Diploma Programme
Programme du diplôme
Programa del Diploma

Chemistry
Higher level
Paper 2

3 November 2025

Zone A morning | **Zone B** morning | **Zone C** morning

Candidate session number

ANSWERS (?)

2 hours 30 minutes

Instructions to candidates

- Write your session number in the boxes above.
- Do not open this examination paper until instructed to do so.
- Answer all questions.
- Answers must be written within the answer boxes provided.
- A calculator is required for this paper.
- A clean copy of the **chemistry data booklet** is required for this paper.
- The maximum mark for this examination paper is **[90 marks]**.

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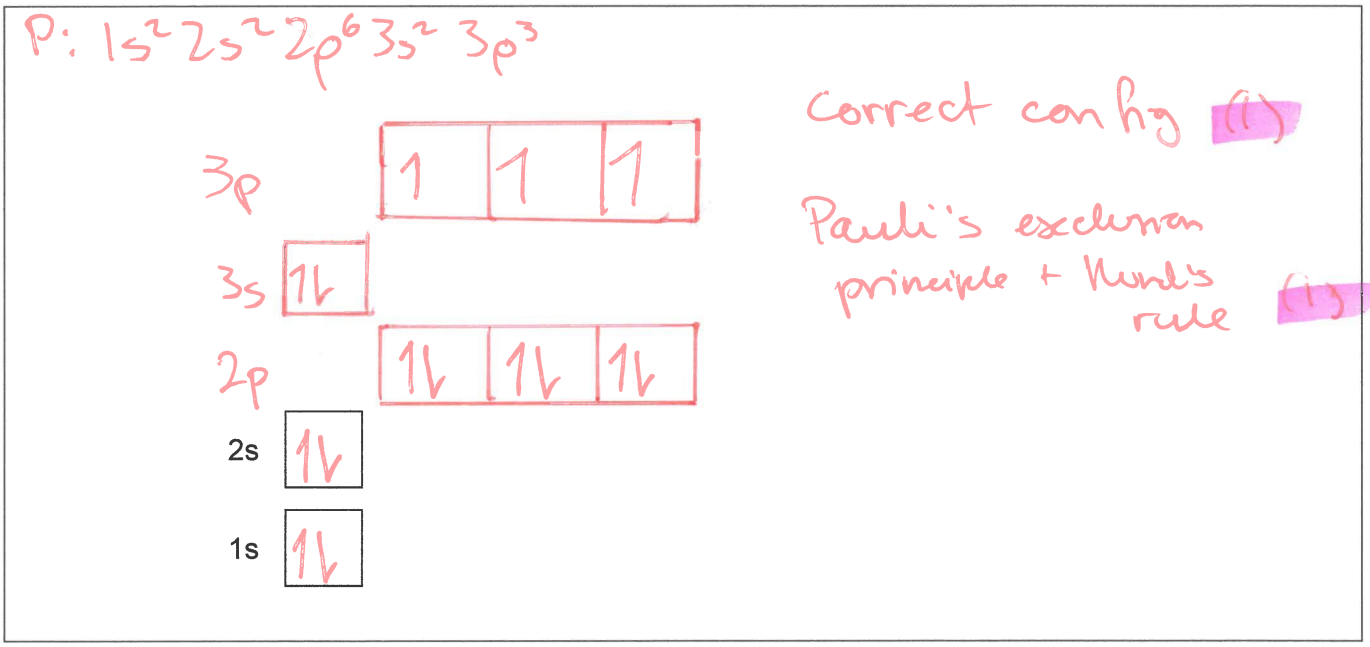
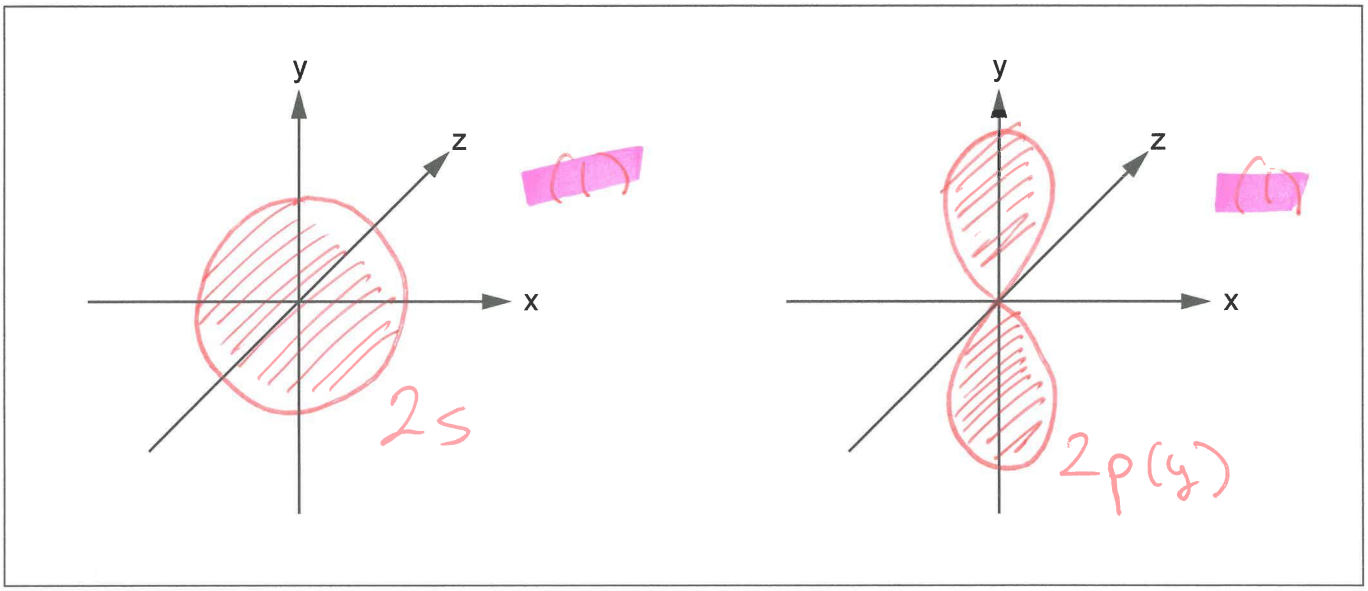
Answer **all** questions. Answers must be written within the answer boxes provided.

1. Phosphorus is an element that is an essential part of the biological molecules involved in both respiration and photosynthesis.

(a) (i) Draw the orbital diagram of the phosphorus atom in the ground state by adding, filling and labelling the orbitals. Use section 7 of the data booklet. [2]



(ii) Sketch the shapes of two different orbital types in the second energy level and label each orbital. [2]



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(Question 1 continued)

(iii) Explain why the first ionization energy decreases as you descend group 15 from nitrogen to bismuth. [2]

As you move down a group the number of orbitals (principal quantum number, n) increases. (1) To remove an electron from the outer shell, the electron must be pulled from the attraction to the nucleus. The larger the quantum number, inner electrons shield outer electrons from the nuclear charge, weakening the attraction ∴ less energy required (1)

(iv) Determine the frequency of electromagnetic radiation, in s^{-1}, equivalent to the first ionization energy of phosphorus. Use sections 1, 2 and 9 of the data booklet. [2]

1st I.E P = 1012 kJ mol^{-1} = 6.022×10^{23}

$E = \frac{1.012 \times 10^6 \text{ J mol}^{-1}}{6.022 \times 10^{23} \text{ mol}^{-1}} = 1.68 \times 10^{-18}$ J (1)

$\nu = E/h = \frac{1.68 \times 10^{-18} \text{ J}}{6.63 \times 10^{-34}}$

$= 2.5 \times 10^{15} \text{ s}^{-1}$ (1)

(b) 7.75 g of phosphorus was combusted in a limited supply of oxygen, the mass of the oxide produced was 13.75 g.

(i) Calculate the number of atoms in 7.75 g of phosphorus. Use sections 2 and 7 of the data booklet. [1]

$n_P = \frac{7.75 \text{ g}}{30.97 \text{ g mol}^{-1}} = 0.250$ mol

# of atoms = $n \times N_A$

$= 0.250 \times 6.022 \times 10^{23} = 1.51 \times 10^{23}$ P atoms (1)

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(Question 1 continued)

(ii) Determine the empirical formula of the oxide formed, show your working. Use section 7 of the data booklet. [3]

$m_O = 13.75 - 7.75 = 6.00\,g$ at O (1)

$n_O = 6.00/16.00 = 0.375$ $\quad n_P = 0.250$

$\div 0.250$

$= 1.5$ $\quad = 1$

$\times 2$

$n_O = 3$ $\quad n_P = 2$ $\quad \therefore P_2O_3$ (1)

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(iii) The M_r of the oxide formed in (b)(ii) was known to be $219.88\,g\,mol^{-1}$.

Determine the molecular formula of the oxide formed, showing your working. Use section 7 of the data booklet. [1]

$mm_{P_2O_3} = 2(31.0) + 3(16.00) = 110\,g$

$\approx 1/2$ give mm

$\therefore$ molecular formula $= 2 \times P_2O_3 = P_4O_6$ (1)

(iv) This oxide of phosphorus has a melting point of 296.9 K.

Outline, with reference to structure and bonding, the reasons why the melting point of this oxide is low. [2]

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P_4O_6 has a low melting point as it is a discrete covalently bonded molecule (1)

It is a non-polar molecule, thus only has / form weak dispersion forces with other P_4O_6 molecules. These intermolecular forces are easily separated with little energy required to separate molecules has a low melting point (1)

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(Question 1 continued)

(v) Describe the nature of the bond between oxygen and phosphorus. Use sections 9 and 17 of the data booklet. [2]

$\chi_P = 2.19$ $\chi_O = 3.44$ $\therefore \Delta\chi = 3.44 - 2.19$

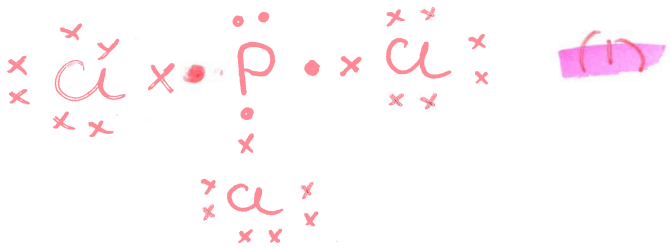
$\Sigma\chi = 3.14 + 2.14/2 = 2.815$ $= 1.25$ (1)

1.25 within range of 0.4 → 1.7

$\therefore$ P–O is a polar covalent bond (1)

(c) Phosphorus has two chlorides, phosphorus (III) chloride, PCl_3, and phosphorus (V) chloride, PCl_5.

(i) Deduce the Lewis formula of PCl_3. [1]



(1)

(ii) Deduce the molecular geometry of PCl_3 and PCl_5. [2]

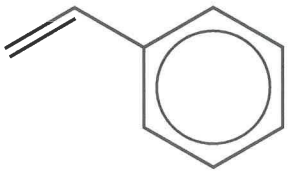
PCl_3: Trigonal pyramidal (1)

PCl_5: Trigonal bipyramidal (1)

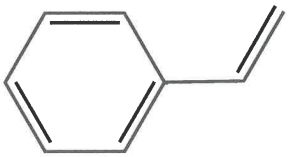
(iii) Suggest a value for the bond angle in PCl_3. [1]

≈ 107° (1)

2. Styrene has the chemical formula C_8H_8 and can be represented by the following structures.



Structure A



Structure B

Structure A is the usual representation of styrene.

(a) Describe what the circle represents in terms of bonding. [1]

Resonance structure due to delocalised π electrons over all six carbon atoms (1)

(b) The Styrene molecule is a derivative of benzene.

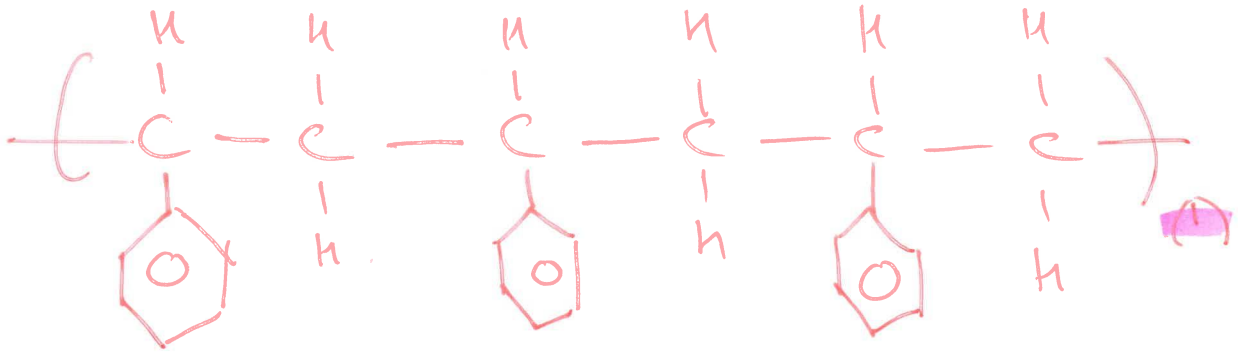
State both a chemical and physical reason structure A is a better representation of benzene. [2]

Chemical reason: Hydrogenation enthalpy of benzene is less than the value of enthalpy for 3x C=C hydrogenation (1)

Physical reason: Equal bond length between all C atoms, as opposed to shorter C=C and longer C–C (1)

(c) Styrene can undergo polymerization.

Draw the structure of the polymer chain. Show three repeating units and state the type of polymerization that occurs. [2]



(1)

Type of polymerization: Addition polymerisation (1)

3. Nitrous acid, HNO_2, is a weak acid which can be used to make acidic buffers.

(a) A 1.00 mol dm^{-3} solution of nitrous acid was prepared. This solution contains two conjugate acid–base pairs.

(i) State the formulas of the conjugate acid and conjugate base in each pair. [2]

Conjugate acid: HNO_2 Conjugate base: NO_2^- (1)

Conjugate acid: H_3O^+ Conjugate base: H_2O (1)

(ii) This 1.00 mol dm^{-3} solution of nitrous acid was used to prepare a buffer with pH 3.00.

Calculate the concentration of the conjugate base of nitrous acid required to make this buffer. The pK_a of nitrous acid is 3.25. [3]

$pH = pK_a + \log \frac{[NO_2^-]}{[HNO_2]}$

$3.00 = 3.25 + \log\left(\frac{[NO_2^-]}{1.00}\right)$ (1)

$\therefore [NO_2^-] = 10^{-(3.00-3.25)}$ (1)

Concentration of conjugate base: 0.562 mol dm^{-3} (1)

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(iii) State the oxidation state of nitrogen in nitrous acid, HNO_2. [1]

$(+1) + x + 2(-2) = 0$

$\therefore x = +3$ (1)

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(This question continues on the following page)

(Question 3 continued)

(b) Picric acid, carbolic acid and aspirin are trivial names of chemical substances.

They can cause misunderstanding when communicating information internationally.

(i) Outline how modern chemists have improved communication when naming chemical substances. [2]

The IUPAC systematic nomenclature (1) uses internationally agreed upon rules (prefixes, suffixes, priority order etc.) which give unique, unambiguous names for every chemical structure (1) to avoid any potential confusion.

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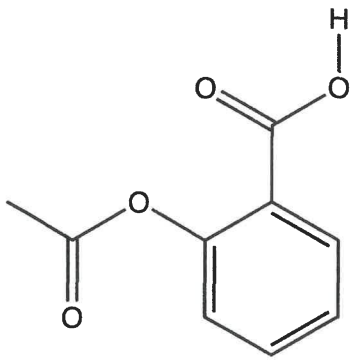
(ii) The molecule of aspirin, shown below, contains an ester functional group.



State the names of the other two functional groups. [2]

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Carboxyl (1)

Phenyl (1)

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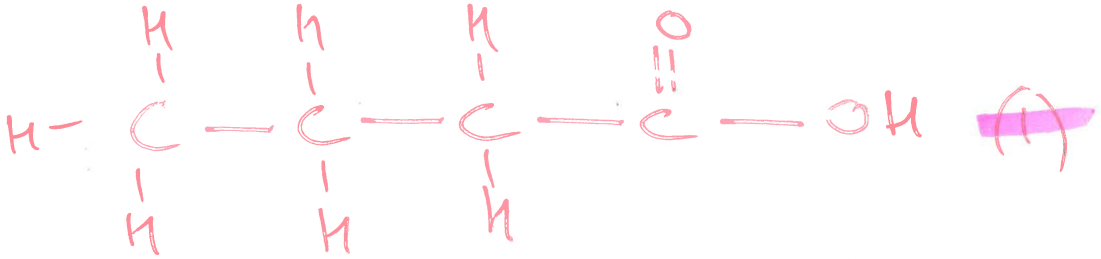
(Question 3 continued)

(iii) Ethyl ethanoate, $C_4H_8O_2$ ($CH_3CO_2CH_2CH_3$) is another ester.

Deduce the structure and name for a functional group isomer of ethyl ethanoate. [2]



Name of isomer: butanoic acid (1)

(c) (i) A catalyst, usually concentrated sulfuric acid, H_2SO_4, is used in the manufacture of this ester.

Explain the action of a catalyst. [2]

Catalyst lowers the activation energy of a reaction (1) by offering an alternate pathway for reaction. This increases the rate of reaction (1)

(ii) Ethyl ethanoate can be produced by the reaction of ethanol with ethanoic acid. Both reactants can be synthesized from ethane through a series of reactions, the first of which is shown.

$$C_2H_6(g) + Cl_2(g) \rightarrow C_2H_5Cl(g) + HCl(g)$$

The first step in this reaction, initiation, is given by the following equation.

$$Cl_2 \rightarrow 2Cl\bullet$$

State an essential condition for this reaction. [1]

(1) UV light to cause homolytic fission of the Cl–Cl bond

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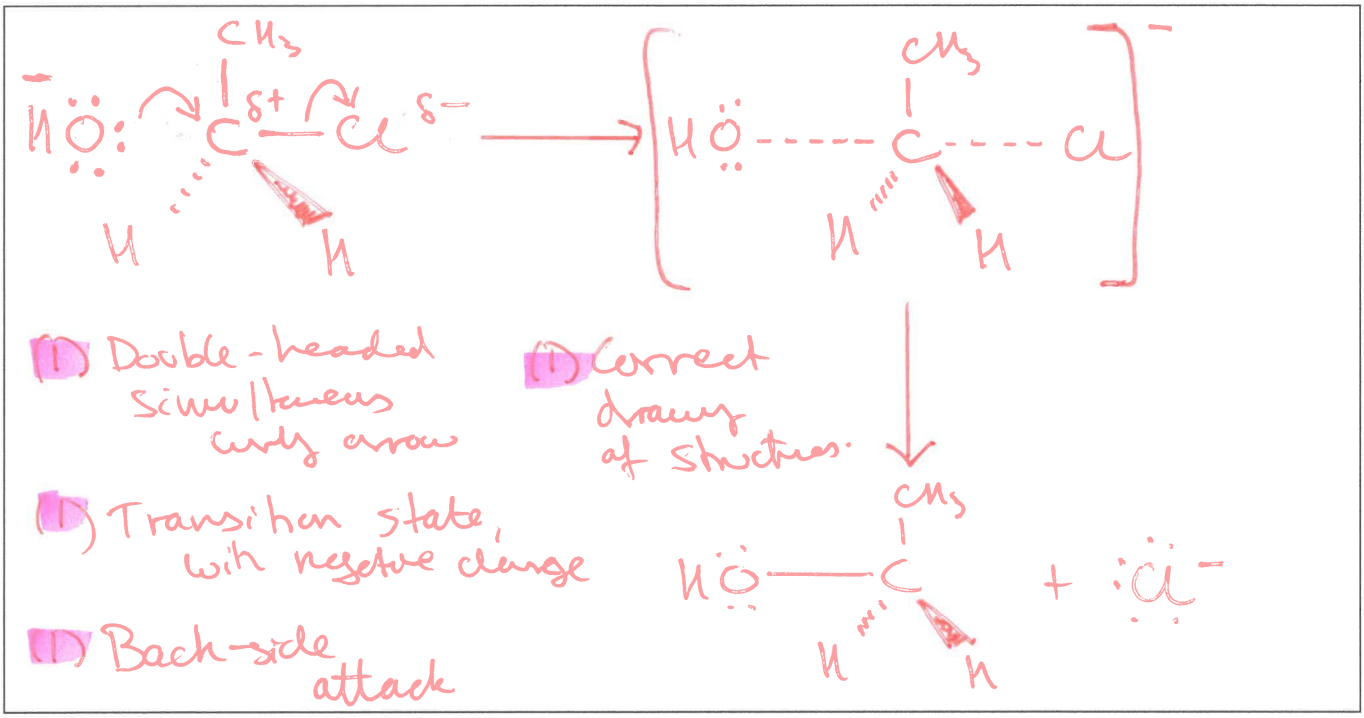
(Question 3 continued)

(iii) Chloroethane is then converted into ethanol using aqueous potassium hydroxide, KOH (aq).

Explain, using curly arrows, the mechanism of this reaction. [4]



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(iv) Deduce the features of a high-resolution ^{1}H NMR spectrum of ethanol, including the number of signals, their expected chemical shifts, integration traces and the splitting patterns. [4]

Number of signals: 3 (for 3 distinct hydrogen environments) (1)

Chemical shift (ppm) range of each signal: H of –OH @ 1.0–6.0 R–CH_2–OH @ 3.3–3.7, H of CH_3 @ 0.9–1.0 (1)

Integration traces: 3 : 2 : 1 (CH_3 : CH_2 : OH) (1)

Splitting pattern expected: CH_3 is a triplet, CH_2 quartet and OH is a singlet. (1)

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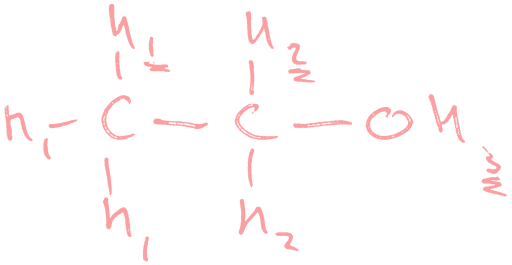
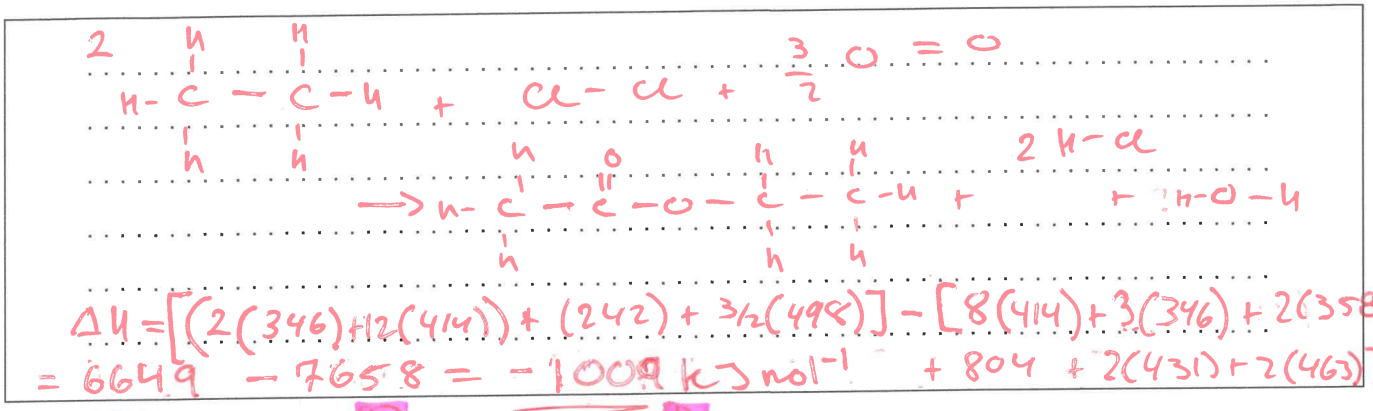


(Question 3 continued)

(d) The overall reaction for the synthesis of ethyl ethanoate from ethane is:

$$2C_2H_6(g) + Cl_2(g) + \frac{3}{2}O_2(g) \rightarrow C_4H_8O_2(g) + 2HCl(g) + H_2O(g)$$

(i) Calculate the enthalpy change for the reaction, ΔH. Use section 12 of the data booklet. [3]



(1) (1) (1)

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(ii) One student used bond enthalpy data and correctly calculated the enthalpy change for the reaction between ethanol and ethanoic acid as 0 kJ mol^{-1}. Another student used enthalpy of formation data and correctly calculated the enthalpy change for the same reaction as –4 kJ mol^{-1}.

$$C_2H_6O(l) + C_2H_4O_2(l) \rightleftharpoons C_4H_8O_2(l) + H_2O(l)$$

Explain how the two students can carry out a calculation for the same reaction and obtain different results when both calculations are correct. [1]

Bond enthalpy values are an average of that bond type, not specific to each molecule. (1) Thus, if there is no net change in bond type the value calculated will be 0.

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(iii) Calculate the standard enthalpy change of formation, ΔH^θ_f, in kJ mol^{-1}, of ethyl ethanoate, $C_4H_8O_2$. Use sections 1 and 13 of the data booklet and the value of –4 kJ mol^{-1} for the standard enthalpy change of reaction, ΔH^θ_r. [2]

$C_2H_5OH_{(l)} + CH_3COOH_{(l)} \rightarrow C_4H_8O_{2(l)} + H_2O_{(l)}$

$\Delta H_f = [\Delta H_f \text{ ester} + \Delta H_f \text{ water}] - [\Delta H_f \text{ ethanol} + \Delta H_f \text{ acid})]$ (1)

$-4\text{ kJ mol} = [\Delta H_f \text{ ester} + (-286)] - [(-278) + (-484)]$

$-4\text{ kJ} = \Delta H_f \text{ ester} + (-286) - (-762)$

$\therefore \Delta H_f \text{ ester} = -480\text{ kJ mol}^{-1}$ (1)

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(Question 3 continued)

(iv) Calculate the standard entropy change, ΔS^{θ}_{r}, in $J K^{-1} mol^{-1}$, for this reaction. Use section 13 of the data booklet and S^{θ} of ethyl ethanoate = $259 J K^{-1} mol^{-1}$. [1]

$\Delta S_r = \Sigma \Delta S_{products} - \Sigma \Delta S_{reactants}$.

$= [(259) + (70)] - [(161) + (160)]$

$= +8 J K^{-1} mol^{-1}$ (1)

(v) Calculate the Gibbs energy change, ΔG^{θ} in $kJ mol^{-1}$, for this reaction under standard conditions. Use the value of $-4 kJ mol^{-1}$ for ΔH^{θ}_{r} and your answer from (d)(iv). If you did not obtain an answer for (d)(iv) use $-10 J K^{-1} mol^{-1}$, although this is not the correct answer. Use sections 1 and 4 of the data booklet. [2]

$\Delta G_r = \Delta H - T\Delta S$ (1)

$= -4 kJ mol^{-1} - (298K)(8/1000 kJ K^{-1} mol^{-1})$

$= -6.4 kJ mol^{-1}$ (1)

(vi) Explain the effect, if any, on the spontaneity of this reaction if the temperature was increased. Use section 1 of the data booklet. [2]

Increasing the temperature makes the reaction more spontaneous (1)

As $\Delta H < 0$ and $\Delta S > 0$, increasing the value of T in $-T\Delta S$, makes ΔG more negative (1)

$\therefore$ more spontaneous.

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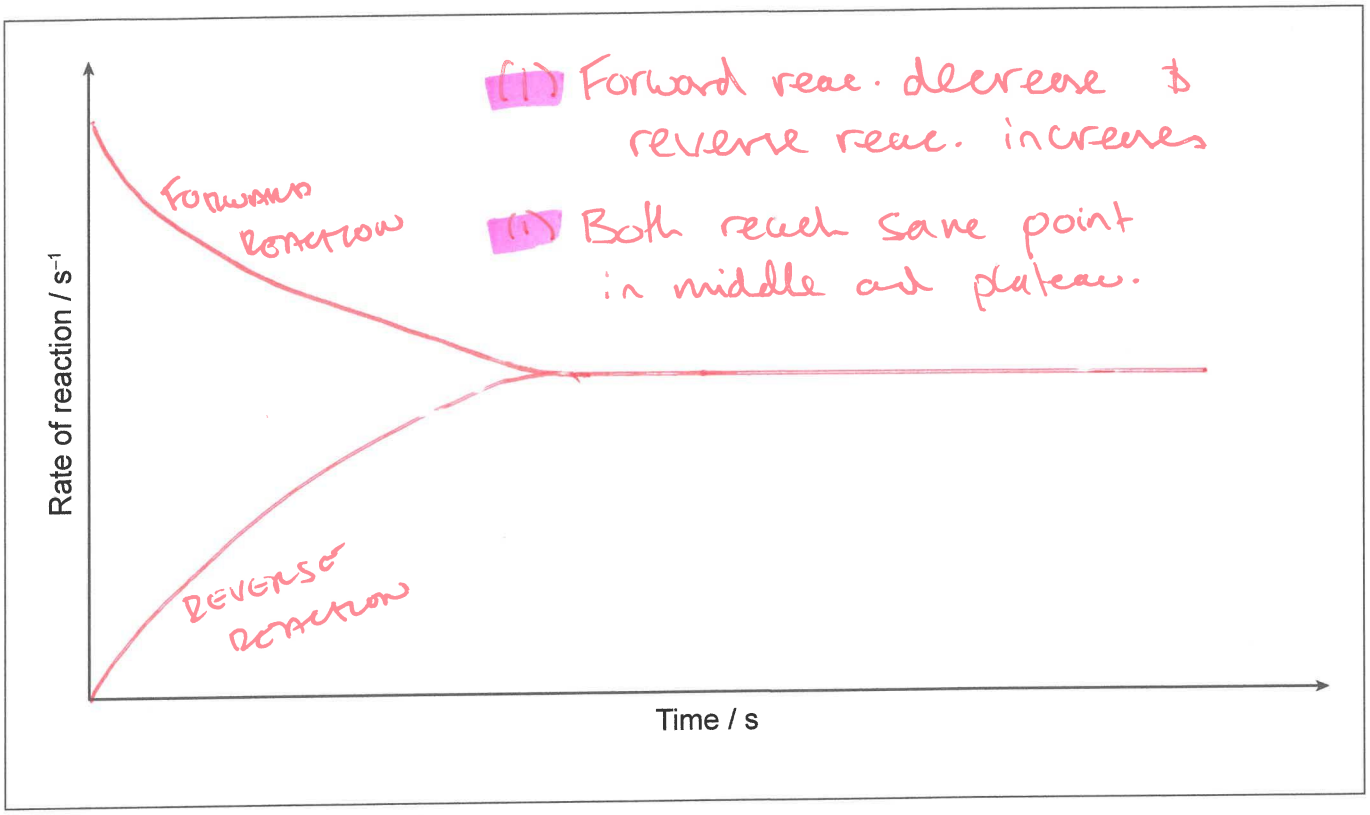
(Question 3 continued)

(vii) The progress of the reaction was followed until equilibrium was reached.

Sketch a graph showing how the rates of the forward and reverse reactions change from the beginning of the reaction, until equilibrium has been reached. [2]



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(viii) Determine the value of the equilibrium constant of this reaction at 60°C. Use sections 1 and 2 of the data booklet and your answer to (d)(iv). If you did not obtain an answer to (d)(iv) use $\Delta G^{\theta} = -8.5\,kJ\,mol^{-1}$ although this is not the correct answer. [2]

$\Delta G = -RT\ln K$

$-6.4\ kJ\ mol^{-1} = -(8.31\ J\ K^{-1}\ mol^{-1})(60 + 273)(\ln K)$ (1)

$\ln K = \frac{(-6.4\ kJ\ mol^{-1}) \times 1000}{-2767.2} = 2.31\ldots$

$\therefore K = e^{2.31} = 10.10$ (1)

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(Question 3 continued)

(e) (i) A student attempted to confirm the value for *K* obtained in (d)(viii).

0.6 moles each of ethanol and ethanoic acid reacted in the presence of an acid catalyst. The volume remained constant. After 10 minutes, 0.2 moles of ethanoic acid remained in the reaction mixture.

$$K = \frac{[C_4H_8O_2][H_2O]}{[C_2H_6O][C_2H_4O_2]}$$

Determine the student's experimental value of K under these conditions. [3]

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	ACID	+ ALCOHOL	⇌ ESTER	+ WATER
i	0.6	0.6	0	0
Δ	−0.4	−0.4	+0.4	+0.4
⇌	0.2	0.2	0.4	0.4

$K = \frac{(0.4)^2}{(0.2)^2} = 4$

(ii) Suggest a reason for the difference between the value of the equilibrium constant, *K*, determined from experimental values in (e)(i) and the correct value calculated for *K*, in (d)(viii).

If you did not obtain values for these, use 7.15 for (d)(viii) and 3.75 for (e)(i), although these are not the correct values. [1]

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Because 10 minutes was not long enough to allow for equilibrium to be reached.

The K value of 4 is actually a Qc = 4

(iii) State the correct name for the value determined in e(i). [1]

Reaction quotient.

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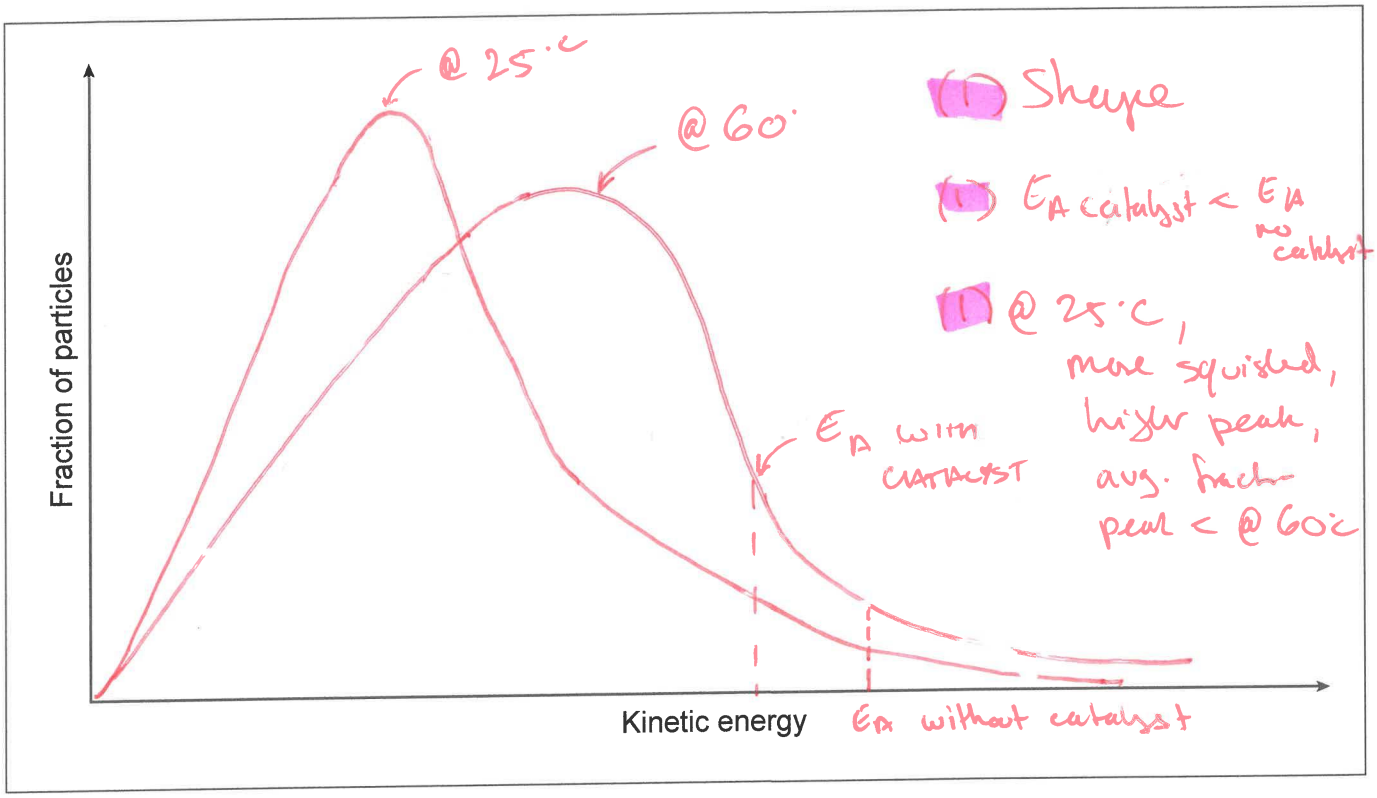
(Question 3 continued)

(f) (i) Sketch the Maxwell–Boltzmann energy distribution curve for this reaction at 60°C. Label the activation energy with and without a catalyst on the diagram. [2]



(ii) Sketch and label the second Maxwell–Boltzmann curve for the same reaction at room temperature, on the axes given in part (f)(i). [1]

(g) Calculate the atom economy for the synthesis of ethyl ethanoate by the reaction below. Use sections 1 and 7 of the data booklet. [2]

$$2C_2H_6(g) + Cl_2(g) + \frac{3}{2}O_2(g) \rightarrow C_4H_8O_2(l) + 2HCl(aq) + H_2O(l)$$

Atom economy = $\frac{\text{rel. mass of desired product}}{\text{rel. mass of total reactants}} \times 100\%$

$= \frac{4(12.01) + 8(1.01) + 2(16.00)}{4(12.01) + 12(1.01) + 2(35.45) + 3/2(2\times16.00)} \times 100\%$ (1)

$= \frac{88.12}{179.06} \times 100\%$

$= 49.2\%$ (1)

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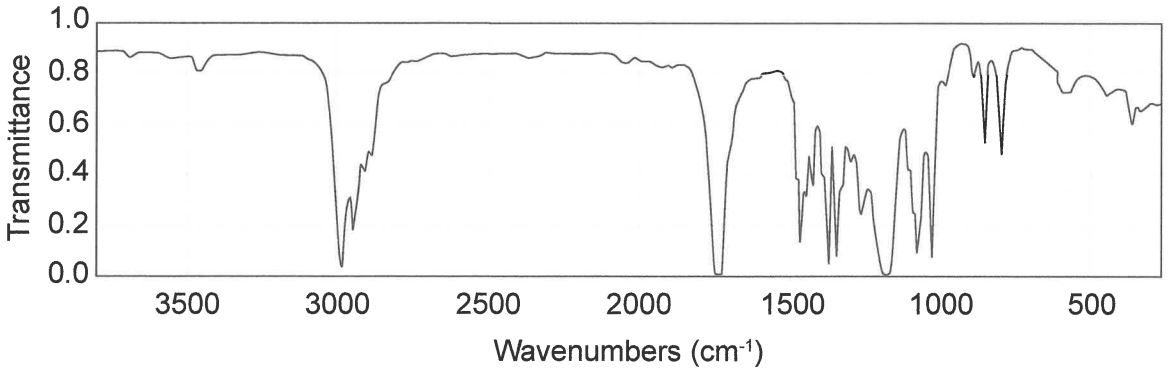
4. Another ester was made following a similar reaction sequence.

(a) The infrared spectrum of the final product is shown below.



(i) Deduce the identity of two peaks that confirm the product is an ester. Use section 20 of the data booklet. [2]

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Peak 1 wavenumber: 1750 cm⁻³ bond: C=O (1)

Peak 2 wavenumber: 1300 cm⁻³ bond: C–O (1)

(ii) Deduce the absorption ranges and the bond(s) responsible for these absorptions that would be present in the IR spectra of alcohols and the carboxylic acids but not in the IR spectrum in part (a). Use section 20 of the data booklet. [1]

There would be an intense broad band at 2500–3000 (RCOOH) and 3200–3600 (ROH) (1)

(b) The mass spectrum shows a molecular ion peak with m/z 102.

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(i) Deduce the molecular formula of this ester if it contains no multiple C–C bonds or rings. Use section 7 of the data booklet. [2]

102 m/z = xC + 2xH + 2(16.00)

∴ 70 = x(12.01) + 2x(1.01) (1)

= 14.01x

∴ x = 70/14.01 = 5 ∴ $C_5H_{10}O_2$ (1)

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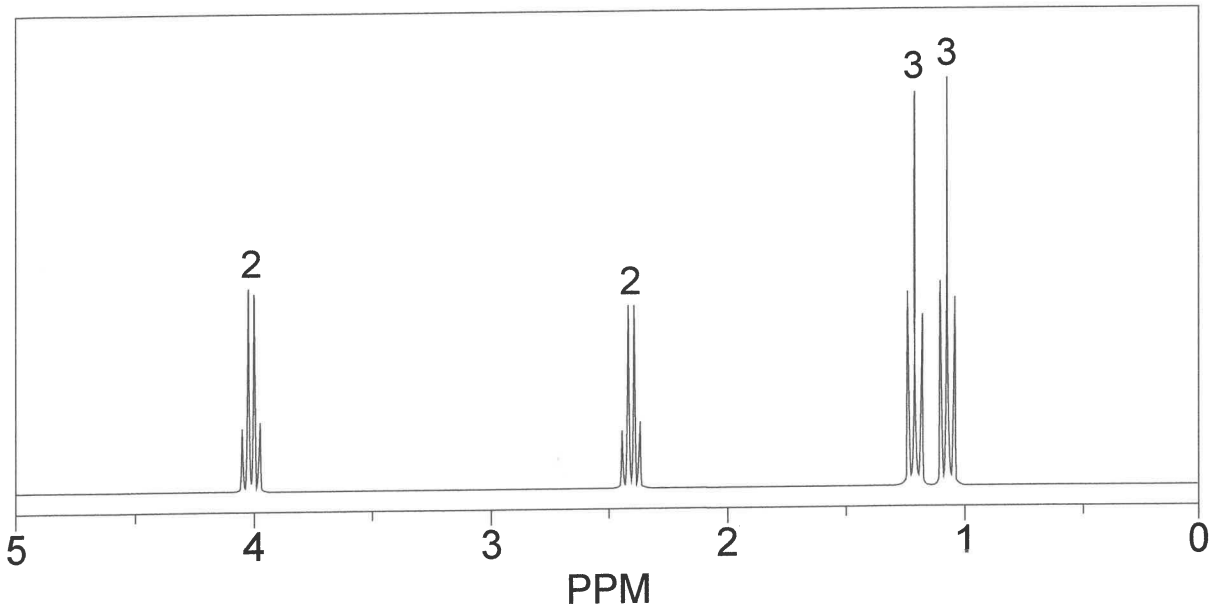
(Question 4 continued)

The high-resolution ^{1}H NMR spectrum of the ester is shown. The integration is indicated above the signals on the trace.



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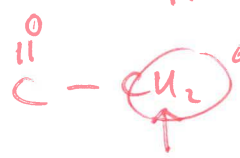
(ii) Deduce the identity of the ester. Use section 21 on the data booklet. [1]

ethyl propanoate (1)

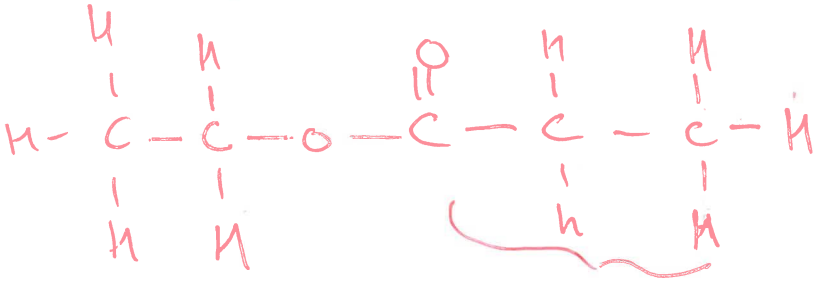
4 hydrogen environments with traces at 3:3:2:2 ← shift @ 4 ppm split into quad ∴ next to CH2 ∴ R-CH2-O-C(=O)-R

@~2.4 ppm



split into quad ∴ next to CH3

from ethanol



from propanoic acid

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5. Transition elements are known for having multiple oxidation states, forming coloured compounds and acting as catalysts. The existence of variable oxidation states means many are used in rechargeable batteries, also known as secondary cells.

(a) (i) A common rechargeable battery is the nickel-cadmium, NiCd, battery where the two reactions during discharge are as follows.

$$Cd(s) + 2OH^-(aq) \rightleftharpoons Cd(OH)_2(s) + 2e^-$$

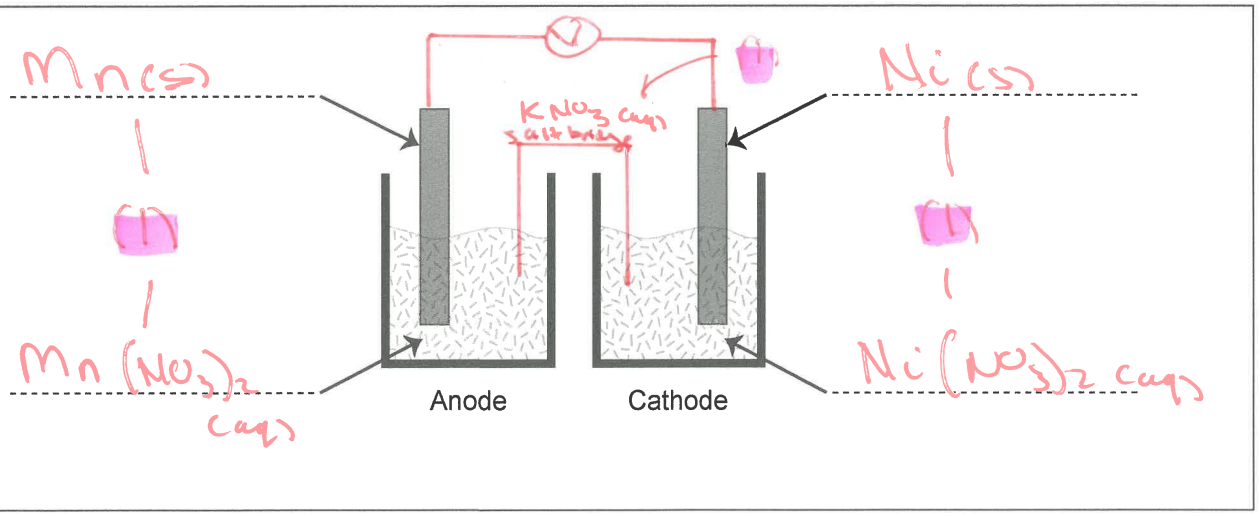
$$2NiO(OH)(s) + H_2O(l) + 2e^- \rightleftharpoons 2Ni(OH)_2(s) + 2OH^-(aq)$$

Deduce the overall cell equation. [1]

$2NiO(OH)_{(s)} + H_2O_{(l)} + Cd_{(s)} \rightleftharpoons Cd(OH)_{2(s)} + 2NiO(OH)_{2(s)}$ (1)

(ii) Simple cells rely on differences in standard electrode potential values between different elements and their ions. The following is an incomplete diagram for measuring a cell potential between $Mn^{2+}(aq)/Mn$ and $Ni^{2+}(aq)/Ni$ half-cells.

Draw the missing components and fully label the diagram to show how the cell potential can be measured. [3]



(iii) Calculate the standard cell potential, E^{θ}_{cell}, for this cell. Use section 19 of the data booklet. [1]

$(+1.18) + (-0.26) = 0.92V$ (1)

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(Question 5 continued)

(b) A different combination of half-cells produced a calculated value of Gibbs energy change, ΔG^{θ}, of $-570.3\,kJ\,mol^{-1}$. The cell involved the transfer of one electron between the electrodes.

Deduce the half-cells involved in this battery. Use sections 1, 2 and 19 of the data booklet. [3]

$\Delta G = -nFE^{\theta}$

$-570.3\,kJ\,mol^{-1} = -(1)(96485\,C\,mol^{-1})\,E^{\theta}$

$\times 1000$

$\therefore E^{\theta} = -570300/96485 = +5.91\,V$ (1)

∴ Potential difference of +5.91

(1) $Li_{(s)} \rightarrow Li^{+}_{(aq)} + e^{-}$ $E^{\theta} = +3.04$ } $= +5.91$

(1) $\frac{1}{2}F_2 + e^{-} \rightarrow F^{-}_{(aq)}$ $E^{\theta} = +2.87$

885

(c) Chromium, Cr, is a transition metal that produces a shiny surface and is used in the automobile industry. The chromium is deposited onto a base metal in an electrolytic cell.

Annotate the table, with ticks, ✓, to show the direction and place of movement of the species shown. [2]

	Direction of movement		Place of movement	
Species	Towards cathode	Towards anode	In the wires	Through the electrolyte
Electrons	✓		✓	
Cr^{3+} ions	✓			✓

(1) (1)

Z000

885

Z000

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