IDX G10 Physics H
Study Guide Issue S1 Midterms
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Contents:

13-9 Kinetic Theory

Kinetic Theory

- The analysis of matter in terms of atoms in continuous random motion

- Ideal Gas: a real gas that follows the ideal gas law closely, found at low pressures and far from its liquefaction point.

Basic Postulates of the Kinetic Theory

1. Large Number: There are large number of molecules N, each of mass m, moving in random directions with a variety of speeds.

2. Far Apart: The molecules are, on the average, far apart from one another (average separation >> diameter of each molecule).

3. Collisions & Forces: The molecules obey the laws of classical mechanics and interact with each other only when colliding. Although molecules exert weak attractive forces on each other between collisions, the potential energy associated with these forces is small compared with kinetic energy, which can be ignored.

4. Elastic Collisions: Collisions are perfectly elastic. The collisions are of very short duration compared to the time between them. The potential energy associated with collisions can be ignored compared to the kinetic energy between collisions.

Formula 1: Pressure in a Gas

- The pressure a gas exerts is expressed in terms of the molecular properties of the gas (derived from the kinetic theory).

$$P = \frac{1}{3}\frac{Nm\overline{v^2}}{V}$$

Formula 2: Temperature and Average Kinetic Energy

- The average translational kinetic energy of molecules is directly proportional to the absolute (Kelvin) temperature of the gas.

$$\overline{KE} = \frac{3}{2}kT$$

  - o   k = Boltzmann's constant = 1.38×10^{-23} J/K
  - o   T = Absolute Temperature (K)

Formula 3: Root-Mean-Square (rms) Speed

$$v_{rms} = \sqrt{\frac{3kT}{m}}$$

14-1 Heat as Energy Transfer

Heat - Definition and Properties

- Definition: Heat is the transfer of thermal energy from one object to another because of a temperature difference.
    - Scalar quantity
    - Symbol: Q
    - Direction of Flow: Heat always flows from higher temperature to lower temperature.

Units of Heat

- SI Unit: joule (J)
- calorie (cal): 1 cal = 4.186 J
- Calorie (Cal): 1 Cal = 1 kcal = 4186 J
- Btu (British thermal unit): 1 Btu = 1055 J

Sign Convention for Heat Transfer

- Q > 0: Object absorbs energy (heat gain)
- Q < 0: Object loses energy (heat loss)

Key Distinction

- Heat vs. Temperature:
    - Temperature measures average kinetic energy of particles
    - Heat is energy transfer due to temperature difference
- Heat Flow Direction: Depends only on temperature, not on amount of internal energy
    - Example: Heat flows from 50 g water at 30°C to 200 g water at 25°C, even though the cooler water has more total internal energy

14-2 Internal Energy

Internal Energy

- Definition: The total energy of all molecules in an object, including both kinetic and potential energy.
    - Symbol: U
    - Note: The term "thermal energy" is sometimes used to mean the same thing but they're different!
    - We only calculate difference of internal energy, since total thermal energy is too large and does not matter in thermodynamics.

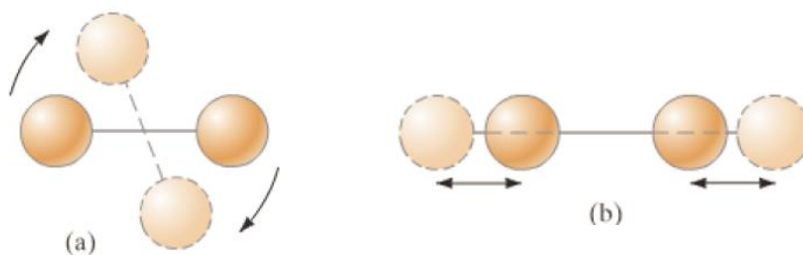Key Distinctions: Internal Energy vs. Heat vs. Temperature

- Temperature: A measure of the average kinetic energy of particles.
- Heat (Q): The transfer of thermal energy due to a temperature difference.
- Internal Energy (U): The total stored energy (kinetic + potential) of all molecules in an object.

Direction of Heat Flow

- Heat flow depends solely on temperature, not on which object has more internal energy.
  - So even if an object has higher internal energy, if it has lower temperature than the other objects in the system, heat will flow towards that object,

Internal Energy of an Ideal Gas

- Monatomic Gases: Internal energy consists only of translational kinetic energy.
  - Formula: $U = N \cdot \overline{KE} = \frac{3}{2}NkT = \frac{3}{2}nRT$
    - N: # number of molecules
    - $\overline{KE}$: average kinetic energy per molecule
    - k: Boltzmann's constant $\approx 1.38 \times 10^{-23}$ J/K
    - n: number of moles
    - R: Ideal gas constant ≈ 8.314 J/(mol · K)
- Gases with Multiple Atoms per Molecule: Internal energy is greater.
  - Includes rotational and vibrational energy in addition to translational KE.
  - Still a function of temperature only (U ∝ T).

(a)   (b)

Internal Energy of Real Gases, Liquids, and Solids

- Real Gases: Internal energy depends mainly on temperature, but also somewhat on pressure and volume due to intermolecular potential energy.
- Liquids and Solids: Internal energy is complex.
  - Includes electrical potential energy associated with the forces (or "chemical" bonds) between atoms and molecules.

14-3 Specific Heat

Specific Heat Capacity

- Definition: The amount of energy required to raise the temperature of 1 kg of a substance by 1°C (or 1 K).
    - It measures a substance's ability to absorb heat.
    - Scalar quantity
    - Symbol: c

Units of Specific Heat

- SI unit: J/kg·°C or J/kg·K
- Common unit: kcal/kg·°C or kcal/kg·K
- Example: c_{water} = 4186 J/kg·°C = 1 kcal/kg·°C

General Properties

- The value of c depends on temperature and slightly on pressure, but is often considered constant for small temperature changes.
- For Liquids and Solids: The specific heat is a property of the material itself.

Specific Heat for Gases

- The specific heat of a gas depends on how the process is carried out.
- c_p: Specific heat at constant pressure.
- c_v: Specific heat at constant volume.
- $c_p > c_v$ for the same gas because at constant pressure, some energy is used to do work as the gas expands, requiring more heat for the same temperature increase.

Heat Transfer Equation

- Formula: $Q = mc\Delta T$
    - Q: Heat transferred (J)
    - m: Mass of substance (kg)
    - c: Specific heat capacity (J/kg·°C)
    - ΔT: Change in temperature (°C or K) = T_final - T_initial
- Sign Convention:
    - Q > 0: Heat gained (temperature increases)
    - Q < 0: Heat lost (temperature decreases)

14-4 Calorimetry

Systems & Isolation

- System: The part of the universe we are focusing on.
- Isolated System: A system where no mass or energy crosses its boundaries. This is the ideal condition for calorimetry.

The Calorimeter

- A device designed to approximate an isolated system.
- Used to measure heat transfer and determine specific heats.
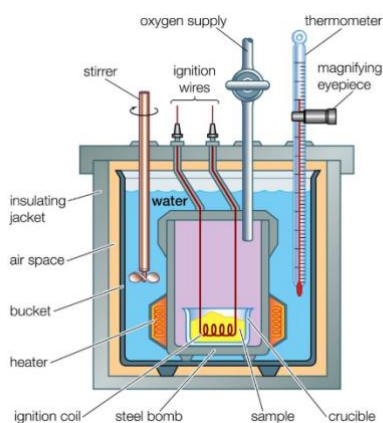
The Core Principle: Conservation of Energy

- For an isolated system, the total energy is constant.
- |Heat Lost| = |Heat Gained|
- Mathematically: $\Sigma Q = 0$
- The heat flowing out of the hotter object(s) must equal the heat flowing into the colder object(s).
- The final temperature (T_f) must be between the initial temperatures of the hot and cold objects.

Problem-Solving Strategy

- Identify all components that gain heat (Q > 0) and lose heat (Q < 0).
- Apply $Q = mc\Delta T$ for each component.
- Set up the equation: $Q_{lost\ by\ hot} + Q_{gained\ by\ cold} = 0$
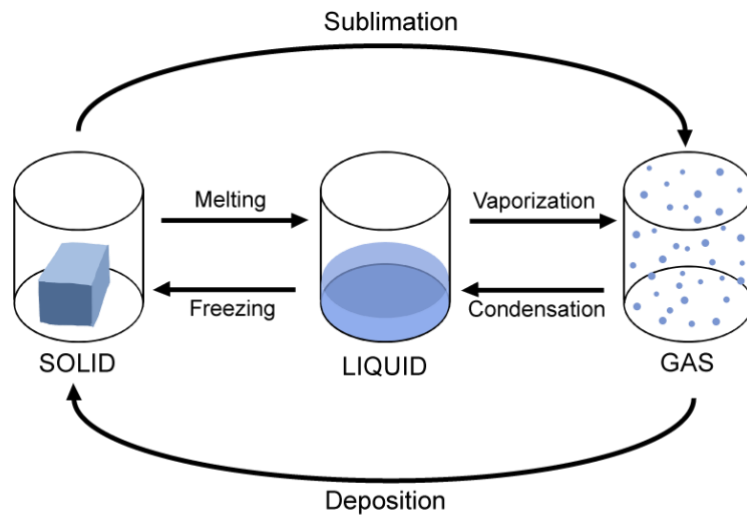- Solve for the unknown

Bomb Calorimetry

- A specialized type used for combustion reactions.
- Measures the heat released by burning a substance to determine its chemical energy content (e.g., food Calories).
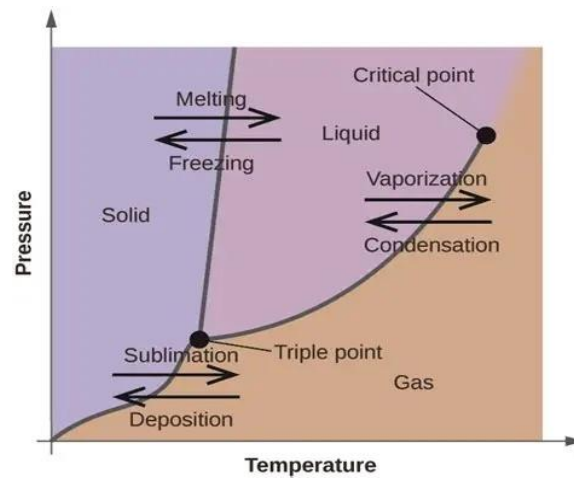
14-5 Latent Heat

Phase Change

Latent Heat

- The amount of energy associated with phase change

    o Measured using calorimetry

- Latent heat of fusion (L_F)

    o Heat required to change 1 kg of a substance from the solid phase to the liquid phase

    o Formula: $Q = mL_F$ (fusion/melting)

    o $Q = -mL_F$ (freezing)

    o SI unit: J/kg

        ▪ kJ/kg, cal/kg, kcal/kg (Cal/kg)

- Latent heat of vaporization (L_V)

    o Heat required to change 1 kg of a substance from the liquid phase to the gas phase

    o Formula: $Q = mL_V$ (vaporization)

    o $Q = -mL_V$ (condensation)

    o SI unit: J/kg

        ▪ kJ/kg, cal/kg, kcal/kg (Cal/kg)

- Kinetic Theory of Latent Heats

    o For a given substance, heat of vaporization is generally much greater than heat of fusion.

        ▪ $L_V \gg L_F$

- Latent heat of fusion overcomes the potential energy
- Phase-Change Diagram (Heating Curve)

14-6 Conduction

- Two materials of different temperatures are in direct contact
- By adjacent molecular collisions:
  - Kinetic energy transferred from faster moving molecules to slower molecules
    - Molecules (and/or electrons) moving over small distance and colliding
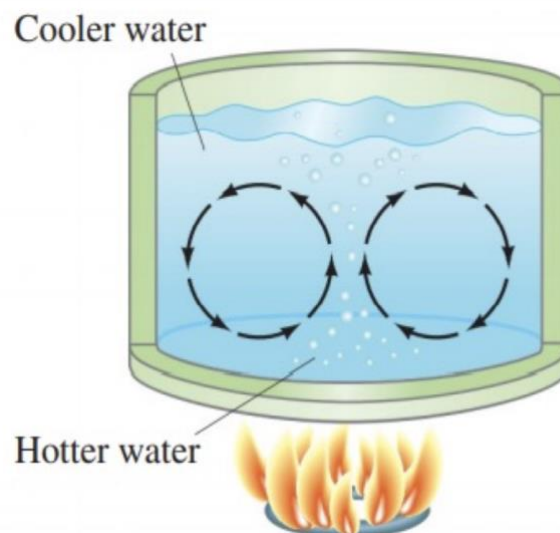   - In metals, free-moving electrons are mainly responsible for heat transfer
- Formula:

$$\frac{Q}{t} = kA\frac{\Delta T}{l}$$

  - Q/t: heat transfer rate (Js^{-1} or W)
  - k: thermal conductivity ($Js^{-1}m^{-1}K^{-1}$)
  - A: cross-sectional area (m^2)
  - l: the distance between the two ends (m)
  - ΔT: the temperature difference between the two ends (°C or K)
- Thermal Conductor Vs Thermal Insulator
  - Conductor: k is large, heat transfer rapidly
  - Insulator: k is small, heat transfer slower
  - Applications of insulators:

1. Double-pane windows with air in between -> thermal conductivity of air < glass
2. Goose down + air in your winter down jacket -> goose down and air both have very low thermal conductivities

14-7 Convection

- Heat flow by the bulk movement of molecules from one place to another via fluid flow
  - Movement of large number of molecules over a large distance
- Convection current
  - Continuous movement of fluid (liquid or gas) caused by differences in temperature and density within that fluid
- **Forced Convection**
  - The fluid is forced to move by an external device such as a fan, pump, or blower to increase heat transfer
- **Natural Convection**
  - The movement of fluid happens naturally, due to temperature differences that create density differences — no external device is used

Cooler water

Hotter water

14-8 Radiation

- Electromagnetic radiation (such as microwaves, infrared radiation, visible light) is emitted or absorbed

  - Does not require a medium

- Formula (not tested) :

$$\frac{Q}{t} = \epsilon\sigma AT^4$$

  - Q/t: Energy transfer rate (Js^{-1} or W)

  - σ (sigma) = Stefan-Boltzmann constant = **5.67×10^{-8}Wm^{-2}K^{-4}**

  - ϵ (epsilon) = Emissivity, a factor between 0~1, characteristic of the surface

    - **ϵ = 1: Black body** - absorbs all the radiation (light, heat, etc.) that falls on it, and does not reflect or transmit any of it.

    - **ϵ = 0: White body** - it reflects all the radiation that falls on it and absorbs none

  - A: surface area (m^2)

Important Physical Constants and Values (*: you likely don't need to memorize these)

Fundamental Constants

- **Universal Gas Constant**: $R = 8.314$ J/mol·K

- **Boltzmann Constant**: $k = 1.381 \times 10^{-23}$ J/K

- **Avogadro's Number**: $N_A = 6.022 \times 10^{23}$ mol^{-1}

- **Atomic Mass Unit**: 1 u = 1.6605×10^{-27} kg

- **Stefan-Boltzmann Constant**: $\sigma = 5.67 \times 10^{-8}$ W/m²K⁴

Standard Conditions

- **Standard Temperature and Pressure (STP)**:

  - T = 273.15 K (0°C)

  - P = 1.013×10^5 Pa = 1 atm

  - Molar volume at STP: 22.4 L/mol

- **Room Temperature**: 293 K (20°C)

Water Properties

- **Specific Heat Capacity**: $c = 4186$ J/kg·K

- **Latent Heat of Fusion**: $L_F = 3.34 \times 10^5$ J/kg

- **Latent Heat of Vaporization**: $L_V = 2.26 \times 10^6$ J/kg

- **Density**: $\rho = 1000$ kg/m³

- **Freezing Point**: 0°C = 273 K

- **Boiling Point**: 100°C = 373 K

Common Substances - Specific Heat Capacities

- Ice: 2100 J/kg·K

- Steam: 2010 J/kg·K

- Aluminum*: 900 J/kg·K

- Iron*: 450 J/kg·K

- Copper*: 385 J/kg·K

Typical RMS Speeds at Room Temperature (300 K) *

- Hydrogen (H_2): $\approx$ 1920 m/s

- Water vapor (H_2O): $\approx$ 645 m/s

- Nitrogen (N_2): $\approx$ 517 m/s

- Oxygen (O_2): ≈ 483 m/s

- Carbon Dioxide (CO_2): ≈ 412 m/s

Energy Conversion Factors

- 1 calorie = 4.186 J

- 1 Calorie = 1 kcal = 4186 J

- 1 Btu = 1055 J

- 1 eV* = 1.602×10^{-19} J

Pressure Conversions

- 1 atm = 1.013×10^5 Pa

- 1 atm = 101.3 kPa

- 1 bar = 10^5 Pa

- $P_{gauge} = P_{absolute} - P_{atm}$ ($P_{atm} = 1$ atm)

Some Questions :D

Question 1: Kinetic Theory & RMS Speed

Problem:

A container holds 0.2 moles of nitrogen gas (N_2) at 27°C. The molar mass of N_2 is 28 g/mol.

a) Calculate the root-mean-square (rms) speed of the nitrogen molecules.

b) If the gas is heated to 127°C at constant volume, what is the new rms speed?

c) How does the rms speed of oxygen (O_2) compare to nitrogen at the same temperature? (O_2 molar mass = 32 g/mol)

Solution:

Part a: Calculate initial rms speed

- Formula: $v_{rms} = \sqrt{\dfrac{3RT}{M}}$

- R = 8.314 J/mol·K, T = 27°C = 300 K, M = 0.028 kg/mol

- $v_{rms} = \sqrt{\dfrac{3 \times 8.314 \times 300}{0.028}} \approx 517 \text{ m/s}$

Part b: Calculate rms speed at higher temperature

- New T = 127°C = 400 K

- $v_{rms} = \sqrt{\dfrac{3 \times 8.314 \times 400}{0.028}} \approx 597 \text{ m/s}$

Part c: Compare nitrogen and oxygen

- $\dfrac{v_{rms,O_2}}{v_{rms,N_2}} = \sqrt{\dfrac{M_{N_2}}{M_{O_2}}} = \sqrt{\dfrac{28}{32}} \approx 0.935$

- Oxygen molecules move about 6.5% slower than nitrogen at the same temperature

Question 2: Calorimetry with Phase Change

Problem:

A 150 g copper calorimeter contains 220 g of water at 25°C. When 45 g of ice at -15°C is added:

a) What is the final temperature of the system? (Latent heat of fusion is 334000 J/kg)

b) What phases are present at equilibrium?

c) How would the answer change if we used 90 g of ice instead?

Solution

Part a:

- Heat required to warm the ice to 0°C: $Q_1 = m_{ice}c_{ice}$ (0 - (-15)) = 0.045 • 2100 • 15 = 1417.5 J.

- Heat to melt the ice at 0°C: $Q_2 = m_{ice}L_f$ = 0.045 • 334000 = 15030 J.

- Total heat needed to get ice to liquid water at 0°C: Q_{ice} = 16447.5 J.

- Heat available by cooling water + copper from 25°C down to 0°C: $Q_{avail} = (m_wc_w + m_{cu}c_{cu})$ • (25 - 0) = (0.22 • 4186 + 0.15 • 385) • 25 = 24466.75 J.

    ○ Since $Q_{avail} > Q_{ice}$, all the ice melts and final temperature $T_f > 0$°C.

- Energy balance for final temperature T_f (all ice melted):

    ○ $(m_wc_w + m_{cu}c_{cu})$ (25-T_f) = Q_1 +Q_2 + $m_{ice}c_w$ (T_f-0).

- Solve for T_f: Plugging numbers gives T_f = 6.87°C.

Answer: Final temperature is 6.9°C.

Part b: All the ice melts, only liquid water is present at equilibrium.

Part c: With 90 g ice, not all ice would melt (need ≈ 33000 J but only have 24467 J available), so final mixture would be at 0°C with both ice and water present. Similar calculations to Part a.