Past-paper walk-through

Collision Model ▪ 5.5

eXercise

Questions in this set

- 2024 Q2
- 2023 Q3
- 2017 Q1
- 2016 Q2
- 2014 Q7

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 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

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

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: $1.543 \text{ g } H_2C_4H_2O_4 \times \frac{1 \text{ mol}}{116.07 \text{ g}} \times \frac{2 \text{ mol } CO_2}{1 \text{ mol acid}} = 0.02659 \text{ mol } CO_2$ (if acid were limiting) vs. $1.251 \text{ g } NaHCO_3 \times \frac{1 \text{ mol}}{84.01 \text{ g}} \times \frac{2 \text{ mol } CO_2}{2 \text{ mol } NaHCO_3} = 0.01489 \text{ mol } CO_2$ (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: p$K_{a_2} = -\log(8.5 \times 10^{-7}) = 6.07$.

Solution 2

(g)

Mark scheme

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

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

Question 3

2023 ▪ Q3

Answer the following questions about an experiment in which $CaCO_3(s)$ is combined with $HCl(aq)$, represented by the following balanced equation.

$$CaCO_3(s) + 2\,HCl(aq) \rightarrow CaCl_2(aq) + CO_2(g) + H_2O(l)$$

(a) Write the balanced net ionic equation for the reaction.

Question 3

2023 ▪ Q3

Answer the following questions about an experiment in which $CaCO_3(s)$ is combined with $HCl(aq)$, represented by the following balanced equation.

$$CaCO_3(s) + 2\,HCl(aq) \rightarrow CaCl_2(aq) + CO_2(g) + H_2O(l)$$

(b) A student performs an investigation to study factors that affect the rate of the reaction. In each trial the student combines 50.0 mL of $HCl(aq)$ at $21.2°C$ with 1.00 g of $CaCO_3(s)$ and measures the time required for the reaction to go to completion. The data are given in the following table.

Trial	Concentration of $HCl(aq)$ (M)	Particle Size of $CaCO_3(s)$	Time of Reaction (s)
1	1.00	Fine powder	67
2	1.00	Small chunks	112
3			

Question 3

1.00 | Large chunk | 342 | | 4 | 3.00 | Fine powder | 22 | | 5 | 3.00 | Small chunks | 227 | | 6 | 3.00 | Large chunk | 114 |

The student correctly identifies that trial 5 is inconsistent with the other trials. Explain why the student's claim is correct using the data in the table.

Question 3

2023 ▪ Q3

Answer the following questions about an experiment in which $CaCO_3(s)$ is combined with $HCl(aq)$, represented by the following balanced equation.

$$CaCO_3(s) + 2\,HCl(aq) \rightarrow CaCl_2(aq) + CO_2(g) + H_2O(l)$$

(c) Based on the reaction conditions and the collisions that occur between particles, explain the reason for the difference in the reaction times for trial 2 and trial 3.

Question 3

2023 ▪ Q3

Answer the following questions about an experiment in which $CaCO_3(s)$ is combined with $HCl(aq)$, represented by the following balanced equation.

$$CaCO_3(s) + 2\,HCl(aq) \rightarrow CaCl_2(aq) + CO_2(g) + H_2O(l)$$

(d) The student claims that the reaction is zero order with respect to $HCl(aq)$. Do you agree or disagree with the student's claim? Justify your answer using the student's data.

Question 3

2023 ▪ Q3

Answer the following questions about an experiment in which $CaCO_3(s)$ is combined with $HCl(aq)$, represented by the following balanced equation.

$$CaCO_3(s) + 2\,HCl(aq) \rightarrow CaCl_2(aq) + CO_2(g) + H_2O(l)$$

(e) The $HCl(aq)$ was present in excess in all trials of the experiment. Determine the molarity of the $HCl(aq)$ in the beaker after the reaction is complete in trial 2. Assume that the volume of the mixture remains constant at 50.0 mL throughout the trial. (The molar mass of $CaCO_3$ is 100.09 g/mol.)

Question 3

2023 ▪ Q3

Answer the following questions about an experiment in which $CaCO_3(s)$ is combined with $HCl(aq)$, represented by the following balanced equation.

$$CaCO_3(s) + 2\,HCl(aq) \rightarrow CaCl_2(aq) + CO_2(g) + H_2O(l)$$

(f)

$$CaCO_3(s) + 2\,HCl(aq) \rightarrow CaCl_2(aq) + CO_2(g) + H_2O(l)$$

In order to measure the enthalpy of the reaction shown, the student repeats trial 1 by mixing 50.0 mL of $HCl(aq)$ with 1.00 g of $CaCO_3(s)$ using a coffee cup calorimeter. The student records the temperature of the system every 20 seconds. The data are given in the following table.

Question 3

Time (s)	Measured Temperature of Solution (°C)
0	21.20
20	21.51
40	21.70
60	21.85
80	21.90
100	21.90

Is the reaction endothermic or exothermic? Justify your answer using the information in the table.

Question 3

2023 ▪ Q3

Answer the following questions about an experiment in which $CaCO_3(s)$ is combined with $HCl(aq)$, represented by the following balanced equation.

$$CaCO_3(s) + 2\,HCl(aq) \rightarrow CaCl_2(aq) + CO_2(g) + H_2O(l)$$

(g)(i) Based on the experimental data, the mass of the system is 51.0 g, and the specific heat of the reaction mixture is 4.0 J/(g · °C).
Calculate the magnitude of heat transfer, q, in joules.
(g)(ii) Calculate the enthalpy of reaction in units of kJ/mol$_{rxn}$. Include the algebraic sign on your answer.

Solution 3

(a)

Mark scheme

- Balanced net ionic equation: $CaCO_3(s) + 2\,H^+(aq) \rightarrow Ca^{2+}(aq) + CO_2(g) + H_2O(l)$ (equivalently with hydronium: $CaCO_3(s) + 2\,H_3O^+(aq) \rightarrow Ca^{2+}(aq) + CO_2(g) + 3\,H_2O(l)$). State symbols not required.

Solution 3

(b)

Mark scheme

- Accept either explanation: (1) Even though [HCl] is greater in trial 5 than trial 2, the reaction time is significantly longer; trials 2 and 5 are otherwise identical, and the trend from trials 1 and 4 shows that a higher [HCl] gives a shorter reaction time, so concentration alone cannot explain trial 5 — particle size must be the cause. (2) The reaction time in trial 5 (small chunks) is longer than in trial 6 (large chunks), even though trials 5 and 6 are otherwise identical; the trend from trials 1, 2, and 3 shows that larger chunks of solid give a longer reaction time.

Solution 3

(c)

Mark scheme

- The reaction time in trial 2 is shorter than in trial 3 because the calcium carbonate in trial 2 has a larger surface area, meaning more $CaCO_3$ particles are exposed to H^+ particles in solution (1 point). A larger interface between the two reacting substances means more particle collisions occur per unit time, giving a higher frequency of successful collisions in which particles react to form products, i.e. a higher reaction rate (1 point).

Solution 3

(d)

Mark scheme

- Disagree. Accept either justification: (1) If the reaction were zeroth order with respect to HCl, changing [HCl] would not affect the reaction rate, so reaction time would be the same for trials differing only in [HCl] — but the data for trials 1 and 4 (and likewise 3 and 6) show that changing [HCl] significantly alters the time of reaction. (2) The reaction appears first order, not zeroth order, with respect to [HCl]: tripling [HCl] results in a reaction time that is $1/3$ of that when $[HCl] = 1.00$ M, meaning the rate has also tripled, indicating a first-order process.

Solution 3

(e) Mark scheme

- Moles of HCl reacted: $1.00 \text{ g CaCO}_3 \times \dfrac{1 \text{ mol}}{100.09 \text{ g}} = 0.00999 \text{ mol CaCO}_3$; $0.00999 \text{ mol CaCO}_3 \times \dfrac{2 \text{ mol HCl}}{1 \text{ mol CaCO}_3} = 0.0200 \text{ mol HCl reacted (1 point)}$. Remaining [HCl]: initial HCl $= 0.0500 \text{ L} \times 1.00 \text{ mol/L} = 0.0500 \text{ mol}$; $0.0500 - 0.0200 = 0.0300 \text{ mol remaining}$; $\dfrac{0.0300 \text{ mol}}{0.0500 \text{ L}} = 0.600\ M \text{ HCl remaining}$ (1 point).

Solution 3

(f)

Mark scheme

- Exothermic. The solution temperature increases as the reaction proceeds (per the calorimeter data), indicating heat is released to the surroundings.

Solution 3

(g)(i)

Mark scheme

- $q_{surr} = mc\Delta T = (51.0\ \text{g})\left(4.0\ \frac{\text{J}}{\text{g}\cdot{}^{\circ}\text{C}}\right)(21.90^{\circ}\text{C} - 21.20^{\circ}\text{C}) = 140\ \text{J}$ (sign not required).

Solution 3

(g)(ii)

Mark scheme

- $q_{sys} = -q_{surr} = -140\ \text{J} = -0.14\ \text{kJ}$; moles reacted
$$= 1.00\ \text{g CaCO}_3 \times \frac{1\ \text{mol CaCO}_3}{100.09\ \text{g CaCO}_3} \times \frac{1\ \text{mol}_{rxn}}{1\ \text{mol CaCO}_3} = 0.00999\ \text{mol}_{rxn};$$
$$\Delta H^\circ_{rxn} = \frac{-0.14\ \text{kJ}}{0.00999\ \text{mol}_{rxn}} = -14\ \text{kJ/mol}_{rxn}$$ (include the algebraic sign).

Question 1

2017 ▪ Q1

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

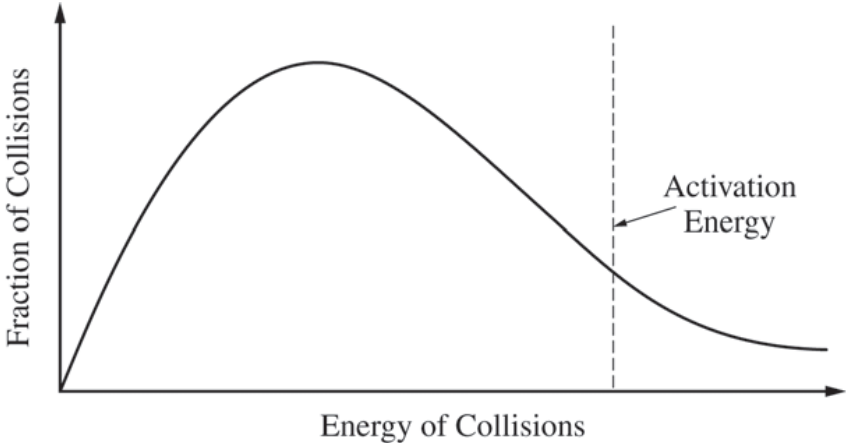
Carbon tetrachloride, $CCl_4(g)$, can be synthesized according to the reaction represented above. A chemist runs the reaction at a constant temperature of $120°C$ in a rigid 25.0 L container.

(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

Cl S S Cl

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 2

2016 ▪ Q2

$$NaHCO_3(s) + HC_2H_3O_2(aq) \rightarrow NaC_2H_3O_2(aq) + H_2O(l) + CO_2(g)$$

A student designs an experiment to study the reaction between $NaHCO_3$ and $HC_2H_3O_2$. The reaction is represented by the equation above. The student places 2.24 g of $NaHCO_3$ in a flask and adds 60.0 mL of 0.875 M $HC_2H_3O_2$. The student observes the formation of bubbles and that the flask gets cooler as the reaction proceeds.

(a) Identify the reaction represented above as an acid-base reaction, precipitation reaction, or redox reaction. Justify your answer.

Question 2

Question 2

2016 ▪ Q2

$$NaHCO_3(s) + HC_2H_3O_2(aq) \rightarrow NaC_2H_3O_2(aq) + H_2O(l) + CO_2(g)$$

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(b) Based on the information above, identify the limiting reactant. Justify your answer with calculations.

Question 2

2016 ▪ Q2

$$NaHCO_3(s) + HC_2H_3O_2(aq) \rightarrow NaC_2H_3O_2(aq) + H_2O(l) + CO_2(g)$$

A student designs an experiment to study the reaction between $NaHCO_3$ and $HC_2H_3O_2$. The reaction is represented by the equation above. The student places 2.24 g of $NaHCO_3$ in a flask and adds 60.0 mL of 0.875 M $HC_2H_3O_2$. The student observes the formation of bubbles and that the flask gets cooler as the reaction proceeds.

(c) The student observes that the bubbling is rapid at the beginning of the reaction and gradually slows as the reaction continues. Explain this change in the reaction rate in terms of the collisions between reactant particles.

Question 2

2016 ▪ Q2

$$NaHCO_3(s) + HC_2H_3O_2(aq) \rightarrow NaC_2H_3O_2(aq) + H_2O(l) + CO_2(g)$$

A student designs an experiment to study the reaction between $NaHCO_3$ and $HC_2H_3O_2$. The reaction is represented by the equation above. The student places 2.24 g of $NaHCO_3$ in a flask and adds 60.0 mL of 0.875 M $HC_2H_3O_2$. The student observes the formation of bubbles and that the flask gets cooler as the reaction proceeds.

(d)(i) In thermodynamic terms, a reaction can be driven by enthalpy, entropy, or both. Considering that the flask gets cooler as the reaction proceeds, what drives the chemical reaction between $NaHCO_3(s)$ and $HC_2H_3O_2(aq)$? Answer by drawing a circle around one of the choices below.

Enthalpy only Entropy only Both enthalpy and entropy

(d)(ii) Justify your selection in part (d)(i) in terms of ΔG°.

Question 2

2016 ▪ Q2

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(e) The HCO_3^- ion has three carbon-to-oxygen bonds. Two of the carbon-to-oxygen bonds have the same length and the third carbon-to-oxygen bond is longer than the other two. The hydrogen atom is bonded to one of the oxygen atoms. In the box below, draw a Lewis electron-dot diagram (or diagrams) for the HCO_3^- ion that is (are) consistent with the given information.

[Empty box provided for the student to draw the Lewis electron-dot diagram(s).]

Question 2

2016 ▪ Q2

$$NaHCO_3(s) + HC_2H_3O_2(aq) \rightarrow NaC_2H_3O_2(aq) + H_2O(l) + CO_2(g)$$

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(f) A student prepares a solution containing equimolar amounts of $HC_2H_3O_2$ and $NaC_2H_3O_2$. The pH of the solution is measured to be 4.7. The student adds two drops of 3.0 M $HNO_3(aq)$ and stirs the sample, observing that the pH remains at 4.7. Write a balanced, net-ionic equation for the reaction between $HNO_3(aq)$ and the chemical species in the sample that is responsible for the pH remaining at 4.7.

Solution 2

(a)

Mark scheme

- It is an acid-base reaction: the weak acid HC2H3O2 reacts with the weak base HCO3—, with HC2H3O2 donating a proton. (Equivalently: no solid precipitates, so it is not a precipitation reaction; no oxidation numbers change, so it is not a redox reaction.) 1 point for identifying the reaction as acid-base, 1 point for a valid justification.

Solution 2

(b)

Mark scheme

- 2.24 g NaHCO3 × (1 mol / 84.0 g) = 0.0267 mol NaHCO3. 60.0 mL × (0.875 mol HC2H3O2 / 1000 mL) = 0.0525 mol HC2H3O2. NaHCO3(s) and HC2H3O2(aq) react in a 1:1 ratio, so the smaller mole amount, NaHCO3(s), is the limiting reactant. 1 point for calculating the number of moles of each reactant, 1 point for correctly identifying NaHCO3 as the limiting reactant, consistent with the calculation.

Solution 2

(c)

Mark scheme

- As the reaction proceeds, both reactants are consumed and their concentrations decrease; collisions between reactant particles become less frequent as concentrations decrease, so the reaction rate slows. 1 point for a valid explanation in terms of collision frequency between reactant particles.

Solution 2

(d)(i)

Mark scheme

- 'Entropy only' should be circled. Because the flask gets cooler as the reaction proceeds, the reaction is endothermic and cannot be driven by a favorable enthalpy change — it must be driven by entropy. 1 point for circling 'Entropy only'.

Solution 2

(d)(ii)

Mark scheme

- $\Delta G^\circ = \Delta H^\circ - T\Delta S^\circ$; a reaction is thermodynamically favorable when ΔG° is negative. Since the reaction is endothermic (flask gets cooler, ΔH° is positive), enthalpy does not help make ΔG° negative, so the reaction is not driven by enthalpy. Because the reactants contain no gas while one product (CO2) is a gas, ΔS° must be positive, which helps make ΔG° negative — so the reaction is entropy-driven. 1 point for a valid justification referencing the signs of ΔH°, ΔS°, and ΔG°.

Solution 2

(e) Mark scheme

- A correct Lewis structure for HCO3— has a central C bonded to three O atoms: one C=O double bond, one C—O single bond to an O bearing three lone pairs (charge −1 on that O), and one C—O single bond to the O—H oxygen (two lone pairs on that O), with the H attached to that same oxygen. Because two C-to-O bonds are equal length and the third (C—OH) is longer, resonance exists between the two equivalent non-OH oxygens — shown either as two resonance structures or as one structure with a double-headed resonance arrow between those two oxygens. 1 point for a correct Lewis structure of HCO3—, 1 point for indicating resonance between the two equivalent (non-OH) oxygens.

Solution 2

(f)

Mark scheme

- $C2H3O2- + H3O+ \rightarrow HC2H3O2 + H2O$ (equivalently: $C2H3O2- + H+ \rightarrow HC2H3O2$). 1 point for a correct, balanced net-ionic equation showing the acetate ion neutralizing the added $H3O+/H+$, which is why the pH remains at 4.7 (buffer action).

Question 7

2014 ▪ Q7

[Structural diagrams: cis-2-butene (H_3C and CH_3 on the same side of the $C=C$ double bond, H atoms on the same side opposite) in equilibrium (double harpoon arrows) with trans-2-butene (H_3C and CH_3 on opposite sides of the $C=C$ double bond).]

The half-life ($t_{1/2}$) of the catalyzed isomerization of cis-2-butene gas to produce trans-2-butene gas, represented above, was measured under various conditions, as shown in the table below.

Trial Number	Initial $P_{cis\text{-}2\text{-}butene}$ (torr)	V (L)	T (K)	$t_{1/2}$ (s)
1	300.	2.00	350.	100.
2	600.	2.00	350.	100.
3	300.	4.00	350.	100.
4	300.	2.00	365	50.

(a) The reaction is first order. Explain how the data in the table are consistent with a first-order reaction.

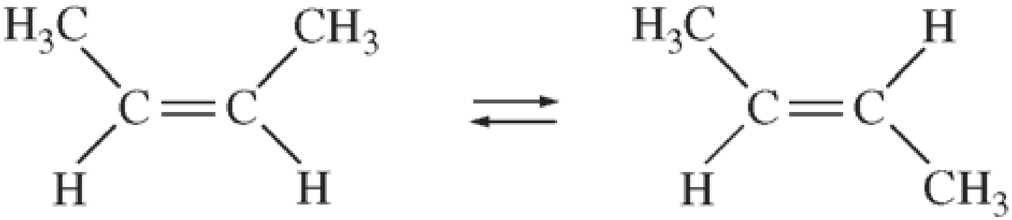
Question 7

(b) Calculate the rate constant, k, for the reaction at 350. K. Include appropriate units with your answer.
(c) Is the initial rate of the reaction in trial 1 greater than, less than, or equal to the initial rate in trial 2? Justify your answer.
(d) The half-life of the reaction in trial 4 is less than the half-life in trial 1. Explain why, in terms of activation energy.

Question 7

Trial Number	Initial $P_{cis\text{-2-butene}}$ (torr)	V (L)	T (K)	$t_{1/2}$ (s)
1	300.	2.00	350.	100.
2	600.	2.00	350.	100.
3	300.	4.00	350.	100.
4	300.	2.00	365	50.

Question 7



cis-2-butene ⇌ *trans*-2-butene

Solution 7

(a)

Mark scheme

- For a first-order reaction, the half-life is independent of the initial reactant concentration (or pressure) at constant temperature. This is consistent with trials 1, 2, and 3: even though the initial pressure of cis-2-butene doubles (300. $\rightarrow$ 600. torr, trial 1 vs. 2) and the volume changes (trial 1 vs. 3), the half-life remains 100. s in all three trials at 350. K.

Solution 7

(b)

Mark scheme

- $k = \dfrac{0.693}{t_{1/2}} = \dfrac{0.693}{100.\ \mathsf{s}} = 0.00693\ \mathsf{s}^{-1}$.

Solution 7

(c)

Mark scheme

- The initial rate in trial 1 is less than the initial rate in trial 2, because rate = k[cis-2-butene] (or rate $= kP_{cis\text{-}2\text{-butene}}$); since k is constant (same temperature, 350. K) and the initial pressure of cis-2-butene in trial 1 (300. torr) is less than in trial 2 (600. torr), the initial rate in trial 1 must be lower.

Solution 7

(d)

Mark scheme

- The temperature in trial 4 (365 K) is higher than in trial 1 (350. K), so the average kinetic energy (KE_avg) of the molecules is greater in trial 4. Consequently, a greater fraction of molecular collisions have sufficient energy to overcome the activation energy barrier, so the rate constant and rate are greater in trial 4, giving it the shorter half-life.