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Chemistry
Higher level
Paper 2

3 November 2023

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

Candidate session number

2 hours 15 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]**.

25 pages

8823 – 6114

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

1. Methanoic acid (HCOOH) is the first member of the homologous series of carboxylic acids.

(a) Outline what is meant by the term “homologous series”. [1]

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(b) Calculate the percentage, by mass, of oxygen in methanoic acid. [2]

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(This question continues on the following page)

(Question 1 continued)

(c) Methanoic acid and ethanal (CH_3CHO) both contain a carbonyl group and have similar molar masses.

(i) Explain why, in terms of the strongest intermolecular forces between the molecules, ethanal has a much lower boiling point than methanoic acid. [2]

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(ii) Outline why ethanal and methanoic acid are both fully miscible with water. [1]

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(iii) Predict, giving an explanation, the relative electrical conductivity of solutions of methanoic acid, ethanal and hydrochloric acid of the same concentration. [3]

Relative electrical conductivity: ______________ < ______________ < ______________

Explanation: . . . .

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(This question continues on the following page)

(Question 1 continued)

(d) Methanoic acid acts as a weak monobasic acid in aqueous solution.

(i) 2.00 dm^3 of a solution of methanoic acid was prepared, and 25.0 cm^3 of this was found to require exactly 20.7 cm^3 of 0.100 $mol\,dm^{-3}$ aqueous sodium hydroxide to completely convert it to sodium methanoate, HCOONa. Calculate the mass of methanoic acid used to make the solution. [2]

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(ii) Determine the pH of the methanoic acid solution. Use section 21 of the data booklet. [3]

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(iii) Predict, using an equation, whether the pH of the solution of sodium methanoate formed would be greater than, less than or equal to 7. [2]

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(This question continues on the following page)

(Question 1 continued)

(iv) Explain why the two carbon–oxygen bonds in the methanoate ion are of equal length, and compare their length to the carbon–oxygen bonds in methanoic acid. [2]

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2. Methanoic acid can be produced by the hydrogenation of carbon dioxide according to the equilibrium

$$CO_2(g) + H_2(g) \rightleftharpoons HCOOH(g)$$

(a) Explain why this process has been extensively investigated in recent years. [2]

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(b) State the equilibrium constant expression for this reaction. [1]

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(This question continues on the following page)

(Question 2 continued)

(c) Bond enthalpies are a useful way of finding approximate enthalpy changes for reactions.

(i) Determine the enthalpy change, $\Delta H^{\ominus}$, of this reaction, using section 11 of the data booklet. [3]

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(ii) Assuming a 0.1 % uncertainty for each bond enthalpy, determine the resultant percentage uncertainty of the calculated enthalpy change of the reaction. [2]

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(iii) Bond enthalpies are usually only approximate values. Identify which of the bond enthalpies you have just used is actually an exact value, and give a reason for your choice. [1]

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(This question continues on the following page)

(Question 2 continued)

(d) Suggest why temperature has a very small effect on the value of the equilibrium constant. [1]

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(e) Calculate the standard entropy change, $\Delta S^{\ominus}$, of the reaction. Use data from section 12 of the data booklet and the given values: [1]

	H_2(g)	**HCOOH(g)**
$S^{\ominus}$	$130.7\,J\,mol^{-1}\,K^{-1}$	$251.0\,J\,mol^{-1}\,K^{-1}$

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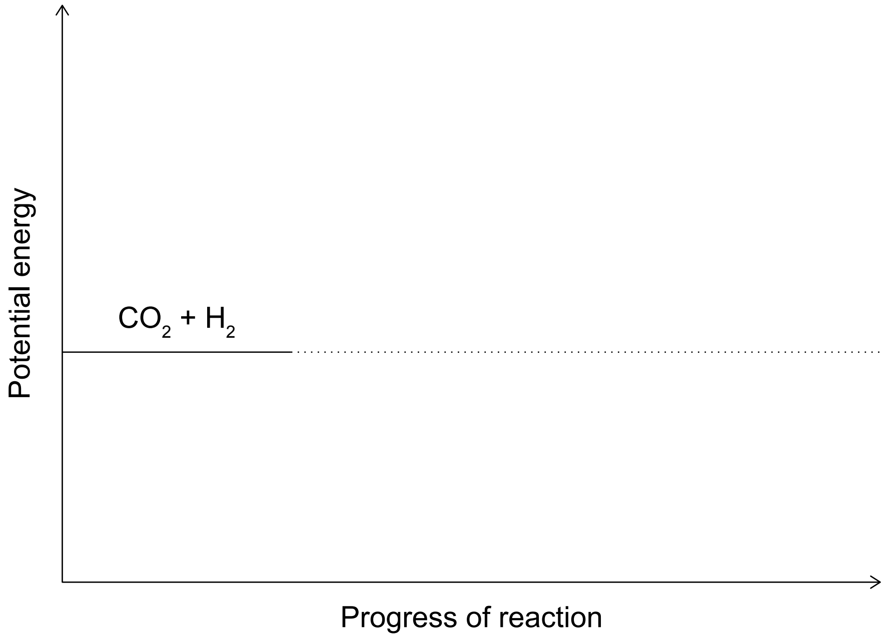
(This question continues on the following page)

(Question 2 continued)

(f) The conversion of carbon dioxide to methanoic acid is usually carried out over an iridium-based catalyst.

(i) Sketch, on the axes provided, energy profiles of the reaction both with and without a catalyst, indicating ΔH and the activation energies. [3]



(ii) State **one** change, other than carrying out the reaction over a catalyst at high temperature, that would increase the reaction rate. [1]

(g) Determine the oxidation state of carbon in methanoic acid. [1]

3. Methanoic acid can be converted into methyl methanoate, $HCOOCH_3$.

(a) State the name of the reagent and catalyst required. [2]

Reagent: . . . .

Catalyst: . . . .

(b) 1.72 g of methyl methanoate is produced from 2.83 g of methanoic acid and excess of the other reagent. Determine the percentage yield. [2]

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(c) The conversion of methanoic acid to methyl methanoate can be followed by changes in spectra.

(i) State **one** similarity and **one** difference you would expect in the infrared (IR) spectra of methanoic acid and methyl methanoate in the region of 1500–3500 cm^{-1}. Use section 26 of the data booklet. [2]

Similarity: . . . .

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Difference: . . . .

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(This question continues on the following page)

(Question 3 continued)

(ii) Deduce, referring to the integration trace, whether the ^1H NMR spectrum shown is that of methanoic acid or methyl methanoate. [1]

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(d) State the class of compounds to which methyl methanoate belongs. [1]

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4. Carbon disulfide, CS_2, undergoes gas phase hydrolysis according to the overall equation

$$CS_2(g) + 2H_2O(g) \rightleftharpoons CO_2(g) + 2H_2S(g)$$

(a) (i) Calculate the enthalpy change in this reaction from section 12 of the data booklet and the given values: [2]

	$CS_2(g)$	**$H_2S(g)$**
$\Delta H_f^\ominus$	$+88.7 \text{ kJ mol}^{-1}$	$-20.6 \text{ kJ mol}^{-1}$

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(ii) Outline why you would expect the entropy change for this reaction to be quite small. [1]

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(iii) Neglecting any entropy change, use your answer to 4(a)(i), section 1 and section 2 of the data booklet to estimate the equilibrium constant, K_c, at 500 K.

(If you did not obtain an answer to 4(a)(i), use a value of $-50.0 \text{ kJ mol}^{-1}$, although this is not the correct answer.) [2]

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(This question continues on the following page)

(Question 4 continued)

(iv) The concentrations of the species involved at equilibrium are:

CS_2 (g)	**H_2O (g)**	**CO_2 (g)**	**H_2S (g)**
$0.0400\ mol\ dm^{-3}$	$0.100\ mol\ dm^{-3}$	$x\ mol\ dm^{-3}$	$2x\ mol\ dm^{-3}$

Calculate the numerical value of x, the concentration of carbon dioxide at equilibrium, using your answer from 4(a)(iii).

(If you did not obtain an answer to 4(a)(iii), then use a value of 1.68×10^5, although this is not the correct answer.) [2]

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(b) Deduce the molecular geometries of CS_2 and H_2S, and the reason why they are different. [2]

Molecular geometry CS_2: . . . .

Molecular geometry H_2S: . . . .

Reason for difference: . . . .

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(This question continues on page 15)

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will not be marked.

(Question 4 continued)

(c) Sulfur has a number of natural isotopes and a sample of sulfur was enriched in ${}^{36}_{16}\mathrm{S}$, to produce a mixture with the following composition:

Isotope	**Percent**
${}^{32}_{16}\mathrm{S}$	90%
${}^{33}_{16}\mathrm{S}$	1%
${}^{34}_{16}\mathrm{S}$	4%
${}^{36}_{16}\mathrm{S}$	5%

(i) Calculate the relative atomic mass of this enriched sample, correct to two decimal places. [2]

(ii) In naturally occurring sulfur, the relative abundance of ${}^{36}_{16}\mathrm{S}$ is only 0.0100%. Calculate the number of atoms of this isotope that would be present in 1.00 g of natural sulfur. Use sections 2 and 6 of the data booklet. [2]

5. Beryllium is a low-density metal that is used in specialized lightweight alloys.

(a) Beryllium has a crystalline structure.

(i) State the technique that would be used to determine the crystal structure of beryllium. [1]

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(ii) Outline the electrostatic attraction in the beryllium crystal structure. [1]

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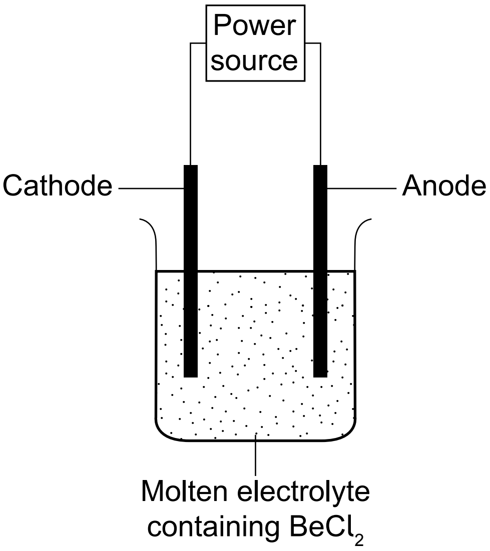
(b) The production of beryllium is illustrated in the diagram.



(i) Outline why molten $BeCl_2$ is considered an electrolyte. [1]

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(This question continues on the following page)

(Question 5 continued)

(ii) Identify the electrode at which beryllium will be produced **and** the polarity of that electrode. [1]

Electrode: . . . .

Polarity: . . . .

(iii) Write a balanced equation for the reaction occurring at the other electrode, to the one you identified in 5(b)(ii). [1]

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(iv) Calculate the mass of beryllium that would be produced by the passage of 1.00×10^6 coulomb of electrical charge. Use sections 2 and 6 of the data booklet. [2]

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(This question continues on the following page)

(Question 5 continued)

(c) Beryllium forms a chloride, $BeCl_2$.

(i) Draw the Lewis (electron dot) structure of the $BeCl_2$ molecule. [1]

(ii) Outline how the Lewis (electron dot) structure of the $BeCl_2$ molecule differs from most Lewis (electron dot) structures. [1]

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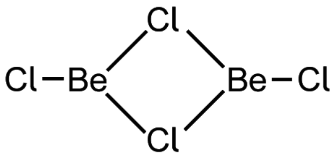
(d) Beryllium chloride, $BeCl_2$, partially dimerizes in the gas phase to produce this molecule:



(i) Identify the hybridization of the beryllium atom in the dimer, Be_2Cl_4. [1]

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(ii) Describe the interactions between the $BeCl_2$ monomers to form the dimer in Lewis' acid-base terms. [1]

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(This question continues on the following page)

(Question 5 continued)

(e) Iron (III) chloride also exists as a dimer in the vapour phase, but iron, unlike beryllium, is a transition element.

(i) Outline, in terms of its electronic structure, what identifies a transition element. [1]

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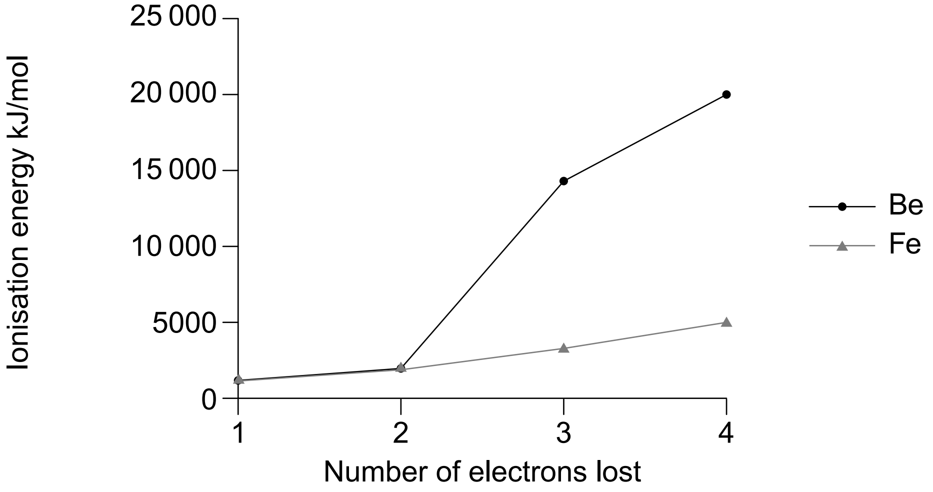
(ii) The first four ionization energies of beryllium and iron are shown.



One common property of transition elements is that they have variable oxidation states. Discuss, referring to the graph, why iron, but not beryllium, displays this characteristic. [3]

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(This question continues on the following page)

(Question 5 continued)

(f) The standard electrode potential, E°, of

$$\text{Be}^{2+}(\text{aq}) + 2\text{e}^- \rightleftharpoons \text{Be}(\text{s})$$

is −1.85 V.

(i) Calculate the cell potential for the reaction

$$\text{Be}(\text{s}) + 2\text{H}_2\text{O}(\text{l}) \rightarrow \text{Be}^{2+}(\text{aq}) + 2\text{OH}^-(\text{aq}) + \text{H}_2(\text{g})$$

Use section 24 of the data booklet. [1]

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(ii) Deduce, giving a reason, whether this reaction is thermodynamically spontaneous. [1]

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(This question continues on the following page)

(Question 5 continued)

(g) Explain, in terms of nuclear charge, electron subshells and the shielding provided by filled electron shells, why the first ionization energy increases from Li to Be, but decreases from Be to B. [4]

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(h) Outline how the first ionization energy of beryllium could be found from its atomic emission spectrum. [1]

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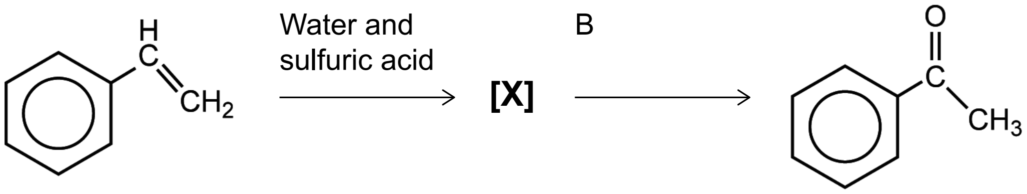
6. Phenylethanone is a fragrant compound that occurs naturally in fruits such as bananas and apples.

(a) Phenylethanone may be synthesised in a two-stage process from phenylethene:



(i) Draw the structural formula of the intermediate compound **[X]**. [1]

(ii) Outline why the intermediate compound, **[X]**, can exhibit stereoisomerism. [1]

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(iii) State the reagent required for the second stage of the synthesis, B. [1]

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(iv) Determine the compound that will be formed as a minor product in this two-stage synthesis, and outline why this will occur. [2]

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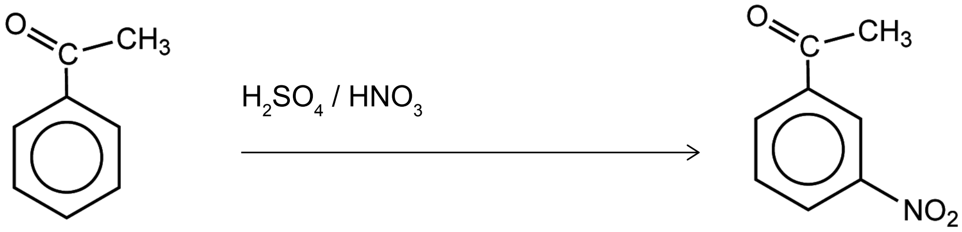
(This question continues on the following page)

(Question 6 continued)

(b) When heated with a mixture of concentrated sulfuric and nitric acids, phenylethanone is nitrated, in a similar manner to benzene, to form 3-nitrophenylethanone.



(i) Write the formula of the electrophile produced in this acid mixture. [1]

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(ii) Explain the mechanism of the reaction between phenylethanone and the nitrating agent, using curly arrows to represent the movement of electron pairs. [4]

(This question continues on page 25)

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(Question 6 continued)

(c) Chemists have a “rule of thumb” that raising the temperature by 10 °C doubles the reaction rate. Deduce the activation energy, in kJ mol^{-1}, assuming that a rise in temperature from 25 °C to 35 °C doubled the rate of this reaction. Use sections 1 and 2 of the data booklet. [3]

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References:

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