Diploma Programme
Programme du diplôme
Programa del Diploma

Chemistry
Higher level
Paper 2

Wednesday 10 November 2021 (afternoon)

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]**.

8821 – 6102

23 pages

Please **do not** write on this page.

Answers written on this page
will not be marked.

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

1. A 4.406 g sample of a compound containing only C, H and O was burnt in excess oxygen. 8.802 g of CO_2 and 3.604 g of H_2O were produced.

(a) Determine the empirical formula of the compound using section 6 of the data booklet. [3]

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(b) Determine the molecular formula of this compound if its molar mass is 88.12 g mol^{-1}. If you did not obtain an answer in (a) use CS, but this is not the correct answer. [1]

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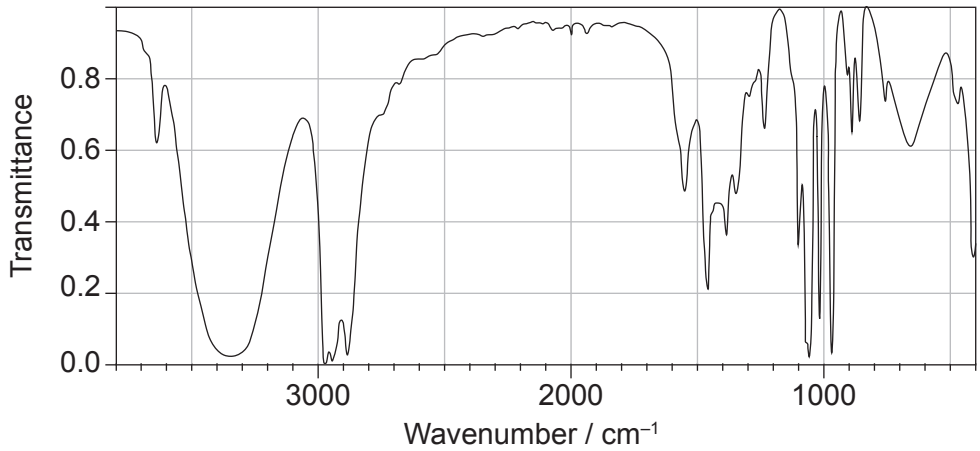
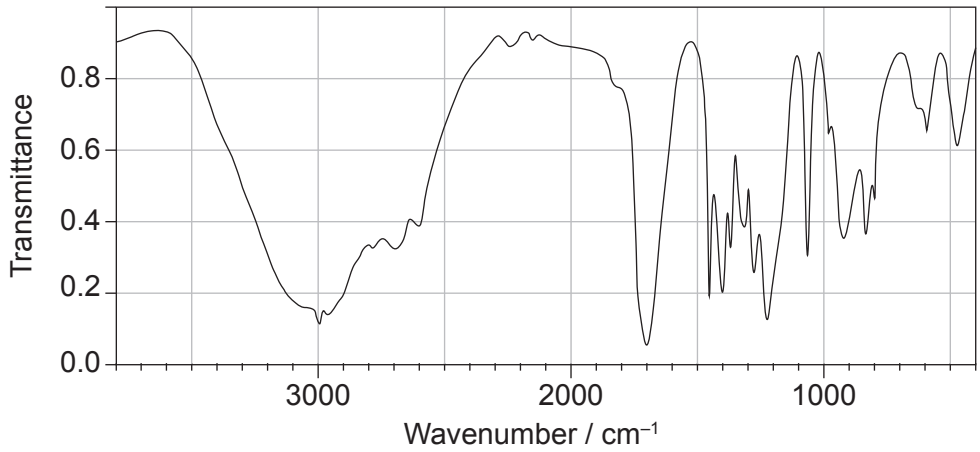
(Question 1 continued)

The following spectrums show the Infrared spectra of propan-1-ol, propanal and propanoic acid.

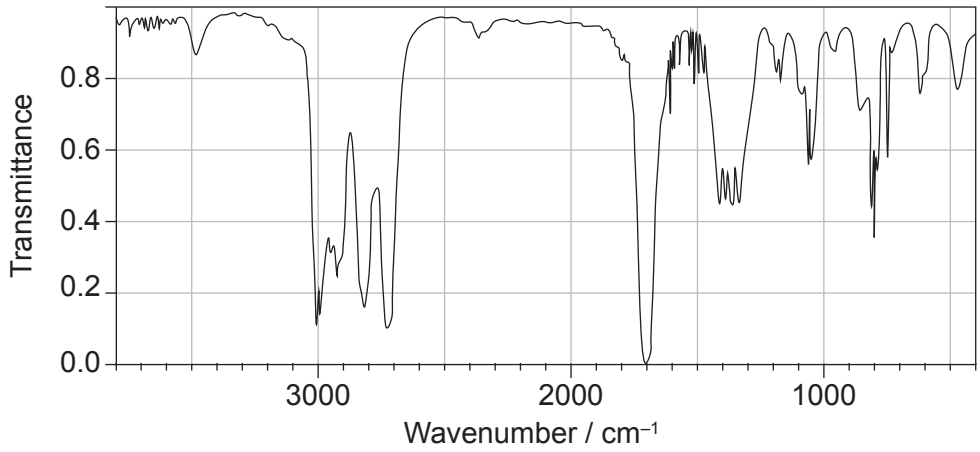
Spectrum A



Spectrum B



Spectrum C



(This question continues on the following page)

(Question 1 continued)

(c) Identify each compound from the spectra given, use absorptions from the range of 1700 cm^{-1} to 3500 cm^{-1}. Explain the reason for your choice, referring to section 26 of the data booklet. [3]

Spectrum	Identity	Reason
A	. . . .	. . . .
B	. . . .	. . . .
C	. . . .	. . . .

(d) Predict the number of ^{1}H NMR signals, and splitting pattern of the $–CH_3$ seen for propanone (CH_3COCH_3) and propanal (CH_3CH_2CHO). [2]

Spectrum	Number of signals	Splitting pattern of $–CH_3$
propanone	. . . .	. . . .
propanal	. . . .	. . . .

(e) Predict the fragment that is responsible for a *m*/*z* of 31 in the mass spectrum of propan-1-ol. Use section 28 of the data booklet. [1]

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2. Electron transitions are related to trends in the periodic table.

(a) Explain the general increase in trend in the first ionization energies of the period 3 elements, Na to Ar. [2]

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(b) Sodium emits yellow light with a frequency of 5.09×10^{14} Hz when electrons transition from 3p to 3s orbitals.

Calculate the energy difference, in J, between these two orbitals using sections 1 and 2 of the data booklet. [1]

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3. White phosphorus is an allotrope of phosphorus and exists as P_4.

(a) (i) Sketch the Lewis (electron dot) structure of the P_4 molecule, containing only single bonds. [1]

(This question continues on the following page)

(Question 3 continued)

(ii) Write an equation for the reaction of white phosphorus (P_4) with chlorine gas to form phosphorus trichloride (PCl_3). [1]

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(b) (i) Deduce the electron domain and molecular geometry using VSEPR theory, and estimate the Cl–P–Cl bond angle in PCl_3. [3]

Electron domain geometry:

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Molecular geometry:

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Bond angle:

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(ii) Outline the reason why PCl_5 is a non-polar molecule, while PCl_4F is polar. [3]

PCl_5 is non-polar:

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PCl_4F is polar:

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(Question 3 continued)

(c) An equilibrium exists between PCl_3 and PCl_5.

$$PCl_3(g) + Cl_2(g) \rightleftharpoons PCl_5(g)$$

(i) Calculate the standard enthalpy change ($\Delta H^{\ominus}$) for the forward reaction in $kJ\,mol^{-1}$.

$$\Delta H^{\ominus}_f PCl_3(g) = -306.4\,kJ\,mol^{-1}$$

$$\Delta H^{\ominus}_f PCl_5(g) = -398.9\,kJ\,mol^{-1}$$ [1]

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(ii) Calculate the entropy change, ΔS, in $J\,K^{-1}mol^{-1}$, for this reaction.

Substance	Entropy $J\,K^{-1}mol^{-1}$
$PCl_3(g)$	311.7
$PCl_5(g)$	364.5
$Cl_2(g)$	223.0

[1]

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(This question continues on the following page)

(Question 3 continued)

(iii) Calculate the Gibbs free energy change (ΔG), in $kJ\,mol^{-1}$, for this reaction at 25 °C. Use section 1 of the data booklet.

If you did not obtain an answer in c(i) or c(ii) use $-87.6\,kJ\,mol^{-1}$ and $-150.5\,J\,mol^{-1}K^{-1}$ respectively, but these are not the correct answers. [2]

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(iv) Determine the equilibrium constant, K, for this reaction at 25 °C, referring to section 1 of the data booklet.

If you did not obtain an answer in (c)(iii), use $\Delta G = -43.5\,kJ\,mol^{-1}$, but this is not the correct answer. [2]

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(v) State the equilibrium constant expression, K_c, for this reaction. [1]

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(vi) State, with a reason, the effect of an increase in temperature on the position of this equilibrium. [1]

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4. 1-chloropentane reacts with aqueous sodium hydroxide.

(a) (i) Identify the type of reaction. [1]

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(ii) Outline the role of the hydroxide ion in this reaction. [1]

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(iii) Suggest, with a reason, why 1-iodopentane reacts faster than 1-chloropentane under the same conditions. Use section 11 of the data booklet for consistency. [2]

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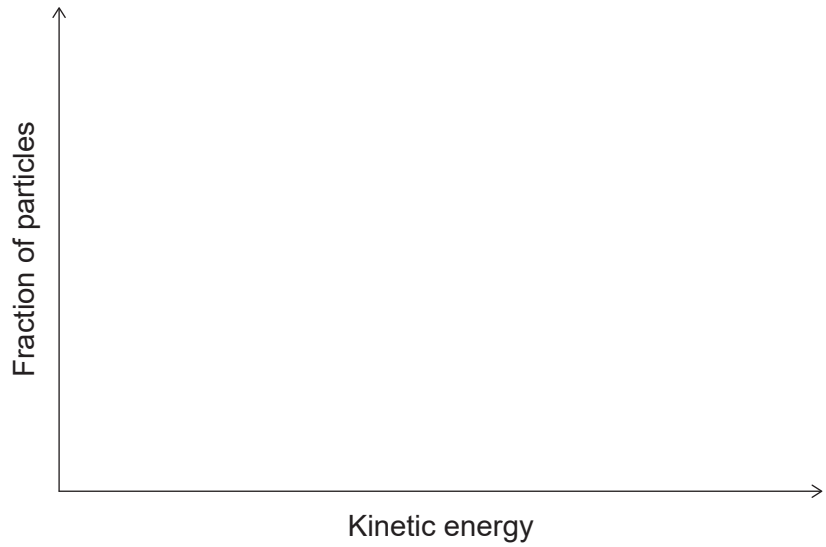
(b) The reaction was repeated at a lower temperature.

Sketch labelled Maxwell–Boltzmann energy distribution curves at the original temperature (T_1) and the new lower temperature (T_2). [2]



5. Phosphoric acid, H_3PO_4 can form three different salts depending on the extent of neutralisation by sodium hydroxide.

(a) Formulate an equation for the reaction of one mole of phosphoric acid with one mole of sodium hydroxide. [1]

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(b) Formulate **two** equations to show the amphiprotic nature of $H_2PO_4^-$. [2]

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(c) Calculate the concentration of H_3PO_4 if 25.00 cm^3 is completely neutralised by the addition of 28.40 cm^3 of 0.5000 mol dm^{-3} NaOH. [2]

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(d) Outline the reasons that sodium hydroxide is considered a Brønsted–Lowry and Lewis base. [1]

Brønsted–Lowry base:

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Lewis Base:

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6. Biochemical oxygen demand (BOD) can be determined by the Winkler Method.

(a) Outline what is measured by BOD. [1]

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(b) A student dissolved $0.1240 \pm 0.0001\,g$ of $Na_2S_2O_3$ to make $1000.0 \pm 0.4\,cm^3$ of solution to use in the Winkler Method.

Determine the percentage uncertainty in the molar concentration. [2]

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(c) A $25.00\,cm^3$ sample of water was treated according to the Winkler Method.

Step I: $2Mn^{2+}(aq) + O_2(g) + 4OH^-(aq) \rightarrow 2MnO_2(s) + 2H_2O(l)$

Step II: $MnO_2(s) + 2I^-(aq) + 4H^+(aq) \rightarrow Mn^{2+}(aq) + I_2(aq) + 2H_2O(l)$

Step III: $2S_2O_3^{2-}(aq) + I_2(aq) \rightarrow 2I^-(aq) + S_4O_6^{2-}(aq)$

The iodine produced was titrated with $37.50\,cm^3$ of $5.000 \times 10^{-4}\,mol\,dm^{-3}$ $Na_2S_2O_3$.

(i) Calculate the amount, in moles of $Na_2S_2O_3$ used in the titration. [1]

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(ii) Deduce the mole ratio of O_2 consumed in step I to $S_2O_3^{2-}$ used in step III. [1]

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(Question 6 continued)

(iii) Calculate the concentration of dissolved oxygen, in mol dm^{-3}, in the sample. [2]

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(iv) The three steps of the Winkler Method are redox reactions.

Deduce the reduction half-equation for step II. [1]

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(v) Suggest a reason that the Winkler Method used to measure biochemical oxygen demand (BOD) must be done at constant temperature. [1]

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7. Alkanes undergo combustion and substitution.

(a) Determine the molar enthalpy of combustion of an alkane if 8.75×10^{-4} moles are burned, raising the temperature of 20.0 g of water by 57.3 °C. [2]

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(b) Formulate equations for the two propagation steps and one termination step in the formation of chloroethane from ethane. [3]

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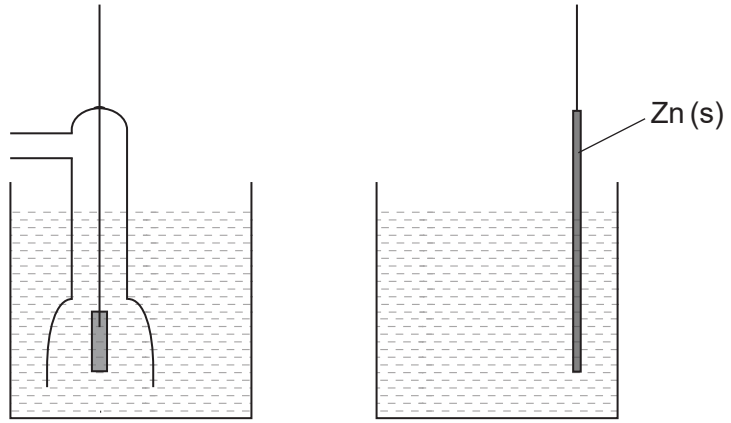
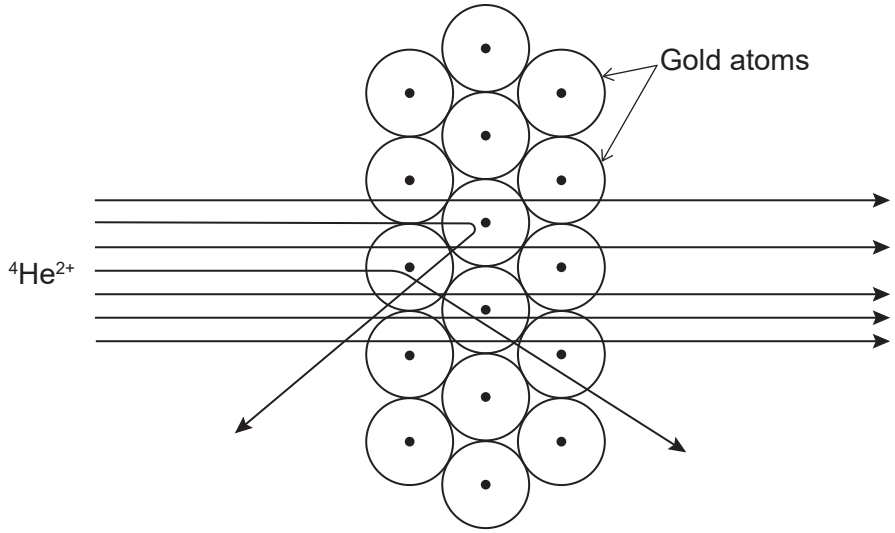
8. The standard electrode potential of zinc can be measured using a standard hydrogen electrode (SHE).

Draw and annotate the diagram to show the complete apparatus required to measure the standard electrode potential of zinc. [4]



9. Fast moving helium nuclei ($^4He^{2+}$) were fired at a thin piece of gold foil with most passing undeflected but a few deviating largely from their path. The diagram illustrates this historic experiment.



(a) Suggest what can be concluded about the gold atom from this experiment. [2]

Most $^4He^{2+}$ passing straight through:

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Very few $^4He^{2+}$ deviating largely from their path:

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(Question 9 continued)

(b) (i) Subsequent experiments showed electrons existing in energy levels occupying various orbital shapes.

Draw diagrams of 1s, 2s and 2p. [2]

1s	2s	2p

(ii) State the electron configuration of copper. [1]

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(iii) Copper is a transition metal that forms different coloured complexes. A complex $[Cu(H_2O)_6]^{2+}(aq)$ changes colour when excess $Cl^-(aq)$ is added.

Explain the cause of this colour change, using sections 3 and 15 from the data booklet. [3]

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10. Hybridization of hydrocarbons affects their reactivity.

(a) (i) Distinguish between a sigma and pi bond. [2]

Sigma (σ) bond:

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Pi (π) bond:

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(ii) Identify the hybridization of carbon in ethane, ethene and ethyne. [1]

	Ethane	**Ethene**	**Ethyne**
Hybridization of carbon	. . . . .	. . . . .	. . . . .

(b) (i) State, giving a reason, if but-1-ene exhibits cis-trans isomerism. [1]

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(ii) State the type of reaction which occurs between but-1-ene and hydrogen iodide at room temperature. [1]

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(Question 10 continued)

(iii) Explain the mechanism of the reaction between but-1-ene with hydrogen iodide, using curly arrows to represent the movement of electron pairs. [4]

(iv) State, giving a reason, if the product of this reaction exhibits stereoisomerism. [1]

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(Question 10 continued)

(c) Experiments were carried out to investigate the mechanism of reaction between 2-chloropentane and aqueous sodium hydroxide.

Experiment	[NaOH] ($mol\,dm^{-3}$)	[$C_5H_{11}Cl$] ($mol\,dm^{-3}$)	Initial rate ($mol\,dm^{-3}\,s^{-1}$)
1	0.20	0.10	2.50×10^{-2}
2	0.20	0.15	3.75×10^{-2}
3	0.40	0.20	1.00×10^{-1}
4	0.60	0.25	

(i) Deduce the rate expression for this reaction. [1]

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(ii) Deduce the units of the rate constant. [1]

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(iii) Determine the initial rate of reaction in experiment 4. [2]

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(Question 10 continued)

(d) Deduce, with a reason, the mechanism of the reaction between 2-chloropentane and sodium hydroxide. [1]

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(e) Discuss the reason benzene is more reactive with an electrophile than a nucleophile. [2]

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11. 50.00 cm^3 of 0.75 mol dm^{-3} sodium hydroxide was added in 1.00 cm^3 portions to 22.50 cm^3 of 0.50 mol dm^{-3} chloroethanoic acid.

(a) Calculate the initial pH before any sodium hydroxide was added, using section 21 of the data booklet. [2]

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(b) The concentration of excess sodium hydroxide was 0.362 mol dm^{-3}. Calculate the pH of the solution at the end of the experiment. [1]

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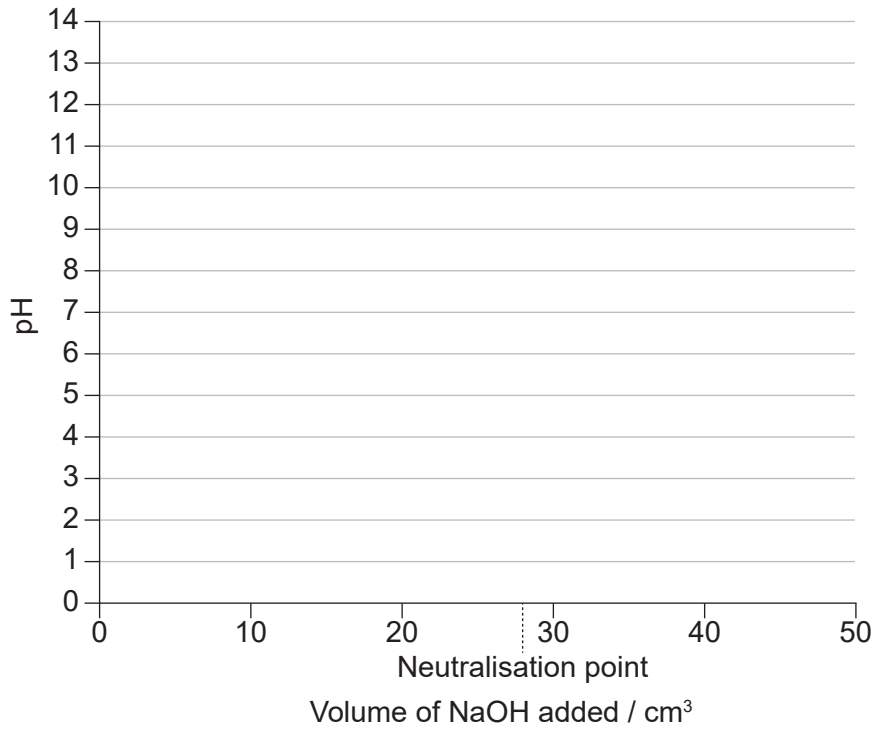
(Question 11 continued)

(c) Sketch the neutralisation curve obtained **and** label the equivalence point. [3]



References:

1. (c) NIST Mass Spectrometry Data Center Collection © 2021 copyright by the U.S. Secretary of Commerce on behalf of the United States of America. All rights reserved. Available at: https://webbook.nist.gov/cgi/cbook.cgi?ID=C71238&Units=SI&Type=IRSPEC&Index=3#IR-SPEC [Accessed 6 May 2020]. Source adapted.

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3. (c) (ii) Chemistry 2e, Chpt. 21 Nuclear Chemistry, Appendix G: Standard Thermodynamic Properties for Selected Substances https://openstax.org/books/chemistry-2e/pages/g-standard-thermodynamic-properties-for-selected-substances#page_667adccf-f900-4d86-a13d-409c014086ea © 1999-2021, Rice University. Except where otherwise noted, textbooks on this site are licensed under a Creative Commons Attribution 4.0 International License. (CC BY 4.0) https://creativecommons.org/licenses/by/4.0/.

9. Figure from *PPLATO / FLAP (Flexible Learning Approach To Physics)*, *http://www.met.reading.ac.uk/pplato2/h-flap/phys8_1.html#top* 1996 The Open University and The University of Reading.