MEGA LECTURE · A LEVEL CHEMISTRY

Chapter 18: Organic Synthesis & Analytical Techniques

OCR A Level Chemistry A (H432) — Structured Practice Worksheet

SPECIFICATION	TOTAL MARKS	SUGGESTED TIME
3.2.4 Synthetic routes, practical techniques, and introductory infrared spectroscopy	80	1 hour 37 minutes

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Instructions to candidates

- Answer **all** questions in the spaces provided. Show all working in calculations.
- Marks are shown in brackets [ ] at the end of each part.

Question 1 — Planning a synthetic route 3.2.4

A chemist plans to convert ethene into ethanoic acid via bromoethane and ethanol.

a. State the reagent(s) and conditions needed to convert ethene into bromoethane. **[3]**

b. State the reagent(s) and conditions needed to convert bromoethane into ethanol. **[3]**

c. State the reagent(s) and conditions needed to convert ethanol into ethanoic acid. **[3]**

d. Identify the type of reaction (addition, substitution, oxidation or elimination) occurring at each of the three steps above. **[3]**

e. Suggest an alternative single-step method by which ethene could be converted directly into ethanol. **[2]**

Question 1 total: 14 marks

Question 2 — Practical techniques 3.2.4

a. State the purpose of heating a reaction mixture under reflux. **[2]**

b. Describe how simple distillation can be used to separate and collect a volatile organic product from a reaction mixture. **[2]**

c. Outline the steps involved in purifying a solid organic product by recrystallisation. **[2]**

d. State the purpose of adding a drying agent, such as anhydrous magnesium sulfate, to a crude organic liquid product, and how the drying agent is subsequently removed. **[2]**

e. Explain how melting point can be used to assess the purity of a solid product. **[2]**

Question 2 total: 10 marks

Question 3 — Introduction to infrared spectroscopy 3.2.4

a. State what happens to a covalent bond in a molecule when it absorbs infrared radiation. **[2]**

b. Explain why different types of bond absorb infrared radiation at different wavenumbers. **[2]**

c. State the quantity, and its units, shown on the x-axis of an infrared spectrum. **[2]**

d. State what is meant by the "fingerprint region" of an infrared spectrum and explain how it can be used to identify a compound. **[2]**

Question 3 total: 8 marks

Question 4 — Interpreting infrared spectra 3.2.4

Bond	Functional group	Wavenumber / cm^{-1}
O−H	alcohol	3200–3550 (broad)
O−H	carboxylic acid	2500–3300 (broad)
C−H	alkane/general	2850–3100
C=O	aldehyde/ketone/acid/ester	1650–1750
C=C	alkene	1620–1680

a. Using the data table above, identify the functional group most likely responsible for absorptions at each of the following wavenumbers: 1710 cm^{-1}; 3450 cm^{-1} (broad); 1650 cm^{-1}; 2950 cm^{-1}. **[4]**

b. Two unlabelled spectra are recorded, one for propan-1-ol and one for propanoic acid. Explain how you could tell, using the O−H absorption alone, which spectrum belongs to which compound. **[3]**

c. State one limitation of using infrared spectroscopy alone to fully identify an unknown organic compound. **[3]**

d. Describe how infrared spectroscopy could be used to monitor the progress of the oxidation of an alcohol to a carboxylic acid over time. **[4]**

Question 4 total: 14 marks

Question 5 — Distinguishing compounds using IR 3.2.4

a. Explain how infrared spectroscopy can be used to distinguish between a ketone and an alcohol of similar relative molecular mass. **[3]**

b. Explain how infrared spectroscopy can be used to distinguish between a carboxylic acid and an alcohol, even though both show an O−H absorption. **[3]**

c. A sample thought to be either butan-1-ol or butanoic acid gives an infrared spectrum showing a very broad absorption at 2500–3300 cm^{-1} and a strong sharp peak at 1715 cm^{-1}. Identify the compound and justify your answer fully, using both absorptions. **[4]**

Question 5 total: 10 marks

Question 6 — Greenhouse gases and infrared absorption 3.2.4

a. Name two gases, other than water vapour, that contribute to the greenhouse effect. **[2]**

b. Explain, in terms of bond vibrations, why molecules such as carbon dioxide and water absorb infrared radiation. **[3]**

c. Explain, in simple terms, how the absorption of infrared radiation by these gases in the atmosphere leads to warming of the Earth's surface and lower atmosphere. **[3]**

d. Identify one human activity that increases the atmospheric concentration of a named greenhouse gas. **[2]**

Question 6 total: 10 marks

Question 7 — Percentage yield in a synthetic route 3.2.4

A student oxidises 6.90 g of ethanol completely to ethanoic acid, obtaining 7.50 g of pure ethanoic acid. (M_r: ethanol = 46.0, ethanoic acid = 60.0)

a. Calculate the theoretical maximum mass of ethanoic acid that could be obtained from 6.90 g of ethanol. **[3]**

b. Calculate the percentage yield of ethanoic acid obtained by the student. **[2]**

c. Suggest two reasons why the percentage yield obtained is less than 100%. **[3]**

Question 7 total: 8 marks

Question 8 — Extended response

Synoptic

A chemist carries out a synthetic route from an alkene, via a haloalkane and an alcohol, to a carboxylic acid, and wants to confirm that each stage has been successful before proceeding to the next. Explain how infrared spectroscopy could be used to monitor the success of the final alcohol-to-carboxylic-acid oxidation step, and discuss the strengths and limitations of using infrared spectroscopy, compared with simple chemical tests, to confirm the identity of organic products at each stage of a synthetic route. **[6]**

This question is marked using a level of response.

Question 8 total: 6 marks

PAPER TOTAL: 80 MARKS

MARK SCHEME — Chapter 18: Organic Synthesis and Analytical Techniques

Award marks independently unless stated. ECF applies to calculations.

Q1 (a) [3]

- Reagent: hydrogen bromide, HBr (gas). (1)
- Passed into/reacted with ethene at room temperature. (1)
- Reaction type: electrophilic addition (ethene reacts directly with HBr). (1)

Q1 (b) [3]

- Reagent: aqueous sodium hydroxide (NaOH(aq)). (1)
- Heated under reflux. (1)
- Bromoethane is hydrolysed by nucleophilic substitution to form ethanol. (1)

Q1 (c) [3]

- Reagent: acidified potassium dichromate(VI) ($K_2Cr_2O_7/H_2SO_4$), in excess. (1)
- Heated under reflux. (1)
- The primary alcohol is fully oxidised (via the aldehyde) to the carboxylic acid. (1)

Q1 (d) [3]

- Step 1 (ethene → bromoethane): electrophilic addition. (1)
- Step 2 (bromoethane → ethanol): nucleophilic substitution. (1)
- Step 3 (ethanol → ethanoic acid): oxidation. (1)

Q1 (e) [2]

- React ethene directly with steam ($H_2O(g)$). (1)
- In the presence of a phosphoric acid catalyst, at about 300 °C and 60–70 atm (catalytic/direct hydration). (1)

Q2 (a) [2]

- Reflux allows a reaction mixture to be heated continuously to increase the rate of reaction. (1)
- The condenser returns any evaporated volatile reactants/products/solvent back into the flask, preventing loss to the surroundings. (1)

Q2 (b) [2]

- The reaction mixture is heated so that the volatile product evaporates. (1)
- The vapour passes into a condenser, where it cools and condenses back into a liquid, which is collected separately, purifying/separating it from the less volatile reaction mixture. (1)

Q2 (c) [2]

- The impure solid is dissolved in a minimum volume of hot solvent, then the hot solution is filtered (if needed) and allowed to cool slowly so that crystals form. (1)
- The crystals are filtered off, washed with a small amount of cold solvent, and dried. (1)

Q2 (d) [2]

- The drying agent removes trace/residual water from the crude organic liquid product. (1)
- Excess drying agent is removed by filtering (or decanting) the liquid away from the solid drying agent. (1)

Q2 (e) [2]

- A pure solid melts sharply, over a narrow range, at a temperature matching the known literature value. (1)
- An impure solid melts over a broader range and at a lower temperature than the pure substance, so comparing the observed melting point/range with the literature value indicates purity. (1)

Q3 (a) [2]

- The bond absorbs (a specific amount/frequency of) infrared energy. (1)
- This causes the bond to vibrate with greater amplitude, by stretching or bending. (1)

Q3 (b) [2]

- Different bonds have different strengths and connect atoms of different mass. (1)
- This means each type of bond has its own characteristic (natural) vibrational frequency, so it absorbs IR radiation at a different, characteristic wavenumber. (1)

Q3 (c) [2]

- Wavenumber. (1)
- Units: cm^{-1}. (1)

Q3 (d) [2]

- The fingerprint region is the region of the spectrum below about 1500 cm^{-1}, where the pattern of absorptions is unique/complex for each individual compound. (1)
- A compound can be identified by comparing its fingerprint region directly with a database of known spectra to find an exact match. (1)

Q4 (a) [4]

- 1710 cm^{-1}: C=O (aldehyde/ketone/acid/ester). (1)
- 3450 cm^{-1} (broad): O−H of an alcohol. (1)
- 1650 cm^{-1}: C=C (alkene). (1)
- 2950 cm^{-1}: C−H. (1)

Q4 (b) [3]

- Both compounds show a broad O−H absorption, but the position (and breadth) differs. (1)
- Propan-1-ol (an alcohol) shows the O−H absorption in the higher range, around 3200–3550 cm^{-1}. (1)
- Propanoic acid (a carboxylic acid) shows a much broader, lower O−H absorption spanning roughly 2500–3300 cm^{-1} (and would also show a C=O peak around 1650–1750 cm^{-1}, absent in the alcohol). (1)

Q4 (c) [3]

- Any one valid limitation, e.g.: IR only identifies which functional groups are present, not the full structure/connectivity of the molecule. (3)

Accept: absorption ranges for different functional groups can overlap, causing ambiguity; the fingerprint region is complex and needs a reference database for a full match; cannot usually distinguish between structural isomers with the same functional groups.

Q4 (d) [4]

- Take an IR spectrum of the reaction mixture at intervals during the reaction. (1)
- The alcohol's O−H absorption (3200–3550 cm^{-1}) should decrease in intensity as the alcohol is used up. (1)
- A new C=O absorption (1650–1750 cm^{-1}) should appear and grow as the carboxylic acid forms. (1)
- The O−H absorption should also broaden/shift to the lower, broader acid range (2500–3300 cm^{-1}) as oxidation proceeds, indicating the reaction is complete when the alcohol O−H peak has disappeared. (1)

Q5 (a) [3]

- A ketone shows a strong, sharp C=O absorption at 1650–1750 cm^{-1} but no O−H absorption. (1)
- An alcohol shows a strong, broad O−H absorption at 3200–3550 cm^{-1} but no C=O absorption. (1)
- Comparing the two spectra for the presence/absence of these two characteristic absorptions distinguishes the compounds. (1)

Q5 (b) [3]

- Both compounds show a broad O−H absorption, but the carboxylic acid's O−H absorption is broader and centred at a lower wavenumber (2500–3300 cm^{-1}) than the alcohol's (3200–3550 cm^{-1}). (1)
- The carboxylic acid additionally shows a strong C=O absorption at 1650–1750 cm^{-1}. (1)
- The alcohol shows no C=O absorption at all, so the presence of a C=O peak alongside a very broad low O−H peak confirms the carboxylic acid. (1)

Q5 (c) [4]

- The compound is butanoic acid, not butan-1-ol. (1)
- The absorption at 2500–3300 cm^{-1} is broad and centred at a low wavenumber, matching the O−H of a carboxylic acid rather than the higher, narrower range typical of an alcohol O−H. (1)
- The peak at 1715 cm^{-1} is a C=O absorption. (1)
- An alcohol (butan-1-ol) would show no C=O absorption at all, so the presence of this peak together with the very broad, low O−H absorption confirms a carboxylic acid. (1)

Q6 (a) [2]

- Any two from: carbon dioxide (CO_2); methane (CH_4); nitrous oxide (N_2O). (2)

Q6 (b) [3]

- These molecules have bonds with a permanent or changing dipole. (1)
- When the bonds stretch or bend (vibrate), the dipole moment of the molecule changes. (1)
- A vibration that changes the dipole moment of the molecule allows it to absorb infrared radiation at the corresponding wavenumber. (1)

Q6 (c) [3]

- The Earth's surface absorbs energy from the Sun and re-radiates it as infrared radiation. (1)
- Greenhouse gas molecules in the atmosphere absorb some of this outgoing infrared radiation. (1)
- The absorbed energy is then re-emitted in all directions, including back towards the Earth's surface, trapping/retaining energy in the atmosphere and causing warming. (1)

Q6 (d) [2]

- Any one valid example, e.g. burning fossil fuels increases atmospheric CO_2; agriculture/livestock farming (or landfill/decomposing waste) increases atmospheric CH_4. (2)

Q7 (a) [3]

- Moles of ethanol = 6.90 ÷ 46.0 = 0.150 mol. (1)
- Since 1 mol ethanol gives 1 mol ethanoic acid, moles of ethanoic acid (theoretical) = 0.150 mol. (1)
- Theoretical mass = 0.150 × 60.0 = 9.00 g. (1)

Q7 (b) [2]

- Percentage yield = (7.50 ÷ 9.00) × 100. (1)
- = 83.3%. (1)

Q7 (c) [3]

- The reaction/oxidation may not go to completion, or a side reaction may occur, leaving some ethanol unreacted or forming other products. (1)
- Some product is lost during transfer between apparatus (e.g. during reflux, distillation or filtration). (1)
- Some product may be lost during purification (e.g. remaining dissolved in the mother liquor, or lost during recrystallisation/drying). (1)

Q8 [6] — Level of response

- **Level 3 (5–6):** Clearly explains how IR spectroscopy could monitor the alcohol-to-acid oxidation (loss of alcohol O−H, appearance/broadening of acid O−H, appearance of C=O), and gives a balanced, well-reasoned discussion of both strengths and limitations of IR compared with chemical tests.
- **Level 2 (3–4):** Explains the monitoring of the oxidation step reasonably well and identifies at least one strength and one limitation of IR, but the discussion is less complete or less clearly linked.
- **Level 1 (1–2):** Makes some relevant, valid points about using IR to follow the reaction and/or about its strengths or limitations, but the answer is limited, one-sided, or lacks clear scientific reasoning.

Indicative content: *As the alcohol is oxidised to the carboxylic acid, the alcohol's characteristic O−H absorption (3200–3550 cm^{-1}) should diminish while a new, broader O−H absorption typical of a carboxylic acid (2500–3300 cm^{-1}) appears, alongside a new C=O absorption (1650–1750 cm^{-1}); the reaction can be considered complete once the alcohol O−H peak has disappeared. IR spectroscopy is quick, non-destructive and can be used at each stage without consuming much sample, and it is very effective at confirming which functional group(s) are present or absent (e.g. distinguishing an alkene, haloalkane's loss of C=C, alcohol, or carboxylic acid). However, IR alone cannot confirm the full structure or purity of a compound, cannot easily distinguish between compounds with the same functional groups (e.g. positional isomers), and overlapping absorption ranges can make interpretation ambiguous, so IR evidence is usually combined with simple chemical tests (e.g. effervescence with carbonate for a carboxylic acid) or other techniques for full confirmation.*

END OF MARK SCHEME · 80 marks