Past-paper walk-through

Ideal Gas Law ▪ 3.4

eXercise

Questions in this set

- 2025 Q5
- 2024 Q2
- 2023 Q5
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- 2016 Q5
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Reading the mark scheme

- **B1** a mark that stands on its own – the point is either made or not.
- **M1** a *method* mark: the right approach, even if the number is wrong.
- **A1** an *answer* mark, and it usually needs its M mark first.
- **C1** a working mark on the way to the answer.
- // separates answers the examiner accepts equally.
- **ecf** = error carried forward: a later part is marked on your own earlier answer.
- **owtte** = "or words to that effect" – the wording need not match.

Question 5

2025 ▪ Q5

Complete Lewis diagrams and some physical properties for compounds X and Y are given.

| Compound | X | Y | |—|—|—| | Lewis diagram | [Lewis structure of compound X: a central chain of three C atoms; the left C is bonded to three H atoms and to the middle C; the middle C is bonded to an O atom above it (O has two lone pairs, drawn as :O:) and to the right C; the right C is bonded to three H atoms and to the middle C; the middle C is also bonded to a fourth C below it, which is bonded to two H atoms.] | [Lewis structure of compound Y: a central chain analogous to X but with a Si atom in place of the middle C; the left C is bonded to three H atoms and to Si; Si is bonded to an O atom above it (O has two lone pairs, drawn as :O:) and to the right C; the right C is bonded to three H atoms and to Si; Si is also bonded to a C below it,

Question 5

which is bonded to two H atoms.] | | Molar mass | 74.1 g/mol | 90.2 g/mol | | Boiling point | 82°C | 98°C |

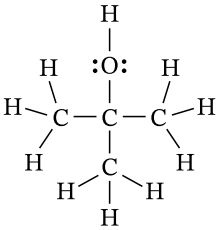
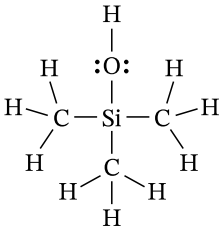
(a) Based on VSEPR theory, predict the geometry around the Si atom in compound Y.

(b) A student claims that compound Y has a higher boiling point than that of compound X because compound Y has stronger London dispersion forces. Do you agree or disagree? Justify your answer.

(c) An equimolar mixture of the two compounds is heated. When the mixture reaches 82°C, which compound will have the higher vapor pressure? Justify your answer.

(d) The mixture is heated to 198°C in a sealed, rigid 12.5 L container, at which point both substances are gases and the total pressure in the container is 2.30 atm. Calculate the number of moles of gas particles in the container.

Question 5

Compound	X	Y
Lewis diagram		
Molar mass	74.1 g/mol	90.2 g/mol
Boiling point	82°C	98°C

Solution 5

(a)

Mark scheme

- Tetrahedral (four bonding domains around the Si atom, no lone pairs, per VSEPR theory).

Solution 5

(b)

Mark scheme

- Agree. Compound Y (containing Si) has a larger, more polarizable electron cloud because the Si atom has more occupied electron shells than the C atom in compound X, giving compound Y stronger London dispersion forces and a higher boiling point than compound X.

Solution 5

(c)

Mark scheme

- Compound X will have the higher vapor pressure at 82°C. Compound X has weaker intermolecular forces than compound Y, so molecules of X are more likely to be in the gas phase at 82°C. Equivalently: at 82°C compound X has reached its boiling point but compound Y has not, so a much greater proportion of X molecules are in the vapor phase, giving X the higher vapor pressure.

Solution 5

(d)

Mark scheme

- Using $PV = nRT$: $n = \dfrac{PV}{RT} = \dfrac{(2.30\ \text{atm})(12.5\ \text{L})}{(0.08206\ \frac{\text{L·atm}}{\text{K·mol}})(471\ \text{K})} = 0.744\ \text{mol}.$

Question 2

2024 ▪ Q2

$$H_2C_4H_2O_4(aq) + 2\,NaHCO_3(aq) \rightarrow 2\,CO_2(g) + 2\,H_2O(l) + Na_2C_4H_2O_4(aq)$$

2. A chemical reaction between maleic acid ($H_2C_4H_2O_4$) and sodium bicarbonate ($NaHCO_3$) occurs in the presence of water to produce carbon dioxide and sodium maleate ($Na_2C_4H_2O_4$), as represented by the following equation.

(a)(i) A student combines equal masses of $H_2C_4H_2O_4(s)$ chunks and $NaHCO_3(s)$ chunks with sufficient water at 20.0°C. The student determines that 0.0114 mol of $CO_2(g)$ is produced after the reaction goes to completion.

Calculate the number of grams of $CO_2(g)$ produced.

(a)(ii) The $CO_2(g)$ produced from the reaction at 20.0°C was collected and found to have a pressure of 1.25 atm. Calculate the volume of $CO_2(g)$, in liters.

Question 2

2024 ▪ Q2

$$H_2C_4H_2O_4(aq) + 2\,NaHCO_3(aq) \rightarrow 2\,CO_2(g) + 2\,H_2O(l) + Na_2C_4H_2O_4(aq)$$

2. A chemical reaction between maleic acid ($H_2C_4H_2O_4$) and sodium bicarbonate ($NaHCO_3$) occurs in the presence of water to produce carbon dioxide and sodium maleate ($Na_2C_4H_2O_4$), as represented by the following equation.

(b)(i) The student performs a second experiment that is identical to the first except that the student grinds the chunks of $H_2C_4H_2O_4(s)$ and $NaHCO_3(s)$ into powder before combining the powder with water.

What happens to the surface area of the reactants when the student grinds the chunks into powder?

Question 2

(b)(ii) The rate-determining step for the overall reaction is the dissolving of the solids. Would the time required for the dissolving of the solids in the second experiment be longer than, shorter than, or the same as the time required in the first experiment? Justify your answer based on the collisions between particles.

(b)(iii) When the reaction is complete, will the volume of $CO_2(g)$ at the end of the second experiment be greater than, less than, or equal to the volume at the end of the first experiment? Justify your answer.

Question 2

2024 ▪ Q2

$$H_2C_4H_2O_4(aq) + 2\,NaHCO_3(aq) \rightarrow 2\,CO_2(g) + 2\,H_2O(l) + Na_2C_4H_2O_4(aq)$$

2. A chemical reaction between maleic acid ($H_2C_4H_2O_4$) and sodium bicarbonate ($NaHCO_3$) occurs in the presence of water to produce carbon dioxide and sodium maleate ($Na_2C_4H_2O_4$), as represented by the following equation.

(c) The student conducts additional trials of the experiment and produces the following data table.

Trial	Mass of $H_2C_4H_2O_4$ (grams)	Mass of $NaHCO_3$ (grams)	Moles of CO_2 Produced (mol)
3	1.543	1.251	0.01489
4	1.543	1.686	0.02007

Based on the student's data, identify the limiting reactant in trial 3. Justify your answer.

Question 2

2024 ▪ Q2

$$H_2C_4H_2O_4(aq) + 2\,NaHCO_3(aq) \rightarrow 2\,CO_2(g) + 2\,H_2O(l) + Na_2C_4H_2O_4(aq)$$

2. A chemical reaction between maleic acid ($H_2C_4H_2O_4$) and sodium bicarbonate ($NaHCO_3$) occurs in the presence of water to produce carbon dioxide and sodium maleate ($Na_2C_4H_2O_4$), as represented by the following equation.

(d) The reaction has a value of ΔS° greater than zero. Using particle-level reasoning, explain why the entropy increases as the reaction progresses.

Question 2

2024 ▪ Q2

$$H_2C_4H_2O_4(aq) + 2\,NaHCO_3(aq) \rightarrow 2\,CO_2(g) + 2\,H_2O(l) + Na_2C_4H_2O_4(aq)$$

2. A chemical reaction between maleic acid ($H_2C_4H_2O_4$) and sodium bicarbonate ($NaHCO_3$) occurs in the presence of water to produce carbon dioxide and sodium maleate ($Na_2C_4H_2O_4$), as represented by the following equation.

(e) The student notices that the temperature of the reaction mixture decreases as the reaction takes place and correctly determines that the reaction is endothermic.
The student claims that the reaction is thermodynamically favorable at all temperatures because $\Delta S^\circ_{rxn} > 0$ and the reaction is endothermic. Do you agree or disagree with the student's claim? Justify your answer.

Question 2

2024 ▪ Q2

$$H_2C_4H_2O_4(aq) + 2\,NaHCO_3(aq) \rightarrow 2\,CO_2(g) + 2\,H_2O(l) + Na_2C_4H_2O_4(aq)$$

2. A chemical reaction between maleic acid ($H_2C_4H_2O_4$) and sodium bicarbonate ($NaHCO_3$) occurs in the presence of water to produce carbon dioxide and sodium maleate ($Na_2C_4H_2O_4$), as represented by the following equation.

(f) Next, the student investigates the acid-base behavior of maleic acid. The student notes that maleic acid is a diprotic acid. The two acid dissociation processes that occur are represented by the following equations.

$$H_2C_4H_2O_4 + H_2O \rightleftharpoons HC_4H_2O_4^- + H_3O^+ \qquad K_{a_1} = 1.5 \times 10^{-2}$$

$$HC_4H_2O_4^- + H_2O \rightleftharpoons C_4H_2O_4^{2-} + H_3O^+ \qquad K_{a_2} = 8.5 \times 10^{-7}$$

Question 2

Calculate the pK_{a_2} value for the $HC_4H_2O_4^-$ ion.

Question 2

2024 ▪ Q2

$$H_2C_4H_2O_4(aq) + 2\,NaHCO_3(aq) \rightarrow 2\,CO_2(g) + 2\,H_2O(l) + Na_2C_4H_2O_4(aq)$$

2. A chemical reaction between maleic acid ($H_2C_4H_2O_4$) and sodium bicarbonate ($NaHCO_3$) occurs in the presence of water to produce carbon dioxide and sodium maleate ($Na_2C_4H_2O_4$), as represented by the following equation.

(g) A buffer solution with a pH of 7.00 is prepared using $C_4H_2O_4^{2-}$ and $HC_4H_2O_4^-$. Calculate the ratio

$$\frac{[C_4H_2O_4^{2-}]}{[HC_4H_2O_4^-]}$$

in this solution.

Solution 2

(a)(i)

Mark scheme

- 0.0114 mol $CO_2 \times \dfrac{44.01\ \text{g}}{1\ \text{mol}} = 0.502\ \text{g}\ CO_2$.

Solution 2

(a)(ii)

Mark scheme

- Using $PV = nRT$:
  $$V = \frac{nRT}{P} = \frac{(0.0114\ \text{mol})(0.08206\ \text{L} \cdot \text{atm}/(\text{mol} \cdot \text{K}))(293\ \text{K})}{1.25\ \text{atm}} = 0.219\ \text{L}.$$

Solution 2

(b)(i)

Mark scheme

- Claim: the surface area of the solid reactants increases when the chunks are ground into powder.

(b)(ii)

Mark scheme

- Shorter than. The powdered solids have a larger surface area than the solid chunks, so collisions between water molecules and the solid surface particles occur more frequently, resulting in a faster rate of dissolution and a shorter time to dissolve the solids.

Solution 2

(b)(iii)

Mark scheme

- Equal to. Both experiments begin with the same amount (mass) of reactants, so they produce the same number of moles of $CO_2(g)$ under the same conditions of pressure and temperature; therefore the final volume of CO_2 will be the same regardless of particle size (rate changes, but the final amount/volume does not).

Solution 2

(c) Mark scheme

- $NaHCO_3$ is the limiting reactant (accept either justification): changing the mass of $NaHCO_3$ alters the amount of CO_2 produced, OR $NaHCO_3$ has the smaller theoretical yield of CO_2:
  1.543 g $H_2C_4H_2O_4 \times \dfrac{1 \text{ mol}}{116.07 \text{ g}} \times \dfrac{2 \text{ mol } CO_2}{1 \text{ mol acid}} = 0.02659$ mol CO_2 (if acid were limiting) vs. 1.251 g $NaHCO_3 \times \dfrac{1 \text{ mol}}{84.01 \text{ g}} \times \dfrac{2 \text{ mol } CO_2}{2 \text{ mol } NaHCO_3} = 0.01489$ mol CO_2 (if $NaHCO_3$ limiting) — the smaller value ($NaHCO_3$) is the actual limiting reactant, matching the trial's observed 0.01489 mol CO_2.

Solution 2

(d)

Mark scheme

- The entropy change is positive because the aqueous/solid reactants produce 2 moles of gas (CO_2) particles, according to the balanced equation. Gases are far more dispersed (occupy many more microstates) than condensed (solid/aqueous) phases, so the entropy of the products is greater than that of the reactants.

Solution 2

(e)

Mark scheme

- Disagree. Accept either justification: (1) The reaction is endothermic ($\Delta H > 0$) with a positive entropy change ($\Delta S > 0$), so it is only thermodynamically favorable at a high enough temperature where the magnitude of $-T\Delta S$ exceeds ΔH — NOT at all temperatures. (2) For a reaction to be thermodynamically favorable ($\Delta G < 0$) at ALL temperatures, it must be exothermic ($\Delta H < 0$) AND have $\Delta S > 0$ — this reaction is endothermic, so it fails that requirement.

Solution 2

(f)

Mark scheme

- Given $K_{a_2} = 8.5 \times 10^{-7}$ for the second dissociation of maleic acid: $\mathrm{p}K_{a_2} = -\log(8.5 \times 10^{-7}) = 6.07$.

Solution 2

(g)

Mark scheme

- Using the Henderson–Hasselbalch equation: $\mathrm{pH} = \mathrm{p}K_{a_2} + \log \dfrac{[\mathrm{C_4H_2O_4^{2-}}]}{[\mathrm{HC_4H_2O_4^-}]}$.

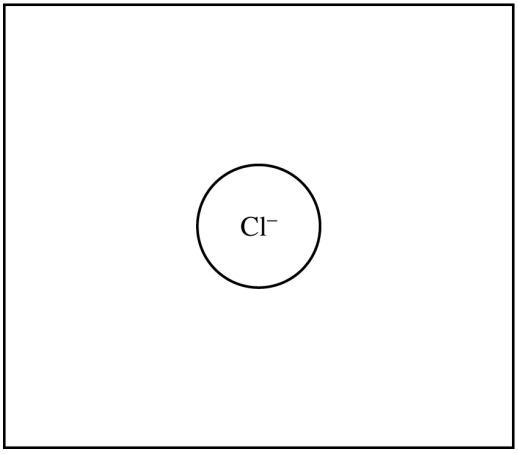
  Solving: $\dfrac{[\mathrm{C_4H_2O_4^{2-}}]}{[\mathrm{HC_4H_2O_4^-}]} = 10^{(\mathrm{pH}-\mathrm{p}K_{a_2})} = 10^{(7.00-6.07)} = 8.5.$

Question 5

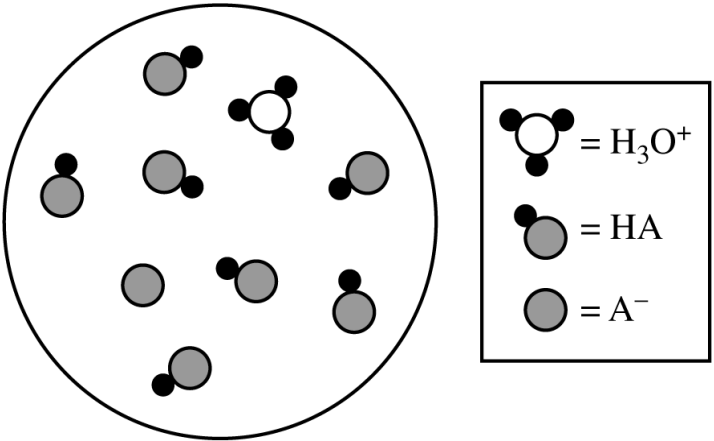
2023 ▪ Q5

HCl is a molecular gas as a pure substance but acts as an acid in aqueous solution.
(a)(i) A sample of HCl(g) is stored in a rigid 6.00 L container at 7.45 atm and 296 K. Calculate the number of moles of HCl(g) in the container.
(a)(ii) The rigid 6.00 L container of HCl(g) is cooled to a temperature of 271 K. Calculate the new pressure, in atm, of the HCl(g).

Question 5



Question 5



Question 5

2023 ▪ Q5

HCl is a molecular gas as a pure substance but acts as an acid in aqueous solution.

(b) When HCl ionizes in aqueous solution, $Cl^-(aq)$ ions are formed. In the following box, draw three water molecules with proper orientation around the Cl^- ion. Use [a water-molecule symbol: a large circle (O) with two small circles (H) attached] to represent water molecules.

[Empty square box with a small circle labeled Cl^- at its center, for the student to draw three water molecules around.]

Question 5

2023 ▪ Q5

HCl is a molecular gas as a pure substance but acts as an acid in aqueous solution.

(c) | Acid (HA) | Anion (A^-) | K_a Value | |—|—|—| | HNO_2 | NO_2^- | 5.6×10^{-4} | | HCl | Cl^- | 2.0×10^7 | | $HClO_4$ | ClO_4^- | 1.6×10^{15} |

The K_a values for three acids are shown in the preceding table.

The following particulate diagram represents the ionization of one of the acids in the data table. Water molecules have been omitted for clarity. Which acid (HNO_2, HCl, or $HClO_4$) is represented in the diagram? Justify your answer using the information in the table.

[Particle diagram: a large circle containing several small particle pairs; legend shows three symbols: a three-circle cluster (two small white circles bonded to one larger white circle) = H_3O^+; a gray circle with a small black dot attached = HA; a plain gray circle = A^-. Inside the large circle: two H_3O^+-like clusters, several HA (gray-with-dot)

Question 5

particles, and several bare A^- (plain gray) particles scattered about — roughly equal numbers of HA and A^- particles with two H_3O^+ clusters, suggesting near-complete/extensive ionization.]

Solution 5

(a)(i)

Mark scheme

- Ideal gas law: $n = \dfrac{PV}{RT} = \dfrac{(7.45\ \text{atm})(6.00\ \text{L})}{\left(0.08206\ \frac{\text{L}\cdot\text{atm}}{\text{mol}\cdot\text{K}}\right)(296\ \text{K})} = 1.84\ \text{mol}.$

Solution 5

(a)(ii)

Mark scheme

- At constant volume and moles, $\frac{P_1}{T_1} = \frac{P_2}{T_2} \Rightarrow P_2 = \frac{P_1 T_2}{T_1} = \frac{(7.45\ \text{atm})(271\ \text{K})}{296\ \text{K}} = 6.82\ \text{atm}$ (equivalently via $P = nRT/V$ using $n = 1.84$ mol).

Solution 5

(b)

Mark scheme

- Draw three water molecules arranged around the central Cl^- ion with the partially-positive hydrogen (H) atom of each water molecule pointed inward, toward the Cl^- ion — reflecting the ion-dipole attraction between the negative Cl^- and the $\delta+$ H atoms of water.

Solution 5

(c)

Mark scheme

- HNO_2. The particulate diagram shows most of the acid molecules still in un-ionized (molecular) form, indicating a weak acid with a K_a value less than 1 — much less than the fully-dissociated strong acids HCl or $HClO_4$ in the table — which is consistent with HNO_2.

Question 2

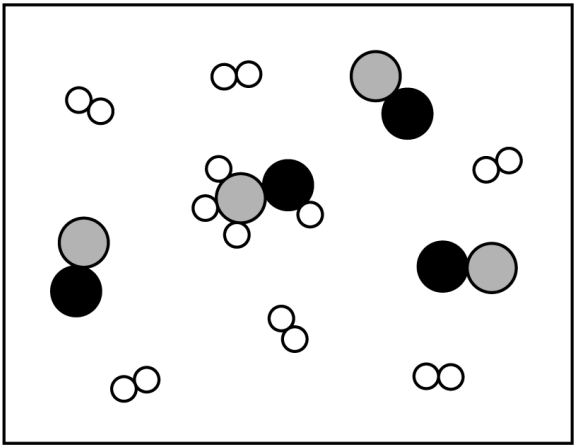
2022 ▪ Q2

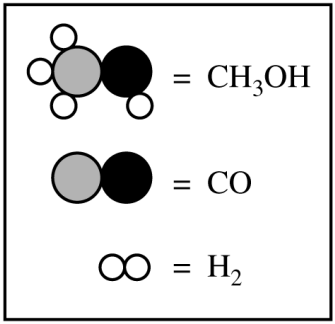
$$\mathrm{CH_3OH}(g) \rightleftharpoons \mathrm{CO}(g) + 2\,\mathrm{H_2}(g) \qquad \Delta H^\circ = 90.0\ \mathrm{kJ/mol}_{rxn}$$

Methanol vapor decomposes to form carbon monoxide gas and hydrogen gas at high temperatures in the presence of a platinum catalyst, as represented by the balanced chemical equation given.

(a) Are the hydrogen atoms oxidized or are they reduced in the forward reaction? Justify your answer in terms of oxidation numbers.

Question 2





Question 2

2022 ▪ Q2

$$CH_3OH(g) \rightleftharpoons CO(g) + 2\,H_2(g) \qquad \Delta H^\circ = 90.0 \text{ kJ/mol}_{rxn}$$

Methanol vapor decomposes to form carbon monoxide gas and hydrogen gas at high temperatures in the presence of a platinum catalyst, as represented by the balanced chemical equation given.

(b) In the following box, draw the complete Lewis electron-dot diagram for the carbon monoxide molecule in which every atom obeys the octet rule. Show all bonding and nonbonding valence electrons.

[A blank box is provided containing the unconnected atomic symbols “C” and “O”, for the student to complete into a full Lewis structure.]

Question 2

2022 ▪ Q2

$$CH_3OH(g) \rightleftharpoons CO(g) + 2\,H_2(g) \qquad \Delta H^\circ = 90.0 \text{ kJ/mol}_{rxn}$$

Methanol vapor decomposes to form carbon monoxide gas and hydrogen gas at high temperatures in the presence of a platinum catalyst, as represented by the balanced chemical equation given.

(c)(i) The values of the standard molar entropies of the compounds involved in the reaction are given in the following table.

Substance	S° (J/(K · mol))
$CH_3OH(g)$	240.
$CO(g)$	198
$H_2(g)$	131

Use the data in the table to calculate the value of the standard entropy change, ΔS°, in J/(K · mol_{rxn}), for the reaction.

Question 2

(c)(ii) Calculate the value of ΔG°, in kJ/mol_{rxn}, for the reaction at 375 K. Assume that ΔH° and ΔS° are independent of temperature.

Question 2

2022 ▪ Q2

$$CH_3OH(g) \rightleftharpoons CO(g) + 2\,H_2(g) \qquad \Delta H^\circ = 90.0 \text{ kJ/mol}_{rxn}$$

Methanol vapor decomposes to form carbon monoxide gas and hydrogen gas at high temperatures in the presence of a platinum catalyst, as represented by the balanced chemical equation given.

(d) The following particle-level diagram shows a representative sample of the equilibrium mixture represented by the equation given.

[A rectangular box (the "container") contains a mixture of particles at equilibrium: several two-linked-open-circle pairs (H), and several three-part particles each made of one gray sphere + one black sphere + one small open circle (CO), plus one larger cluster shown as CH OH. A key box beside it identifies: a cluster of one gray sphere +

Question 2

one black sphere + three small open circles = CH_3OH; one gray sphere + one black sphere = CO; two small open circles joined = H_2. Counting the container: there appear to be 1 CH OH particle, 4 CO particles, and 8 H particles.]

Use information from the particle diagram to calculate the partial pressure of CO at equilibrium when the total pressure of the equilibrium mixture is 12.0 atm.

Question 2

2022 ▪ Q2

$$CH_3OH(g) \rightleftharpoons CO(g) + 2\,H_2(g) \qquad \Delta H^\circ = 90.0 \text{ kJ/mol}_{rxn}$$

Methanol vapor decomposes to form carbon monoxide gas and hydrogen gas at high temperatures in the presence of a platinum catalyst, as represented by the balanced chemical equation given.

(e) Write the expression for the equilibrium constant, K_p, for the reaction.

Question 2

2022 ▪ Q2

$$CH_3OH(g) \rightleftharpoons CO(g) + 2\,H_2(g) \qquad \Delta H^\circ = 90.0 \text{ kJ/mol}_{rxn}$$

Methanol vapor decomposes to form carbon monoxide gas and hydrogen gas at high temperatures in the presence of a platinum catalyst, as represented by the balanced chemical equation given.

(f)

$$CH_3OH(g) \rightleftharpoons CO(g) + 2\,H_2(g)$$

The reaction system represented by the equation is allowed to achieve equilibrium at a different temperature. The following table gives the partial pressure of each species in the equilibrium mixture.

Question 2

| Substance | Partial Pressure at Different Temperature | |—|—| | $CH_3OH(g)$ | 2.7 atm | | $CO(g)$ | 4.2 atm | | $H_2(g)$ | 8.4 atm |

Use the information in the table to calculate the value of the equilibrium constant, K_p, at the new temperature.

Question 2

2022 ▪ Q2

$$CH_3OH(g) \rightleftharpoons CO(g) + 2\,H_2(g) \qquad \Delta H^\circ = 90.0 \text{ kJ/mol}_{rxn}$$

Methanol vapor decomposes to form carbon monoxide gas and hydrogen gas at high temperatures in the presence of a platinum catalyst, as represented by the balanced chemical equation given.

(g) The volume of the container is rapidly doubled with no change in temperature. As equilibrium is re-established, does the number of moles of $CH_3OH(g)$ increase, decrease, or remain the same? Justify your answer by comparing the value of the reaction quotient, Q, with the value of the equilibrium constant, K_p.

Solution 2

(a)

Mark scheme

- The H atoms are reduced because they change from an oxidation number of $+1$ (in CH3OH) to 0 (in H2) in the forward reaction.

Solution 2

(b)

Mark scheme

- Complete Lewis electron-dot diagram for CO obeying the octet rule: a carbon–oxygen triple bond (:C≡≡O:) with one lone pair on carbon and one lone pair on oxygen, giving each atom an octet (triple bond = 6 shared electrons + 1 lone pair = 8 electrons around each atom).

Solution 2

(c)(i)

Mark scheme

- $\Delta S°rxn = \Sigma \Delta S°products - \Sigma \Delta S°reactants = (\Delta S°CO(g) + 2\Delta S°H2(g)) - \Delta S°CH3OH(g)$ (1 point for correct stoichiometry, may be implicit). Using the table values ($S°$: $CH3OH(g) = 240.\ J/(K \cdot mol)$, $CO(g) = 198\ J/(K \cdot mol)$, $H2(g) = 131\ J/(K \cdot mol)$): $\Delta S°rxn = 198 + 2(131) - 240. = 220.\ J/(K \cdot mol\_rxn)$ (1 point for the correct calculated value).

Solution 2

(c)(ii)

Mark scheme

- $\Delta G^\circ = \Delta H^\circ - T\Delta S^\circ = 90.0\ \text{kJ/mol\_rxn} - (375\ \text{K})(0.220\ \text{kJ/(K} \cdot \text{mol\_rxn})) = +7.5\ \text{kJ/mol\_rxn}$ (assuming ΔH° and ΔS° are independent of temperature).

Solution 2

(d)

Mark scheme

- From the particle-level diagram, CO particles make up 3 of the 10 total gas particles shown in the container. With a total pressure of 12.0 atm: P_CO $=$ $(3/10)(12.0\ \text{atm}) = 3.6\ \text{atm}$.

Solution 2

(e)

Mark scheme

- Kp = (P_CO)(P_H2)^2 / (P_CH3OH).

Solution 2

(f)

Mark scheme

- Using the partial pressures at the new equilibrium temperature (CH3OH = 2.7 atm, CO = 4.2 atm, H2 = 8.4 atm): Kp = (P_CO)(P_H2)^2 / (P_CH3OH) = (4.2)(8.4)^2 / (2.7) = 110.

Solution 2

(g) Mark scheme

- Comparison of Q and K (1 point): doubling the container volume causes the partial pressure of each species to decrease by a factor of two; because there are more moles of gaseous products than reactants, the resulting decrease in the numerator of Q is larger (raised to a higher net power) than the decrease in the denominator, making $Qp < Kp$ — explicitly $Qp = [(P\_CO/2)(P\_H2/2)^2] / (P\_CH3OH/2) = Kp/4 \approx 27 < Kp$. Answer and justification (1 point): the number of moles of CH3OH(g) will decrease. Since $Qp < Kp$, the reaction proceeds forward as equilibrium re-establishes, increasing the partial pressures (moles) of the products and decreasing the moles of CH3OH.

Question 1

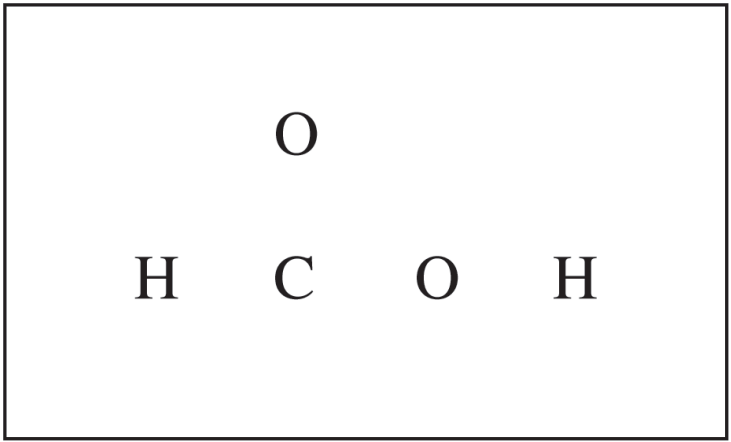
2021 ▪ Q1

$$HCOOH(aq) + H_2O(l) \rightleftharpoons H_3O^+(aq) + HCOO^-(aq) \qquad K_a = 1.8 \times 10^{-4}$$

Methanoic acid, HCOOH, ionizes according to the equation above.

(a) Write the expression for the equilibrium constant, K_a, for the reaction.

Question 1



Question 1

2021 ▪ Q1

$$HCOOH(aq) + H_2O(l) \rightleftharpoons H_3O^+(aq) + HCOO^-(aq) \qquad K_a = 1.8 \times 10^{-4}$$

Methanoic acid, HCOOH, ionizes according to the equation above.

(b) Calculate the pH of a 0.25 *M* solution of HCOOH.

Question 1

2021 ▪ Q1

$$HCOOH(aq) + H_2O(l) \rightleftharpoons H_3O^+(aq) + HCOO^-(aq) \qquad K_a = 1.8 \times 10^{-4}$$

Methanoic acid, HCOOH, ionizes according to the equation above.

(c) In the box below, complete the Lewis electron-dot diagram for HCOOH. Show all bonding and nonbonding valence electrons.

[Box containing the skeletal atom arrangement of HCOOH (no bonds or lone pairs drawn), laid out as:

```
        O
        |
H - C - O - H
```

Question 1

i.e. a central C bonded to: an O atom above it (drawn separated, no bond line shown), an H atom to its left, and an O atom to its right which is in turn bonded to a further H atom on the far right. The student must add all bonding and nonbonding valence electrons to complete the Lewis structure.]

Question 1

2021 ▪ Q1

$$HCOOH(aq) + H_2O(l) \rightleftharpoons H_3O^+(aq) + HCOO^-(aq) \qquad K_a = 1.8 \times 10^{-4}$$

Methanoic acid, HCOOH, ionizes according to the equation above.

(d)(i)

$$H_2NNH_2(aq) + H_2O(l) \rightleftharpoons H_2NNH_3^+(aq) + OH^-(aq) \qquad K_b = 1.3 \times 10^{-6}$$

In aqueous solution, the compound H_2NNH_2 reacts according to the equation above. A 50.0 mL sample of 0.25 *M* $H_2NNH_2(aq)$ is combined with a 50.0 mL sample of 0.25 *M* $HCOOH(aq)$.

Write the balanced net ionic equation for the reaction that occurs when H_2NNH_2 is combined with HCOOH.

(d)(ii) Is the resulting solution acidic, basic, or neutral? Justify your answer.

Question 1

2021 ▪ Q1

$$HCOOH(aq) + H_2O(l) \rightleftharpoons H_3O^+(aq) + HCOO^-(aq) \qquad K_a = 1.8 \times 10^{-4}$$

Methanoic acid, HCOOH, ionizes according to the equation above.

(e) When a catalyst is added to a solution of $HCOOH(aq)$, the reaction represented by the following equation occurs.

$$HCOOH(aq) \rightarrow H_2(g) + CO_2(g)$$

Is the reaction a redox reaction? Justify your answer.

Question 1

2021 ▪ Q1

$$HCOOH(aq) + H_2O(l) \rightleftharpoons H_3O^+(aq) + HCOO^-(aq) \qquad K_a = 1.8 \times 10^{-4}$$

Methanoic acid, HCOOH, ionizes according to the equation above.

(f) [Graph: Total Pressure (atm) on the y-axis (from 0 to above 24, with a dashed horizontal line at 24) vs. Time (hours) on the x-axis. The curve rises steeply from the origin, curving and leveling off asymptotically to a plateau at a total pressure of 24 atm.]

The reaction occurs in a rigid 4.3 L vessel at 25°C, and the total pressure is monitored, as shown in the graph above. The vessel originally did not contain any gas. Calculate the number of moles of $CO_2(g)$ produced in the reaction. (Assume that the amount of $CO_2(g)$ dissolved in the solution is negligible.)

Question 1

2021 ▪ Q1

$$HCOOH(aq) + H_2O(l) \rightleftharpoons H_3O^+(aq) + HCOO^-(aq) \qquad K_a = 1.8 \times 10^{-4}$$

Methanoic acid, HCOOH, ionizes according to the equation above.

(g) After the reaction has proceeded for several minutes, does the amount of catalyst increase, decrease, or remain the same? Justify your answer.

Solution 1

(a)

Mark scheme

- $K_a = \dfrac{[H_3O^+][HCOO^-]}{[HCOOH]}$ — the correct equilibrium-constant expression for the dissociation of HCOOH (products over reactant; water omitted as pure liquid).

Solution 1

(b)

Mark scheme

- ICE table for HCOOH + H2O H3O+ + HCOO-, initial [HCOOH]=0.25 M: $K_a = 1.8 \times 10^{-4} = \dfrac{x^2}{0.25 - x}$. Assuming $x \ll 0.25$: $x^2 = (1.8 \times 10^{-4})(0.25) \Rightarrow x = [\mathrm{H_3O^+}] = 0.0067$ *M* (1 pt). Then $\mathrm{pH} = -\log[\mathrm{H_3O^+}] = -\log(0.0067) = 2.17$ (1 pt, consistent with the calculated concentration).

Solution 1

(c)

Mark scheme

- Correct complete Lewis structure of HCOOH (formic acid): H–C(=O)–O–H. The central C is bonded to: an H atom (single bond), a terminal O by a double bond (that terminal O carries 2 lone pairs), and a second O by a single bond (that O carries 2 lone pairs and is also single-bonded to the second H). All bonding pairs and all nonbonding (lone) pairs of valence electrons must be shown explicitly.

Solution 1

(d)(i)

Mark scheme

- $H_2NNH_2(aq) + HCOOH(aq) \rightarrow H_2NNH_3^+(aq) + HCOO^-(aq)$ — the weak base H2NNH2 accepts a proton from the weak acid HCOOH; already balanced as written (state symbols not required).

Solution 1

(d)(ii)

Mark scheme

- Acidic. The resulting solution is a mixture of the conjugate acid H2NNH3+ and the conjugate base HCOO-. Because the K_a of $H_2NNH_3^+$ is greater than the K_b of $HCOO^-$, production of $H_3O^+(aq)$ occurs to a greater extent than production of $OH^-(aq)$, so the solution is acidic.

Solution 1

(e)

Mark scheme

- Yes, it is a redox reaction. Accept either valid justification: the oxidation number of hydrogen changes from $+1$ in HCOOH to 0 in H2 (reduction); or the oxidation number of carbon changes from $+2$ in HCOOH to $+4$ in CO2 (oxidation).

Solution 1

(f) Mark scheme

- Reaction HCOOH(aq) $\rightarrow$ H2(g) + CO2(g) produces H2 and CO2 in a 1:1 mole ratio, so each contributes half the total pressure: $P_{CO_2} = 24 \text{ atm} \times \frac{1 \text{ atm } CO_2}{2 \text{ atm product}} = 12 \text{ atm}$ (1 pt, may be implicit). Then using the ideal gas law $PV = nRT$ with V=4.3 L, T=298 K: $n = \frac{PV}{RT} = \frac{(12 \text{ atm})(4.3 \text{ L})}{(0.08206 \text{ L} \cdot \text{atm} \cdot \text{mol}^{-1}\text{K}^{-1})(298 \text{ K})} = 2.1 \text{ mol } CO_2$ (1 pt).

Solution 1

(g)

Mark scheme

- It would remain the same. In a catalyzed reaction the catalyst is not consumed — it participates in the mechanism but is regenerated — so the net amount of catalyst present stays constant over time.

Question 7

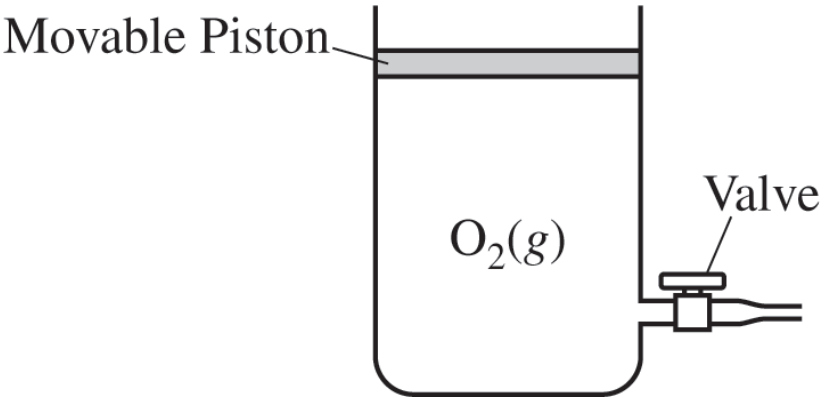
2021 ▪ Q7

[Diagram: A rigid cylindrical container standing upright, fitted with a "Movable Piston" (shown as a shaded bar) near the top that can slide up and down. Below the piston, the container holds "$O_2(g)$". A "Valve" is shown on the side of the container near the piston.]

A student investigates gas behavior using a rigid cylinder with a movable piston of negligible mass, as shown in the diagram above. The cylinder contains 0.325 mol of $O_2(g)$.

(a) The cylinder has a volume of 7.95 L at 25°C and 1.00 atm. Calculate the density of the $O_2(g)$, in g/L, under these conditions.

Question 7



Question 7

2021 ▪ Q7

[Diagram: A rigid cylindrical container standing upright, fitted with a "Movable Piston" (shown as a shaded bar) near the top that can slide up and down. Below the piston, the container holds "$O_2(g)$". A "Valve" is shown on the side of the container near the piston.]

A student investigates gas behavior using a rigid cylinder with a movable piston of negligible mass, as shown in the diagram above. The cylinder contains 0.325 mol of $O_2(g)$.

(b) Attempting to change the density of the $O_2(g)$, the student opens the valve on the side of the cylinder, pushes down on the piston to release some of the gas, and closes the valve again. The temperature of the gas remains constant at 25°C. Will this action change the density of the gas remaining in the cylinder? Justify your answer.

Question 7

2021 ▪ Q7

[Diagram: A rigid cylindrical container standing upright, fitted with a "Movable Piston" (shown as a shaded bar) near the top that can slide up and down. Below the piston, the container holds "$O_2(g)$". A "Valve" is shown on the side of the container near the piston.]

A student investigates gas behavior using a rigid cylinder with a movable piston of negligible mass, as shown in the diagram above. The cylinder contains 0.325 mol of $O_2(g)$.

(c) The student tries to change the density of the $O_2(g)$ by cooling the cylinder to -55°C, which causes the volume of the gas to decrease. Using principles of kinetic molecular theory, explain why the volume of the $O_2(g)$ decreases when the temperature decreases to -55°C.

Question 7

2021 ▪ Q7

[Diagram: A rigid cylindrical container standing upright, fitted with a "Movable Piston" (shown as a shaded bar) near the top that can slide up and down. Below the piston, the container holds "$O_2(g)$". A "Valve" is shown on the side of the container near the piston.]

A student investigates gas behavior using a rigid cylinder with a movable piston of negligible mass, as shown in the diagram above. The cylinder contains 0.325 mol of $O_2(g)$.

(d) The student further cools the cylinder to -180°C and observes that the measured volume of the $O_2(g)$ is substantially smaller than the volume that is calculated using the ideal gas law. Assume all equipment is functioning properly. Explain why the measured volume of the $O_2(g)$ is smaller than the calculated volume. (The boiling point of $O_2(l)$ is -183°C.)

Solution 7

(a) Mark scheme

- 0.325 mol $O_2 \times \dfrac{32.00 \text{ g } O_2}{1 \text{ mol } O_2} = 10.4 \text{ g } O_2$; density $D = \dfrac{m}{V} = \dfrac{10.4 \text{ g}}{7.95 \text{ L}} = 1.31 \text{ g/L}$ (equivalently via $D = \dfrac{P(MM)}{RT} = \dfrac{(1.0 \text{ atm})(32.00 \text{ g/mol})}{(0.08206 \text{ L} \cdot \text{atm} \cdot \text{mol}^{-1}\text{K}^{-1})(298 \text{ K})} = 1.31 \text{ g/L}$).

Solution 7

(b) Mark scheme

- No, releasing some gas at constant temperature does not change the density of the O2 remaining in the cylinder, because P, R, and T all remain constant, and the mass and volume of O2 decrease proportionately as gas is released (density $D = \frac{m}{V} = \frac{n \times MM}{nRT/P} = \frac{P \times MM}{RT}$ depends only on P, molar mass, R, and T — not on the amount n of gas present — so D is unchanged).

Solution 7

(c)

Mark scheme

- As the gas cools, the average kinetic energy (speed) of the O2 molecules decreases, so the molecules rebound with less energy when they collide with each other and the container walls. To maintain a constant rate/force of collisions with the walls (i.e., to keep the pressure at 1.00 atm), the spacing between particles must decrease — so the volume occupied by the gas decreases.

Solution 7

(d) Mark scheme

- The ideal gas law assumes gas particles experience no interparticle (intermolecular) attractions. As the real O2 gas cools further toward its boiling point of -183°C, intermolecular (London dispersion) forces have an increasingly significant effect as the average molecular speed decreases, pulling molecules closer together than ideal behavior predicts (more inelastic/attractive collisions). To still maintain the gas pressure of 1.00 atm, the actual volume must decrease more than the ideal gas law predicts, so the measured volume is smaller than the calculated ideal-gas volume.

Question 2

2019 ▪ Q2

Answer the following questions relating to the chemistry of the halogens.

(a) The molecular formulas of diatomic bromine, chlorine, fluorine, and iodine are written below. Circle the formula of the molecule that has the longest bond length. Justify your choice in terms of atomic structure.

$$Br_2 \qquad Cl_2 \qquad F_2 \qquad I_2$$

A chemistry teacher wants to prepare Br_2. The teacher has access to the following three reagents: $NaBr(aq)$, $Cl_2(g)$, and $I_2(s)$.

| Half-Reaction | E° at 25°C (V) | |—|—| | $Br_2 + 2\,e^- \rightarrow 2\,Br^-$ | 1.07 | | $Cl_2 + 2\,e^- \rightarrow 2\,Cl^-$ | 1.36 | | $I_2 + 2\,e^- \rightarrow 2\,I^-$ | 0.53 |

Question 2

Half-Reaction	$E°$ at 25°C (V)
$Br_2 + 2\ e^- \rightarrow 2\ Br^-$	1.07
$Cl_2 + 2\ e^- \rightarrow 2\ Cl^-$	1.36
$I_2 + 2\ e^- \rightarrow 2\ I^-$	0.53

Question 2

Bond	Bond Energy (kJ/mol)
Br – Br	193
Cl – Cl	243
Br – Cl	?

Question 2

2019 ▪ Q2

Answer the following questions relating to the chemistry of the halogens.

(b) Using the data in the table above, write the balanced equation for the thermodynamically favorable reaction that will produce Br_2 when the teacher combines two of the reagents. Justify that the reaction is thermodynamically favorable by calculating the value of E° for the reaction.

Br_2 and Cl_2 can react to form the compound BrCl.

Question 2

2019 ▪ Q2

Answer the following questions relating to the chemistry of the halogens.

(c) The boiling point of Br_2 is 332 K, whereas the boiling point of BrCl is 278 K. Explain this difference in boiling point in terms of all the intermolecular forces present between molecules of each substance.

The compound BrCl can decompose into Br_2 and Cl_2, as represented by the balanced chemical equation below.

$$2\,BrCl(g) \rightleftharpoons Br_2(g) + Cl_2(g) \qquad \Delta H^\circ = 1.6 \text{ kJ/mol}_{rxn}$$

A 0.100 mole sample of pure $BrCl(g)$ is placed in a previously evacuated, rigid 2.00 L container at 298 K. Eventually the system reaches equilibrium according to the equation above.

Question 2

2019 ▪ Q2

Answer the following questions relating to the chemistry of the halogens.

(d) Calculate the pressure in the container before equilibrium is established.

Question 2

2019 ▪ Q2

Answer the following questions relating to the chemistry of the halogens.

(e) Write the expression for the equilibrium constant, K_{eq}, for the decomposition of BrCl.

After the system has reached equilibrium, 42 percent of the original BrCl sample has decomposed.

Question 2

2019 ▪ Q2

Answer the following questions relating to the chemistry of the halogens.

(f) Determine the value of K_{eq} for the decomposition reaction of BrCl at 298 K.

Question 2

2019 ▪ Q2

Answer the following questions relating to the chemistry of the halogens.

(g) Calculate the bond energy of the Br-Cl bond, in kJ/mol, using ΔH° for the reaction (1.6 kJ/mol_{rxn}) and the information in the following table.

Bond	Bond Energy (kJ/mol)
$Br-Br$	193
$Cl-Cl$	243
$Br-Cl$	?

Solution 2

(a)

Mark scheme

- I2 (circled). I2 has the longest bond length because the atomic radius of I is greater than the radii of the other halogen atoms (Br, Cl, F), so the internuclear distance between the two bonded I atoms is greater than in the other diatomic halogens. 1 point for circling I2 with a valid atomic-structure justification.

Solution 2

(b)

Mark scheme

- Balanced equation (Cl2 is a strong enough oxidizer to oxidize Br since E°(Cl2/Cl)=1.36 V > E°(Br2/Br)=1.07 V, whereas I2 cannot): 2 Br (aq) + Cl2(g) → Br2 + 2 Cl (aq). 1 point for the correct balanced equation. E° = E°(reduced species) − E°(oxidized species) = 1.36 V − 1.07 V = +0.29 V; a positive E° confirms the reaction is thermodynamically favorable. 1 point for the correct E° calculation.

Solution 2

(c)

Mark scheme

- Br2(l) has only London dispersion forces between its nonpolar molecules. BrCl(l) is polar, so it has both London forces and dipole-dipole forces. 1 point for correctly identifying the IMFs present in each substance. However, Br2 has a larger, more polarizable electron cloud than BrCl, so the London forces in Br2(l) are stronger than the combined (London + dipole-dipole) forces in BrCl(l); this is why Br2's boiling point (332 K) is higher than BrCl's (278 K) despite BrCl being polar. 1 point for this valid explanation invoking polarizability.

Solution 2

(d)

Mark scheme

- $P = nRT/V = (0.100\ \text{mol})(0.08206\ \text{L} \cdot \text{atm} \cdot \text{mol}^{-1} \cdot \text{K}^{-1})(298\ \text{K}) / (2.00\ \text{L})$ $= 1.22$ atm. 1 point for the correct pressure with consistent units.

Solution 2

(e)

Mark scheme

- Keq = [Br2][Cl2] / $[BrCl]^2$ (equivalently, in terms of partial pressures: Keq = P(Br2) · P(Cl2) / $P(BrCl)^2$). 1 point for a correct equilibrium expression.

Solution 2

(f)

Mark scheme

- ICE table (partial pressures, atm) for 2 BrCl(g) $\rightleftharpoons$ Br2(g) + Cl2(g): Initial 1.22, 0, 0; Change $-2x$, $+x$, $+x$; Equilibrium 0.71, 0.26, 0.26. Since 42% of BrCl decomposed, P(BrCl decomposed) $= (0.42)(1.22\ \text{atm}) = 0.51\ \text{atm} = 2x$, so $x = 0.26$ atm. 1 point for the correct stoichiometric (ICE) values at equilibrium. Keq $= (0.26)(0.26)/(0.71)^2 = 0.13$. 1 point for a Keq value consistent with the student's ICE table (a molar-concentration-based solution also earns full credit).

Solution 2

(g)

Mark scheme

- $\Delta H^\circ = \Sigma$(bond energies)broken $-$ Σ(bond energies)formed. 1.6 kJ/mol $=$ 2(Br—Cl bond energy) $-$ (193 kJ/mol $+$ 243 kJ/mol); (436 $+$ 1.6) kJ/mol $=$ 2(Br—Cl bond energy); Br—Cl bond energy $=$ 219 kJ/mol. 1 point for the correct calculation.

Question 4

2019 ▪ Q4

A student is doing experiments with $CO_2(g)$. Originally, a sample of the gas is in a rigid container at 299 K and 0.70 atm. The student increases the temperature of the $CO_2(g)$ in the container to 425 K.

(a) Describe the effect of raising the temperature on the motion of the $CO_2(g)$ molecules.

(b) Calculate the pressure of the $CO_2(g)$ in the container at 425 K.

(c) In terms of kinetic molecular theory, briefly explain why the pressure of the $CO_2(g)$ in the container changes as it is heated to 425 K.

(d) The student measures the actual pressure of the $CO_2(g)$ in the container at 425 K and observes that it is less than the pressure predicted by the ideal gas law. Explain this observation.

Solution 4

(a)

Mark scheme

- The average speed (and kinetic energy) of the CO2 molecules increases as the temperature increases. 1 point for the correct answer.

Solution 4

(b)

Mark scheme

- Using Gay-Lussac's law (constant V, constant n): $P1/T1 = P2/T2 \Rightarrow 0.70$ atm / 299 K = P2 / 425 K $\Rightarrow$ P2 = 0.99 atm. 1 point for the correct answer.

Solution 4

(c)

Mark scheme

- As temperature increases, the CO2 molecules move faster, so they collide with the container walls more frequently and/or more forcefully, which increases the pressure. 1 point for a correct kinetic-molecular-theory explanation (frequency or force of collisions).

Solution 4

(d)

Mark scheme

- The measured pressure is lower than the ideal-gas-law prediction because real CO2 molecules experience attractive intermolecular forces with each other, which reduce the force/frequency of their collisions with the container walls compared to an ideal (non-interacting) gas — an effect the ideal gas law ignores. 1 point for a correct explanation citing intermolecular attractive forces.

Question 4

2018 ▪ Q4

[Key: Sulfur atom = large gray circle; Carbon atom = small black circle; Oxygen atom = small white circle.]

| Compound | Molecular Structure | Boiling Point at 1 atm (K) | |—|—|—| | CS_2 | gray–black–gray (S=C=S, linear, symmetric) | 319 | | COS | gray–black–white (S=C=O, linear, asymmetric) | 223 |

The table above gives the molecular structures and boiling points for the compounds CS_2 and COS.

(a) In terms of the types and relative strengths of all the intermolecular forces in each compound, explain why the boiling point of $CS_2(l)$ is higher than that of $COS(l)$.

(b) A 10.0 g sample of $CS_2(l)$ is put in an evacuated 5.0 L rigid container. The container is sealed and heated to 325 K, at which temperature all of the $CS_2(l)$ has vaporized. What is the pressure in the container once all of the $CS_2(l)$ has vaporized?

Question 4

Sulfur atom = ● Carbon atom = ● Oxygen atom = ○

Compound	Molecular Structure	Boiling Point at 1 atm (K)
CS_2		319
COS		223

Solution 4

(a)

Mark scheme

- CS2 is nonpolar (linear, symmetric) and has only London dispersion forces. COS is polar (asymmetric) and has both London dispersion forces and dipole-dipole forces. However, the London dispersion forces in CS2 (larger, more polarizable S atoms on both ends) are stronger than the combined London dispersion + dipole-dipole forces in COS, so CS2 has the higher boiling point. 1 point is earned for correctly identifying all of the intermolecular forces in both molecules; 1 point is earned for a valid explanation of why CS2's IMFs are stronger overall.

Solution 4

(b)

Mark scheme

- 10.0 g CS2 x (1 mol CS2/76.13 g CS2) = 0.131 mol CS2. Using PV = nRT: P = nRT/V = (0.131 mol)(0.08206 L atm/(mol K))(325 K)/5.0 L = 0.70 atm. 1 point is earned for the correct number of moles of CS2; 1 point is earned for the correct calculation of pressure with appropriate units.

Question 1

2017 ▪ Q1

$$CS_2(g) + 3\,Cl_2(g) \rightarrow CCl_4(g) + S_2Cl_2(g)$$

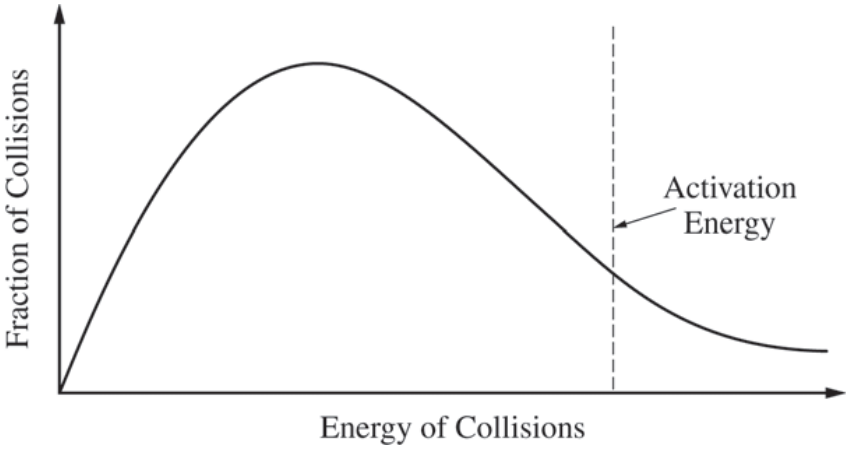
Carbon tetrachloride, $CCl_4(g)$, can be synthesized according to the reaction represented above. A chemist runs the reaction at a constant temperature of $120°C$ in a rigid 25.0 L container.

(a)(i) Chlorine gas, $Cl_2(g)$, is initially present in the container at a pressure of 0.40 atm.

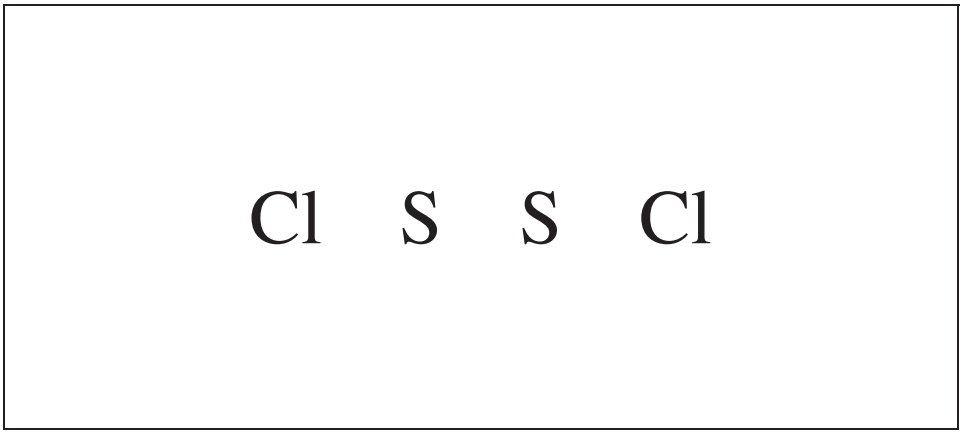
How many moles of $Cl_2(g)$ are in the container?

(a)(ii) How many grams of carbon disulfide, $CS_2(g)$, are needed to react completely with the $Cl_2(g)$?

Question 1


Fraction of Collisions
Activation
Energy
Energy of Collisions

Question 1



Question 1

2017 ▪ Q1

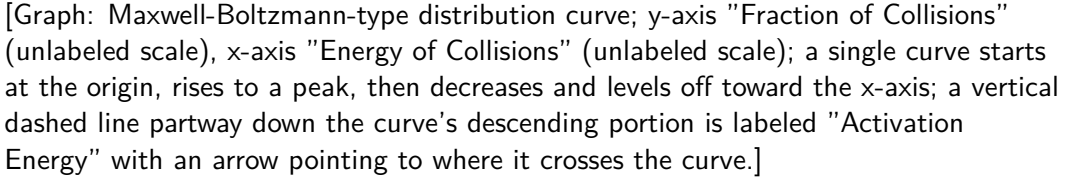
$$CS_2(g) + 3\,Cl_2(g) \rightarrow CCl_4(g) + S_2Cl_2(g)$$

Carbon tetrachloride, $CCl_4(g)$, can be synthesized according to the reaction represented above. A chemist runs the reaction at a constant temperature of 120°C in a rigid 25.0 L container.

(b)(i) At 30°C the reaction is thermodynamically favorable, but no reaction is observed to occur. However, at 120°C, the reaction occurs at an observable rate. Explain how the higher temperature affects the collisions between the reactant molecules so that the reaction occurs at an observable rate at 120°C.

(b)(ii) The graph below shows a distribution for the collision energies of reactant molecules at 120°C. Draw a second curve on the graph that shows the distribution for the collision energies of reactant molecules at 30°C.

Question 1



[Graph: Maxwell-Boltzmann-type distribution curve; y-axis "Fraction of Collisions" (unlabeled scale), x-axis "Energy of Collisions" (unlabeled scale); a single curve starts at the origin, rises to a peak, then decreases and levels off toward the x-axis; a vertical dashed line partway down the curve's descending portion is labeled "Activation Energy" with an arrow pointing to where it crosses the curve.]

Question 1

2017 ▪ Q1

$$CS_2(g) + 3\,Cl_2(g) \rightarrow CCl_4(g) + S_2Cl_2(g)$$

Carbon tetrachloride, $CCl_4(g)$, can be synthesized according to the reaction represented above. A chemist runs the reaction at a constant temperature of 120°C in a rigid 25.0 L container.

(c)(i) S_2Cl_2 is a product of the reaction.

In the box below, complete the Lewis electron-dot diagram for the S_2Cl_2 molecule by drawing in all of the electron pairs.

[Box showing the unfinished skeletal structure: Cl S S Cl (four atoms in a row, single bonds implied between adjacent atoms, no lone pairs or additional dots drawn yet).]

(c)(ii) What is the approximate value of the Cl–S–S bond angle in the S_2Cl_2 molecule that you drew in part (c)(i) ? (If the two Cl–S–S bond angles are not equal, include both angles.)

Question 1

2017 ▪ Q1

$$CS_2(g) + 3\,Cl_2(g) \rightarrow CCl_4(g) + S_2Cl_2(g)$$

Carbon tetrachloride, $CCl_4(g)$, can be synthesized according to the reaction represented above. A chemist runs the reaction at a constant temperature of 120°C in a rigid 25.0 L container.

(d)(i) $CCl_4(g)$ can also be produced by reacting $CHCl_3(g)$ with $Cl_2(g)$ at 400°C, as represented by the equation below.

$$CHCl_3(g) + Cl_2(g) \rightarrow CCl_4(g) + HCl(g)$$

At the completion of the reaction a chemist successfully separates the $CCl_4(g)$ from the $HCl(g)$ by cooling the mixture to 70°C, at which temperature the $CCl_4(g)$ condenses while the $HCl(g)$ remains in the gaseous state.

Question 1

Identify all types of intermolecular forces present in $HCl(l)$.

(d)(ii) What can be inferred about the relative strengths of the intermolecular forces in $CCl_4(l)$ and $HCl(l)$? Justify your answer in terms of the information above.

Solution 1

(a)(i)

Mark scheme

- n = PV/RT = (0.40 atm x 25.0 L) / (0.08206 L*atm/(mol*K) x 393 K) = 0.31 mol Cl2. 1 point earned for the correct answer with supporting work.

(a)(ii)

Mark scheme

- 0.31 mol Cl2 x (1 mol CS2 / 3 mol Cl2) x (76.13 g CS2 / 1 mol CS2) = 7.9 g CS2. 1 point for using the correct mole ratio (may be implicit); 1 point for the correct mass of CS2.

Solution 1

(b)(i)

Mark scheme

- At the higher temperature the particles have a greater average kinetic energy than at the lower temperature. Thus there are more collisions with sufficient energy to overcome the activation energy. 1 point earned for an appropriate explanation that includes a reference to molecular collisions.

Solution 1

(b)(ii)

Mark scheme

- Draw a second curve on the graph for the 30C collision-energy distribution. 1 point earned for a curve that has a peak above and to the left of the given (120C) curve (lower T -> lower average kinetic energy, so the peak shifts to lower energy and is taller/narrower); 1 point earned for a curve that is below the given curve in the region beyond the activation energy (fewer molecules have collision energy exceeding Ea at the lower temperature).

Solution 1

(c)(i)

Mark scheme

- Completed Lewis structure: :Cl-S-S-Cl: with each Cl bearing 3 lone pairs and each S bearing 2 lone pairs, so every atom (C excluded, none here) satisfies the octet rule across the Cl-S-S-Cl skeleton with single bonds throughout. 1 point earned for a correctly drawn diagram (all electron pairs shown).

Solution 1

(c)(ii)

Mark scheme

- Any value between 104 degrees and 110 degrees is acceptable (bent/angular arrangement about each central S atom, which has 2 bonding pairs and 2 lone pairs, similar to the geometry around O in H2O2). 1 point earned for an acceptable angle that is consistent with the Lewis diagram drawn in part (c)(i).

Solution 1

(d)(i)

Mark scheme

- Dipole-dipole forces and London dispersion forces. 1 point earned for identifying both types of forces (HCl is a polar molecule, so dipole-dipole forces are present in addition to the London dispersion forces present between all molecules).

Solution 1

(d)(ii)

Mark scheme

- The intermolecular forces among CCl4 molecules must be stronger than those among HCl molecules, because the CCl4 condenses at a higher temperature (70C) than HCl, which remains gaseous at that temperature. 1 point earned for the correct answer with a valid justification.

Question 5

2016 ▪ Q5

$$2\ C_4H_6(g) \rightarrow C_8H_{12}(g)$$

At high temperatures the compound C_4H_6 (1,3-butadiene) reacts according to the equation above. The rate of the reaction was studied at 625 K in a rigid reaction vessel. Two different trials, each with a different starting concentration, were carried out. The data were plotted in three different ways, as shown below.

[Graph 1: "$[C_4H_6]$ vs. Time" — x-axis Time (s) from 0 to 20; y-axis $[C_4H_6]$ (mol/L) from 0 to 0.020. Trial 1 (open circles) starts at approximately (0, 0.0183) and decays smoothly to approximately (20, 0.0065). Trial 2 (filled squares) starts at approximately (0, 0.0096) and decays smoothly to approximately (20, 0.0049). Both curves show a decreasing, concave-up (leveling-off) shape.]

Question 5

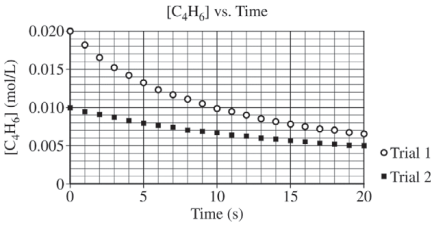
[Graph 2: "$\ln[C_4H_6]$ vs. Time" — x-axis Time (s) from 0 to 20; y-axis $\ln[C_4H_6]$ from -5.5 to -3.5. Trial 1 (open circles) starts at approximately (0, -4.0) and decreases roughly linearly-curved to approximately (20, -5.0). Trial 2 (filled squares) starts at approximately (0, -4.65) and decreases to approximately (20, -5.3). Both curves are slightly concave, not perfectly straight lines.]
[Graph 3: "$1/[C_4H_6]$ vs. Time" — x-axis Time (s) from 0 to 20; y-axis $1/[C_4H_6]$ (L/mol) from 0 to 250. Trial 1 (open circles) starts at approximately (0, 55) and increases in a straight line to approximately (20, 155). Trial 2 (filled squares) starts at approximately (0, 104) and increases in a straight line to approximately (20, 205). Both trials appear linear in this plot.]
(a) For trial 1, calculate the initial pressure, in atm, in the vessel at 625 K. Assume that initially all the gas present in the vessel is C_4H_6.

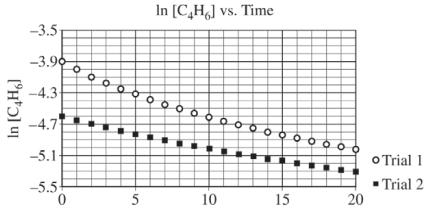
Question 5

(b) Use the data plotted in the graphs to determine the order of the reaction with respect to C_4H_6.

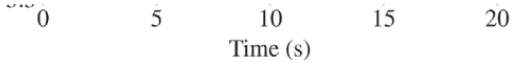
(c) The initial rate of the reaction in trial 1 is 0.0010 mol/(L · s). Calculate the rate constant, k, for the reaction at 625 K.

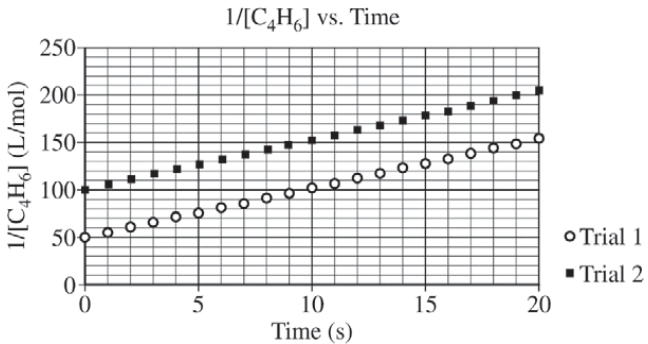
Question 5


[C4H6] vs. Time
0.020
0.015
0.010
0.005
0
[C4H6] (mol/L)
0
5
10
15
20
Time (s)
Trial 1
Trial 2


ln [C4H6] vs. Time
−3.5
−3.9
−4.3
−4.7
−5.1
−5.5
ln [C4H6]
0
5
10
15
20
Trial 1
Trial 2

Question 5


0
5
10
15
20
Time (s)


1/[C4H6] vs. Time
250
200
150
100
50
0
1/[C4H6] (L/mol)
0
5
10
15
20
Time (s)
Trial 1
Trial 2

Solution 5

(a)

Mark scheme

- For trial 1, n/V = 0.020 mol/L (assuming the vessel volume is 1.0 L, n(C4H6) = 0.020 mol). Using PV = nRT: P = nRT/V = (0.020 mol)(0.08206 L $\cdot$ atm $\cdot$ mol^{1} $\cdot$ K^{1})(625 K) / (1.0 L) = 1.0 atm. 1 point for a correct setup, 1 point for the correct answer ($\approx$1.0 atm).

Solution 5

(b)

Mark scheme

- Second order with respect to C4H6, because the plot of $1/[C_4H_6]$ versus time is a straight line (linear), which is the signature of a second-order integrated rate law. 1 point for correctly identifying second order.

Solution 5

(c)

Mark scheme

- Using the second-order differential rate law, rate = k[C4H6]^2: k = rate / [C4H6]^2 = 0.0010 mol/(L · s) / (0.020 mol/L)^2 = 2.5 L/(mol · s). (Equivalently, from the integrated form 1/[C4H6]t = 2kt + 1/[C4H6]0, the slope of the 1/[C4H6] vs. time plot equals 2k = 5.0 L/(mol · s), giving k = 2.5 L/(mol · s); a student who uses this method but omits the factor of 2, reporting k = 5.0 L/(mol · s), still earns the point.) 1 point for the correct value of k (2.5 L/(mol · s) via the differential method, or 5.0 L/(mol · s) if the slope method is used without doubling).

Question 4

2014 ▪ Q4

$$CaCO_3(s) \rightleftharpoons CaO(s) + CO_2(g)$$

When heated, calcium carbonate decomposes according to the equation above. In a study of the decomposition of calcium carbonate, a student added a 50.0 g sample of powdered $CaCO_3(s)$ to a 1.00 L rigid container. The student sealed the container, pumped out all the gases, then heated the container in an oven at 1100 K. As the container was heated, the total pressure of the $CO_2(g)$ in the container was measured over time. The data are plotted in the graph below.

[Graph of Pressure (atm) vs. Time (min); x-axis Time (min) 0 to 20 (gridlines at 0, 5, 10, 15, 20), y-axis Pressure (atm) 0 to 1.25 (gridlines at 0, 0.25, 0.50, 0.75, 1.00, 1.25); curve starts at (0, 0), rises steeply and roughly linearly to about (5, 0.65),

Question 4

continues rising with decreasing slope through about (10, 0.95), levels off and becomes essentially flat at a pressure of about 1.0-1.05 atm from about $t = 12$ min to $t = 20$ min.]

The student repeated the experiment, but this time the student used a 100.0 g sample of powdered $CaCO_3(s)$. In this experiment, the final pressure in the container was 1.04 atm, which was the same final pressure as in the first experiment.

(a) Calculate the number of moles of $CO_2(g)$ present in the container after 20 minutes of heating.

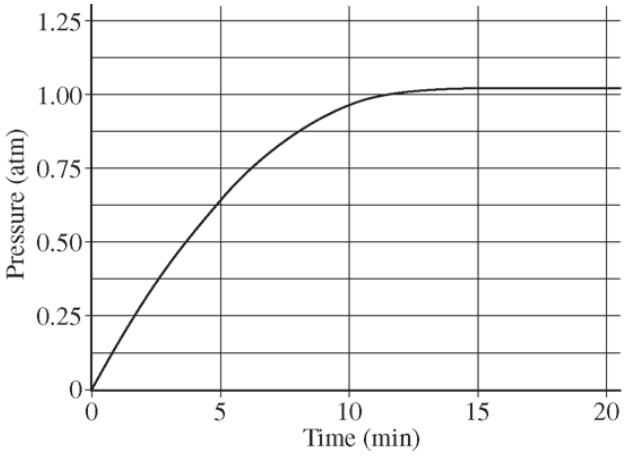
(b) The student claimed that the final pressure in the container in each experiment became constant because all of the $CaCO_3(s)$ had decomposed. Based on the data in the experiments, do you agree with this claim? Explain.

Question 4

(c) After 20 minutes some $CO_2(g)$ was injected into the container, initially raising the pressure to 1.5 atm. Would the final pressure inside the container be less than, greater than, or equal to 1.04 atm? Explain your reasoning.

(d) Are there sufficient data obtained in the experiments to determine the value of the equilibrium constant, K_p, for the decomposition of $CaCO_3(s)$ at 1100 K? Justify your answer.

Question 4



Solution 4

(a)

Mark scheme

- Using the ideal gas law:
$$n = \frac{PV}{RT} = \frac{(1.04\ \text{atm})(1.00\ \text{L})}{(0.0821\ \text{L} \cdot \text{atm/mol} \cdot \text{K})(1100\ \text{K})} = 0.0115\ \text{mol CO}_2.$$

Solution 4

(b)

Mark scheme

- Do not agree with the claim. In experiment 1, moles of $CaCO3$ = 50.0 g / 100.09 g/mol = 0.500 mol $CaCO3$; if the reaction had gone to completion, 0.500 mol of $CO2$ would have been produced, but only 0.0115 mol was produced (part a), so the claim is false. Alternatively: the two experiments (50.0 g and 100.0 g of $CaCO3$) both reached the same constant final pressure of 1.04 atm; since adding more reactant did not produce more product, not all of the $CaCO3$ could have reacted — an equilibrium condition was reached instead, with some solid $CaCO3$ remaining.

Solution 4

(c)

Mark scheme

- The final pressure would be equal to 1.04 atm. Equilibrium was reached in both experiments at this temperature, giving an equilibrium CO2 pressure of 1.04 atm. Raising the pressure to 1.5 atm shifts the reaction toward the reactant (Le Chatelier's principle), and CO2(g) is consumed until the pressure returns to the equilibrium value of 1.04 atm.

Solution 4

(d)

Mark scheme

- Yes. For this equilibrium, at a given temperature the equilibrium pressure of CO2 determines the equilibrium constant. Since the measured pressure of CO2 (1.04 atm) is the equilibrium pressure, $K_p = P_{CO_2} = 1.04$. (Alternate credit: if part (b) claimed all CaCO3 decomposed, the point can instead be earned by stating that the system never reached equilibrium in either experiment, so Kp cannot be calculated from the data.)