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Chemistry Higher level Paper 2

3 November 2025

Zone A morning | Zone B morning | Zone C morning

Candidate session number

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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]**.



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]

A large rectangular box for drawing the orbital diagram. On the left side, there are two empty square boxes. The top box is labeled '2s' and the bottom box is labeled '1s'.

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

Two identical 3D Cartesian coordinate systems are provided for sketching orbitals. Each system has three axes: a vertical y-axis, a horizontal x-axis pointing to the right, and a diagonal z-axis pointing up and to the right. The axes are labeled with their respective letters.

(This question continues on the following page)



(Question 1 continued)

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

[2]

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- (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]

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- (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]

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(This question continues on the following page)



(Question 1 continued)

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

[3]

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- (iii) The M_r of the oxide formed in (b)(ii) was known to be $219.88 \text{ g mol}^{-1}$.
Determine the molecular formula of the oxide formed, showing your working.
Use section 7 of the data booklet.

[1]

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- (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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(This question continues on the following page)



(Question 1 continued)

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

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- (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]

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

PCl_3 :

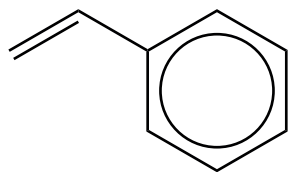
PCl_5 :

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

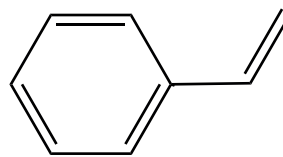
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2. Styrene has the chemical formula C_8H_8 and can be represented by the following structures.



Structure A



Structure B

Structure A is the usual representation of styrene.

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

[1]

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(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:

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Physical reason:

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(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]

Type of polymerization:



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:	Conjugate base:
Conjugate acid:	Conjugate base:

(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]

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

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(Question 3 continued)

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

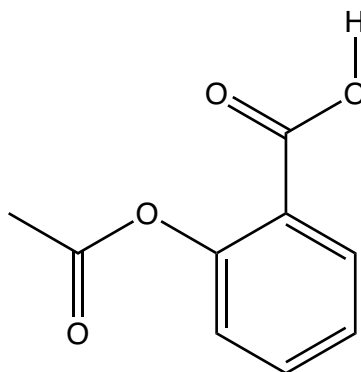
They can cause misunderstanding when communicating information internationally.

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

[2]

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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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(This question continues on the following page)



(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]

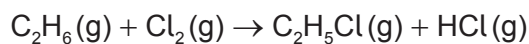
Name of isomer:

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

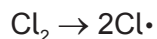
Explain the action of a catalyst. [2]

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(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.



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



State an essential condition for this reaction. [1]

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(This question continues on the following page)



(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]

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

[4]

Number of signals:

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Chemical shift (ppm) range of each signal:

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Integration traces:

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Splitting pattern expected:

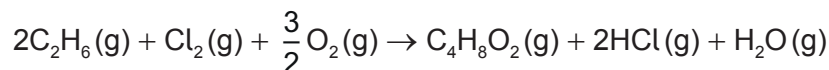
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(Question 3 continued)

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



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

[3]

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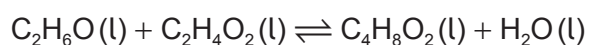
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(ii) One student used bond enthalpy data and correctly calculated the enthalpy change for the reaction between ethanol and ethanoic acid as 0 kJ mol^{-1} . Another student used enthalpy of formation data and correctly calculated the enthalpy change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



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

[1]

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(iii) Calculate the standard enthalpy change of formation, ΔH_f^θ , in kJ mol^{-1} , of ethyl ethanoate, $\text{C}_4\text{H}_8\text{O}_2$. 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_r^θ .

[2]

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(This question continues on the following page)



(Question 3 continued)

- (iv) Calculate the standard entropy change, ΔS^\ominus_r , in $\text{JK}^{-1}\text{mol}^{-1}$, for this reaction. Use section 13 of the data booklet and S^\ominus of ethyl ethanoate = $259\text{JK}^{-1}\text{mol}^{-1}$. [1]

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

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- (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]

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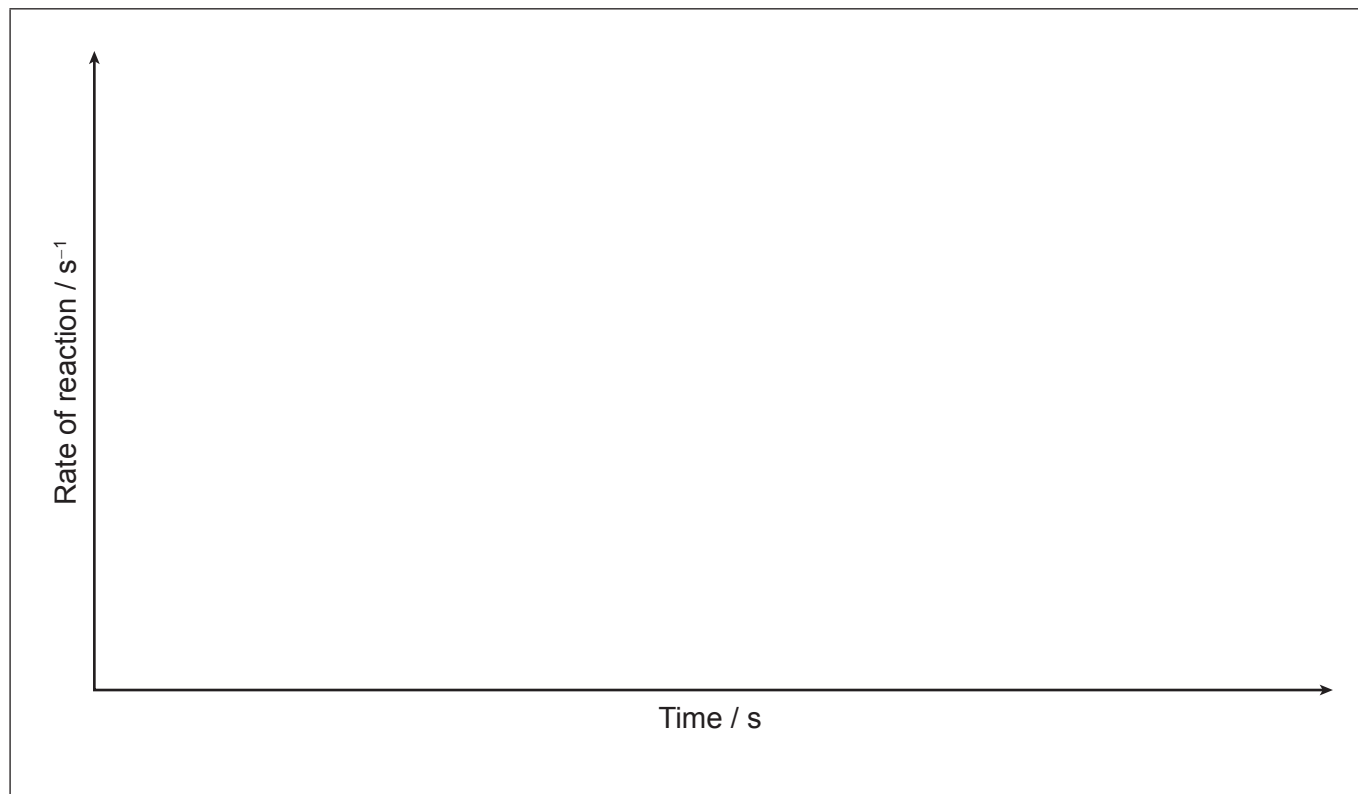
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(Question 3 continued)

(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]



(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)(v). If you did not obtain an answer to (d)(v) use $\Delta G^\theta = -8.5 \text{ kJ mol}^{-1}$ although this is not the correct answer. [2]

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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.

$$K = \frac{[\text{C}_4\text{H}_8\text{O}_2][\text{H}_2\text{O}]}{[\text{C}_2\text{H}_6\text{O}][\text{C}_2\text{H}_4\text{O}_2]}$$

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

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

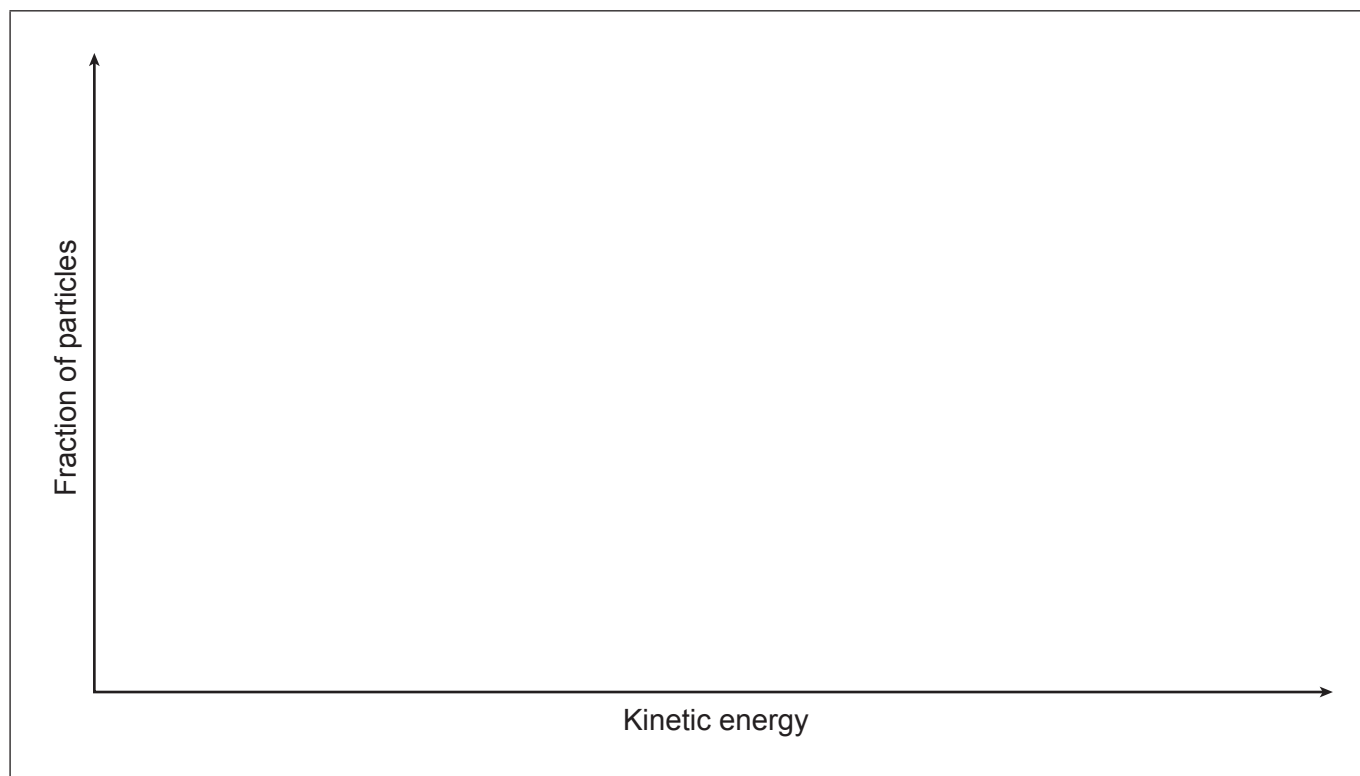
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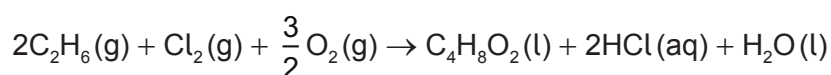


(Question 3 continued)

- (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]



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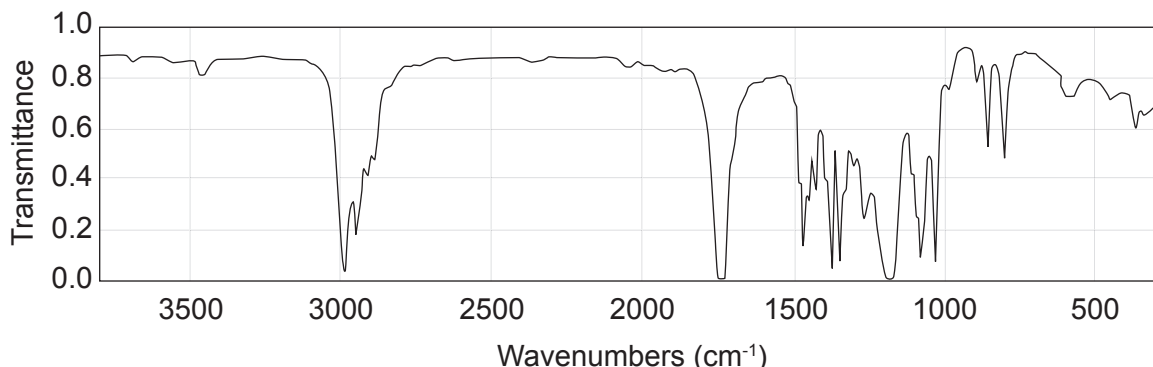
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4. Another ester was made following a similar reaction sequence.

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



[Source: Used with permission. © United States of America as represented by the Secretary of Commerce.]

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

Peak 1 wavenumber:	bond:
Peak 2 wavenumber:	bond:

(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]

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

(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]

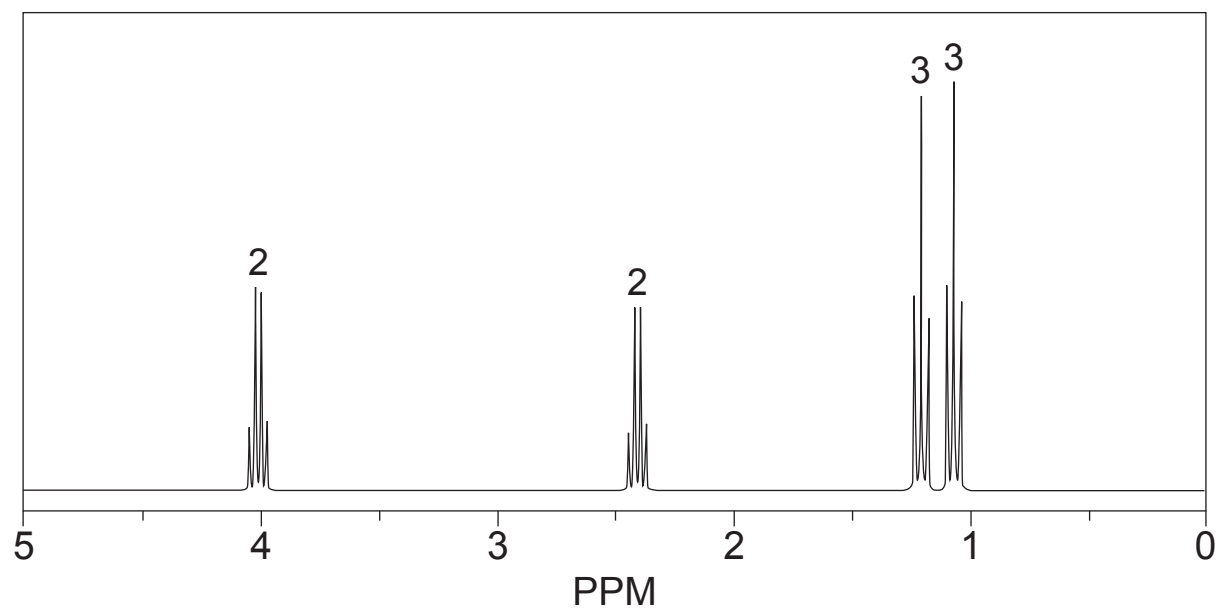
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(Question 4 continued)

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



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

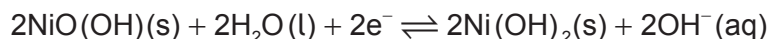
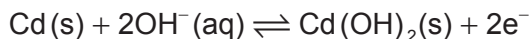
[1]

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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.



Deduce the overall cell equation.

[1]

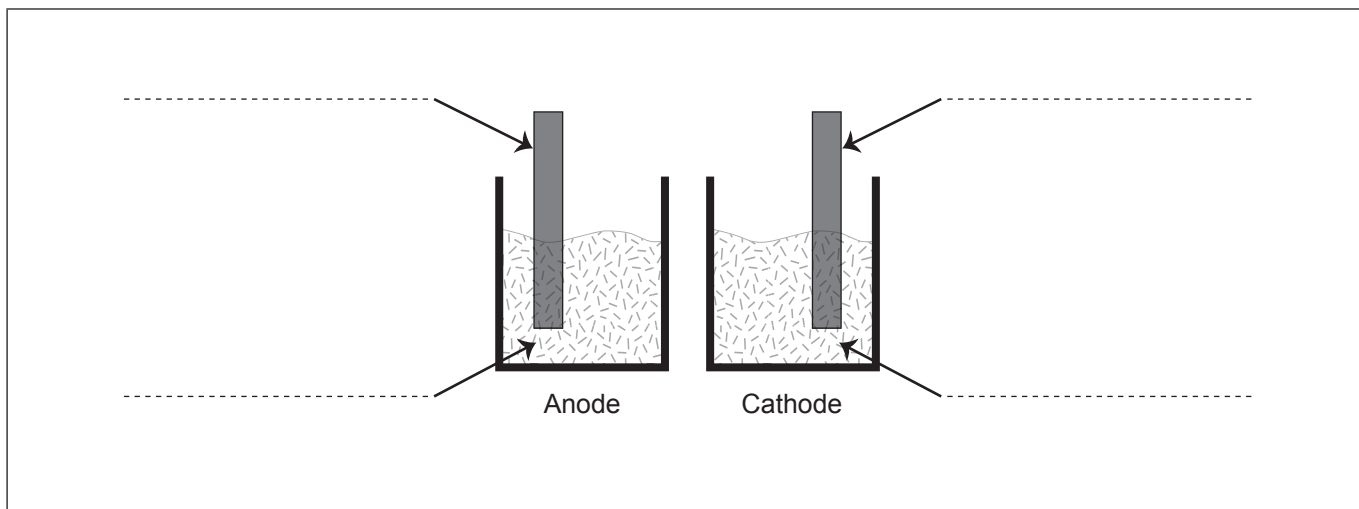
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(ii) Simple cells rely on differences in standard electrode potential values between different elements and their ions. The following is an incomplete diagram for measuring a cell potential between $\text{Mn}^{2+}(\text{aq})/\text{Mn}$ and $\text{Ni}^{2+}(\text{aq})/\text{Ni}$ 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°_{cell} , for this cell. Use section 19 of the data booklet.

[1]

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(This question continues on the following page)



(Question 5 continued)

- (b) A different combination of half-cells produced a calculated value of Gibbs energy change, ΔG^\ominus , of $-570.3 \text{ kJ mol}^{-1}$. 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]

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- (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, \checkmark , to show the direction and place of movement of the species shown.

[2]

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



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