecules $N = nN_A$. **Molar mass** (M_r, in kg mol^{-1}): mass of substance $m = nM_r$, so $n = m/M_r$. Example: 8.0 g of oxygen ($M_r = 0.032\ \text{kg mol}^{-1}$) contains $n = 0.008/0.032 = 0.25$ mol.

WORKED EXAMPLE

Worked Example B3 — Gas in a cylinder:

A fixed amount of ideal gas is enclosed in a cylinder. Initially, $T_1 = 300$ K, $p_1 = 1.0 \times 10^5$ Pa, and $V_1 = 2.0 \times 10^{-3}\ \text{m}^3$. The gas is heated at constant volume until $T_2 = 450$ K.

(a) Find the final pressure p_2.

(b) Calculate the number of moles of gas.

(a) Using Gay-Lussac's Law (constant V):

$$\frac{p_1}{T_1} = \frac{p_2}{T_2} \implies p_2 = p_1 \times \frac{T_2}{T_1} = 1.0 \times 10^5 \times \frac{450}{300} = 1.5 \times 10^5\ \text{Pa}$$

(b) Using $pV = nRT$:

$$n = \frac{p_1V_1}{RT_1} = \frac{1.0\times10^5\times2.0\times10^{-3}}{8.31\times300} = \frac{200}{2493} \approx 0.080\ \text{mol}$$

EXAM ALERT

Always check: is volume constant, pressure constant, or temperature constant? Identify which law applies before calculating. If two of p, V, T change, use the combined gas law. If you have mass information, find n first via $n = m/M_r$, then use $pV = nRT$.

▸Watch: Ideal Gas Law — Khan Academy VIDEO

Section 3: Molecular Model of an Ideal Gas

Assumptions of the Kinetic Theory

The **kinetic model** explains macroscopic gas behaviour (pressure, temperature) in terms of molecular motion.

MEMORISE THIS

Six assumptions of an ideal gas (state these precisely in exam answers):

1. The gas consists of a large number of identical molecules (or atoms for monatomic gases).
2. Molecules are **point masses** — their volume is negligible compared with the volume of the container.
3. Molecules undergo **random motion** in all directions with a range of speeds.
4. Collisions between molecules and with container walls are **perfectly elastic** — no kinetic energy is lost.
5. There are **no intermolecular forces** except during collisions.
6. The duration of collisions is negligible compared with the time between collisions.

Pressure from Molecular Motion

Pressure arises from the force exerted when molecules collide with the container walls. Using Newton's second law and the impulse of a molecule bouncing off a wall, kinetic theory gives:

MEMORISE THIS

$pV = \frac{1}{3}Nm\langle v^2\rangle$

where N is the total number of molecules, m is the mass of one molecule, and $\langle v^2\rangle$ is the mean square speed.

The **root mean square (rms) speed** is $v_{\text{rms}} = \sqrt{\langle v^2\rangle}$.

IB TIP

You are not required to reproduce the full derivation at SL, but you should be able to describe the physical reasoning (molecular collisions with walls → impulse → force → pressure) and use the result. The formula is in the data booklet.

Mean Kinetic Energy and Temperature

Comparing $pV = \frac{1}{3}Nm\langle v^2\rangle$ with $pV = NkT$ (where $k = R/N_A$ is the Boltzmann constant):

MEMORISE THIS

$\frac{1}{2}m\langle v^2\rangle = \frac{3}{2}kT$

The average translational kinetic energy of a molecule is directly proportional to absolute temperature.

Constant	Value	Unit
k (Boltzmann constant)	1.38×10^{-23}	J K^{-1}
R (gas constant)	8.31	$\text{J mol}^{-1}\text{K}^{-1}$
Relationship	$k = R/N_A$	—

For one mole of gas: mean total kinetic energy $= \frac{3}{2}RT$.

WORKED EXAMPLE

Worked Example B4 — rms speed of a gas:

Calculate the rms speed of nitrogen molecules ($M_r = 0.028\ \text{kg mol}^{-1}$) at $T = 300\ \text{K}$.

Using $\frac{1}{2}mv_{\text{rms}}^2 = \frac{3}{2}kT$:

$$v_{\text{rms}} = \sqrt{\frac{3kT}{m}} = \sqrt{\frac{3RT}{M_r}} = \sqrt{\frac{3\times 8.31\times 300}{0.028}} = \sqrt{\frac{7479}{0.028}} = \sqrt{267{,}000} \approx 517\ \text{m s}^{-1}$$

Note: $m = M_r/N_A$ for one molecule, so the formula can also be written $v_{\text{rms}} = \sqrt{3RT/M_r}$ using molar quantities.

EXAM ALERT

Temperature must be in Kelvin in ALL kinetic theory equations. Also note that $\frac{1}{2}m\langle v^2\rangle = \frac{3}{2}kT$ gives the average kinetic energy per **molecule** (using k), not per mole. For per mole, multiply by N_A: $E_{K,\text{mol}} = \frac{3}{2}RT$.

Section 4: Real Gases and Phase Changes

Departures from Ideal Behaviour

Real gases deviate from ideal gas behaviour because real molecules:

- Do have a finite volume (so at very high pressure, V cannot be compressed to zero)
- Do have intermolecular forces — attractive at moderate distances, repulsive at very short distances

MEMORISE THIS

When does a real gas behave most like an ideal gas?

- **High temperature** — molecules have enough kinetic energy that intermolecular potential energy is negligible

- **Low pressure** — molecules are far apart, so intermolecular forces and finite volume are negligible

When does a real gas deviate most from ideal behaviour?

- **High pressure** (molecules close together — volume effect matters)
- **Low temperature** — especially near the boiling point (intermolecular attractions significant)

HL The van der Waals equation corrects for real gas behaviour:

$$\left(p + \frac{an^2}{V^2}\right)(V - nb) = nRT$$

where a accounts for intermolecular attractions and b accounts for the finite volume of molecules. This is beyond SL but useful context.

Evaporation and Boiling

These are two distinct processes by which a liquid becomes a gas.

MEMORISE THIS

Feature	Evaporation	Boiling
Where it occurs	Surface only	Throughout the liquid (bubbles form)
Temperature	Any temperature below boiling point	At the boiling point (fixed for given pressure)
Rate	Increases with temperature, surface area, air flow	Depends on heating rate
Effect on liquid	Cools the liquid (highest-energy molecules escape)	Temperature stays constant while boiling

IB TIP

Exam command: “Explain in terms of molecular behaviour why the temperature of a liquid drops during evaporation.” Model answer: The molecules that escape have above-average kinetic energy. The remaining molecules therefore have a lower average kinetic energy. Since temperature is proportional to average kinetic energy, the temperature of the liquid decreases. (3 marks — include: high-energy molecules escape, average KE of remainder decreases, temperature proportional to average KE.)

Exam-Style Practice Questions

Paper 1 Style (MCQ)

Q1. A gas is heated at constant volume. Which of the following correctly describes what happens?

A. The pressure decreases because molecules move faster and collide less frequently.

B. The pressure increases because molecules move faster and hit the walls with greater force and frequency.

C. The volume increases to maintain constant pressure.

D. The number of moles of gas increases.

▶ Answer

Q2. An ideal gas is compressed isothermally (at constant temperature) to half its original volume. Which of the following statements is correct?

A. The pressure doubles and the mean kinetic energy of molecules doubles.

B. The pressure doubles and the mean kinetic energy of molecules is unchanged.

C. The pressure halves and the mean kinetic energy of molecules is unchanged.

D. The pressure is unchanged because temperature is constant.

▶ Answer

Paper 2 Style (Structured Response)

Q3. A sealed container of volume $5.0 \times 10^{-3}\ \mathrm{m}^3$ contains an ideal gas at pressure $2.0 \times 10^5\ \mathrm{Pa}$ and temperature $27\ ^\circ\mathrm{C}$.

(a) Show that the number of moles of gas is approximately 0.40 mol. [2]

(b) The temperature is raised to $127\ ^\circ\mathrm{C}$ at constant volume. Calculate the new pressure. [2]

(c) State and explain the effect on the pressure if the same number of moles of a real gas (rather than an ideal gas) were used under these conditions (high temperature, moderate pressure). [2]

▶ Mark-scheme answers

⚠ **EXAM ALERT**

Common Theme B errors that cost marks:

1. Using °C instead of K in gas law and kinetic theory equations — always add 273 (or 273.15).
2. Confusing $Q = mc\Delta T$ (sensible heat) and $Q = mL$ (latent heat) — during a phase change, use L not c.
3. Stating “temperature is thermal energy” — temperature is proportional to **average kinetic energy per particle**.
4. Forgetting that the mean kinetic energy equation gives energy per **molecule** (use k); for per mole, use $\frac{3}{2}RT$.
5. Drawing a heating curve with equal-length plateaus — the vaporisation plateau is always longer than the melting plateau ($L_v \gg L_f$).
6. Describing evaporation incorrectly — it cools the liquid because **high-energy** molecules escape, lowering the average KE of those remaining.

May 2026 Exam Predictions

Based on past IB Physics paper patterns, Theme B questions in May 2026 are likely to include:

- **Paper 1 MCQ:** Boyle’s Law graph interpretation (which graph is correct at constant T), or a temperature/kinetic energy question.
- **Paper 2 Short Answer:** A multi-step gas law calculation requiring temperature conversion and identification of the correct law. Likely 4–6 marks total.
- **Paper 2 Extended Answer:** An “explain using the molecular model” question (2–3 marks) — most commonly asking students to explain why pressure increases when temperature increases at constant volume, or to explain evaporative cooling at the molecular level.
- **Specific latent heat calculation:** Often combined with $Q = mc\Delta T$ (calculate total energy to melt ice and warm the resulting water).

IB TIP

Highest-value skill in Theme B: Writing molecular-level explanations. The mark scheme always awards marks for: (1) a specific statement about molecular motion or energy, (2) a link to the macroscopic property being asked about. Vague answers like “the molecules move more” score zero. Precise answers like “the molecules move faster, so they collide with the walls more frequently and with greater change in momentum, increasing the force on the walls” score full marks.