UNIVERSITY OF CALGARY

FACULTY OF SCIENCE

FINAL EXAMINATION

CHEMISTRY 351

Version 01

December 15th 2025

Time: 2 Hours

READ ALL THE INSTRUCTIONS CAREFULLY

WRITE YOUR **NAME**, **STUDENT I.D. NUMBER** AND **VERSION NUMBER 1** ON ***BOTH*** **YOUR MULTIPLE CHOICE ANSWER SHEET** AND **WRITTEN ANSWER SHEET**.

The exam consists of **Parts 1 - 8**, each of which should be attempted. Some Parts provide you with a choice of questions, *e.g*. answer any 5 out of 6. These will be graded in numerical order until the required number have been completed, regardless of whether they are right or wrong. **Parts 1 - 5** are to be answered on the multiple choice answer sheet, and **Parts 6 - 8** are to be answered **IN THE APPROPRIATE BOX ON THE WRITTEN ANSWER SHEET PROVIDED**.

Parts 1 - 5 consist of a series of multiple choice questions numbered **1 - 34** to be answered on the multiple choice answer sheet. Indicate your answer by completely blackening out the appropriate space, A, B, C, D or E on the answer sheet for that specific question. Use a soft pencil only, ***not ink***. In some cases it is required that you indicate ***multiple*** items for a complete and/or correct answer by blackening out ***more than one space***. In some other cases, more than five options are available and some of these also require more than one space to be blackened out. For an example, an option specified as AB requires that you blacken out ***both*** space A and space B. Part marks may be awarded in some of the questions. Incorrect answers must be ***erased cleanly***.

A periodic table with atomic numbers and atomic weights and spectroscopic data tables and 2 pages of scrap paper for rough work are included with this examination paper.

Molecular models are permitted during the exam; calculators are also permitted, ***but NOT programmable calculators***. **Absolutely no other electronic devices are allowed.**

14% PART 1: RELATIVE PROPERTIES

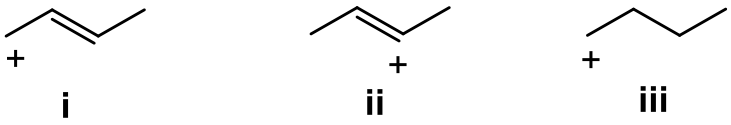
ANSWER ANY SEVEN (7) OF QUESTIONS 1 TO 8 (2 points each).

Arrange the items in questions 1-8 in DECREASING ORDER (i.e. greatest, most etc. first) with respect to the indicated property

Use the following code to indicate your answers.

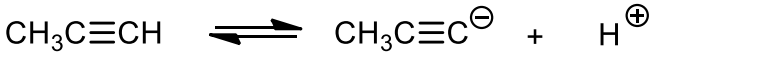
A.	**i > ii > iii**	**D**.	**ii > iii > i**
B.	**i > iii > ii**	**E**.	**iii > i > ii**
C.	**ii > i > iii**	**AB**.	**iii > ii > i**

1. The relative stability of the following carbocations :

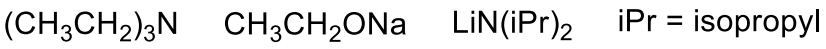


i **ii** **iii**

2. The relative amount of the conjugate base of propyne formed by the reaction of 1 mole equivalent of each of the following:



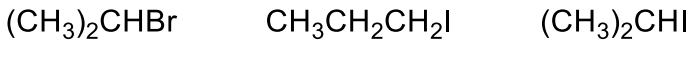
$CH_3C{\equiv}CH \rightleftharpoons CH_3C{\equiv}C^{\ominus} + H^{\oplus}$



$(CH_3CH_2)_3N$ CH_3CH_2ONa $LiN(iPr)_2$ iPr = isopropyl

i **ii** **iii**

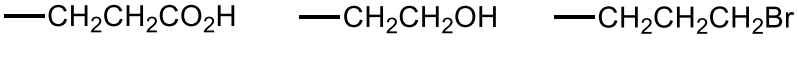
3. The relative rate of reaction when each of the following was treated with NaCN / DMF:



$(CH_3)_2CHBr$ $CH_3CH_2CH_2I$ $(CH_3)_2CHI$

i **ii** **iii**

4. The relative priority of each of the following groups when assigning stereochemistry according to the Cahn-Ingold-Prelog priority rules*:*



$—CH_2CH_2CO_2H$ $—CH_2CH_2OH$ $—CH_2CH_2CH_2Br$

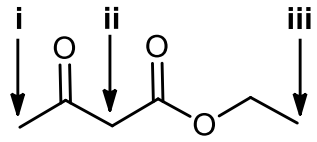
i **ii** **iii**

Cont'd -->

Use the following code to indicate your answers.

A.	**i > ii > iii**	**D**.	**ii > iii > i**
B.	**i > iii > ii**	**E**.	**iii > i > ii**
C.	**ii > i > iii**	**AB**.	**iii > ii > i**

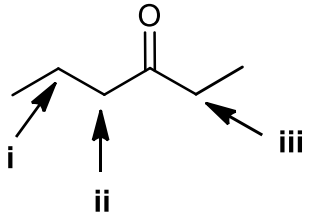
5. The relative ^{1}H-NMR chemical shifts /ppm for the hydrogen atoms indicated by arrows in the following structure:



6. The relative rate of reaction when each of the following was heated with H_2SO_4:

i. 1-butanol **ii**. sec-butanol **iii**. t-butanol

7. The number of lines observed in the coupling patterns in the ^{1}H-NMR spectra for the H atoms at the positions indicated below :



8. The relative yield of the Zaitsev product formed when 1-bromo-1-methylcyclohexane is heated with each of the following:

$NaOCH_3$	$NaOC(CH_3)_3$	$NaOCH_2CH_3$
i	**ii**	**iii**

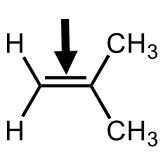
Cont'd -->

15% **PART 2: MOLECULAR PROPERTIES**

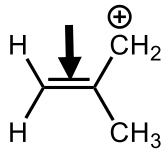
ANSWER ALL SIX (6) OF THE QUESTIONS 9 TO 14 (2.5 points each).

In questions 9-13 choose the single option that provides the best answer.

9. Which of the indicated bonds is longer and why?



I



II

A. **I** because it has more sp^3 character.

B. **I** because it is a localized double bond.

C. **I** because of symmetry.

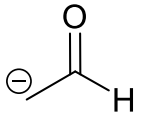
D. **II** because it is involved in a delocalized double bond.

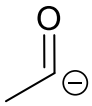
E. **II** because the cation is electron withdrawing.

AB. **II** because it is asymmetric.

10. Which of the following is formed when ethanal reacts with a strong base ?

III





IV

A. **III** because the negative charge can be delocalized to the oxygen.

B. **III** because the negative charge is further from the electronegative oxygen.

C. **III** because the negative charge is on an sp^3-hybridized atom.

D. **IV** because the negative charge is stabilized by resonance.

E. **IV** because the negative charge is closer to the more electronegative oxygen

AB. **IV** because the sp^2-hybridized C-H bond is the most acidic.

11. Which cyclohexane isomer is the more stable, cis-1,3-dimethylcyclohexane or trans-1,3-dimethylcyclohexane?

A. equal “stability” because stereoisomers have the same heat of combustion.

B. cis-1,3-dimethylcyclohexane because there are more 1,3-diaxial interactions.

C. cis-1,3-dimethylcyclohexanebecause it can adopt a di-equatorial conformation.

D. trans-1,3-dimethylcyclohexane because there are more 1,3-diaxial interactions.

E. trans-1,3-dimethylcyclohexane because it can adopt a di-equatorial conformation.

Cont'd -->

12. Which of the alcohols (**V** and **VI**) shown below, would undergo nucleophilic substitution with HBr and why?

V **VI**

A. Both substitutions are equally effective.

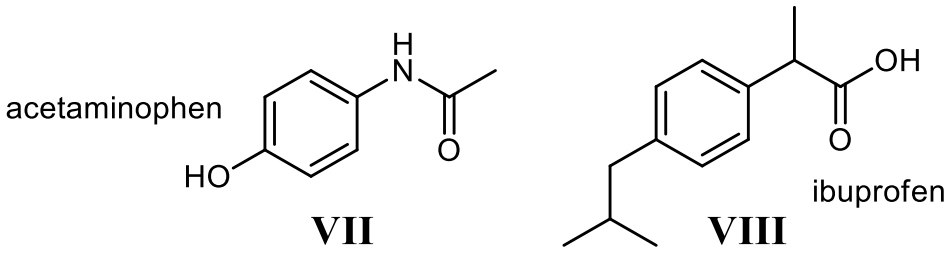
B. **V** because it is more acidic.

C. **V** because it proceeds via a resonance stabilized carbocation.

D. **VI** because it is less sterically hindered in the SN2 reaction.

E. **VI** because it proceeds via a resonance stabilized carbocation.

13. Which of the following would have the highest Rf value in normal phase TLC? (*i.e.* similar conditions to the TLC experiment in the CHEM 351 laboratory).



VII **VIII**

A. **VII** because it is less polar.

B. **VII** because it is more polar.

C. **VIII** because it is less polar.

D. **VIII** because it is more polar.

E. **VIII** because it has a higher molecular weight.

14. If you did an extraction of a compound where the KD (ether : water) = 3, what % of the compound would be extracted from a 25 mL aqueous solution with 25 mL of ether ?

A 25 **B** 33 **C** 50 **D** 67 **E** 75

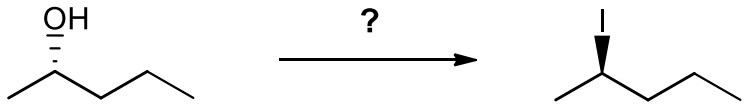
Cont'd -->

10% PART 3: REACTIONS

ANSWER ANY FIVE (5) of questions 15-20 (2 marks per question)

For each of questions 15-20, selecting the MISSING component (the best starting material, the major product, or the best reagents) required to BEST complete the reaction schemes.

15.



A 1. Thionyl chloride / Et_3N
2. NaI / acetone

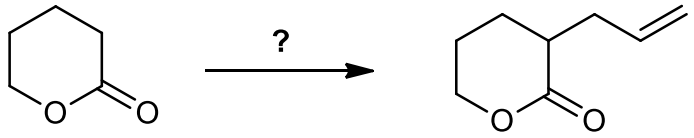
B 1. Br_2 / UV
2. NaI / acetone

C 1. NaH
2. HI

D HI

E 1. Tosyl chloride / Et_3N
2. NaI / acetone

16.



A 1. $LiN(i\text{-}Pr)_2$; 2. allyl acohol

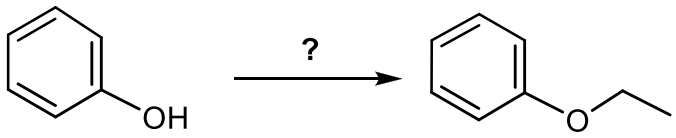
B 1. Br_2/UV; 2. allyl alcohol

C 1. $LiN(i\text{-}Pr)_2$; 2. allyl bromide

D 1. H_2SO_4; 2. allyl bromide

E 1. Cl_2 / uv light; 2. allyl bromide

17.



A 1. $SOCl_2$ / Et_3N;
2. $NaOCH_2CH_3$

B H_2SO_4 / bromoethane

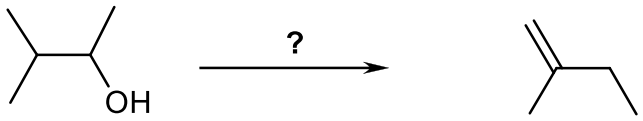
C Na_2CO_3 / bromoethane

D 1. p-TsCl / Et_3N
2. Chloroethane

E 1. Cl_2 / uv light
2. Ethanol

Cont'd -->

18.



A 1. Br_2
2. KO ^{t}Bu / t-BuOH / heat

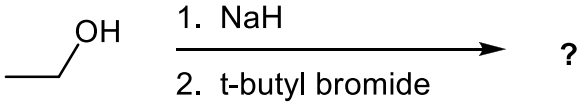
B 1. $SOCl_2$ / Et_3N
2. KOH / EtOH / heat

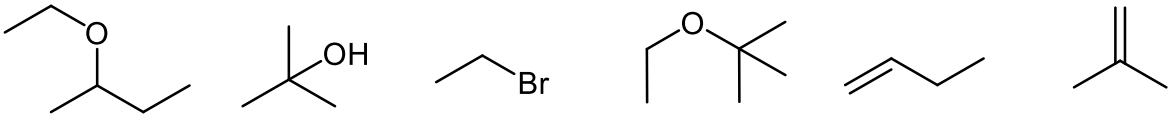
C 1. PBr_3 / Et_3N
2. KO ^{t}Bu / t-BuOH / heat

D 1. HBr
2. KO ^{t}Bu / t-BuOH / heat

E Conc. H_2SO_4 / heat

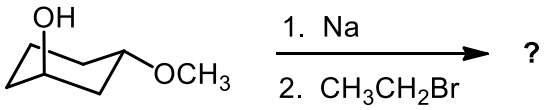
19.

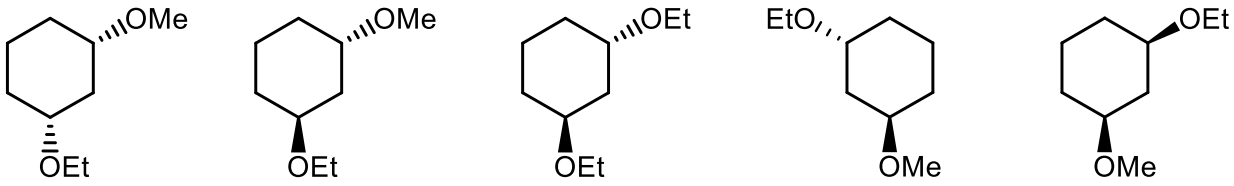




A **B** **C** **D** **E** **AB**

20.





A **B** **C** **D** **E**

Cont'd -->

14% PART 4: CONFORMATIONAL ANALYSIS

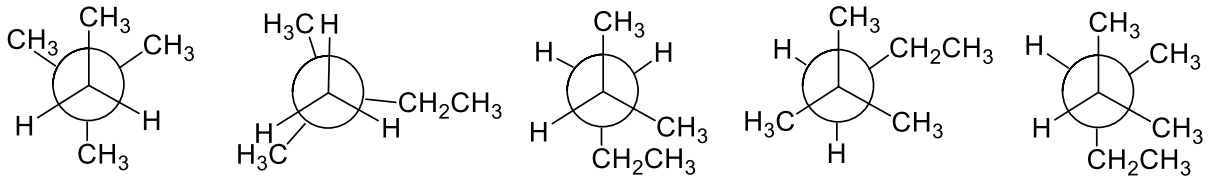
ANSWER ANY SEVEN (7) OF THE QUESTIONS 21 TO 28 (2 points each).

For each of the questions 21-28 select the answer(s) from those provided. In some cases more than one answer may be correct in which case all correct answers should be selected for full marks.

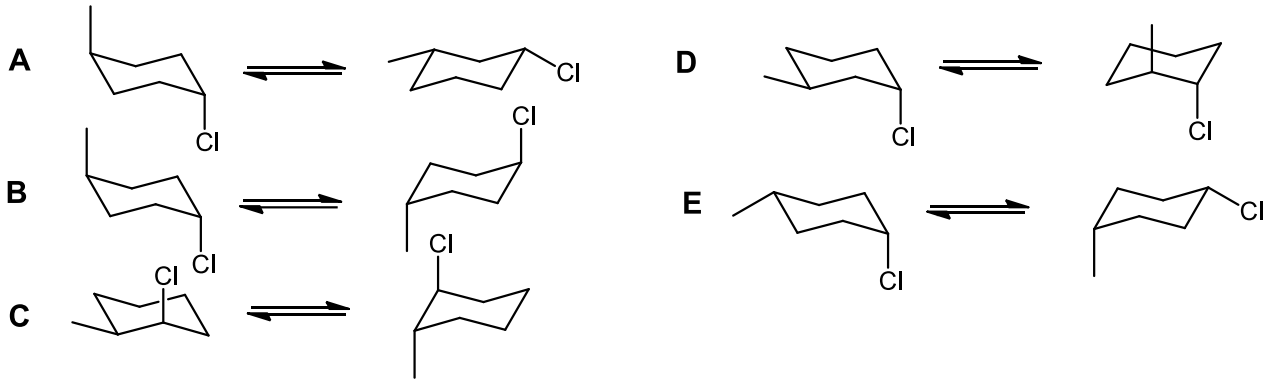
21. How many equatorial hydrogen atoms are there in the most stable conformation of trans-1,2-dichlorocyclohexane?

A 11 **B** 10 **C** 6 **D** 5 **E** 4 **AB** 3

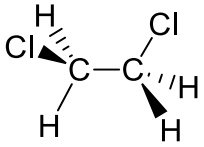
22. Which of the Newman projections represent conformations of 2,2-dimethylpentane ? (**select all that apply**)



23. Which of the following best represents a ring flip?



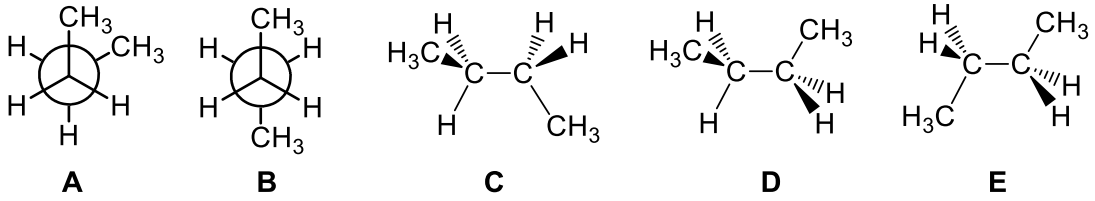
24. What is the **torsional angle** between the **two C-Cl bonds** in the conformation of 1,2-dichloroethane shown below?



A 0° **B** 60° **C** 90° **D** 109.5° **E** 120° **AB** 180°

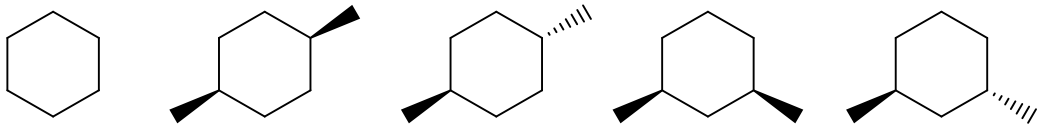
Cont'd -->

25. Which of the following molecules has the **least strain** in the conformation shown ? (**select all that apply)**



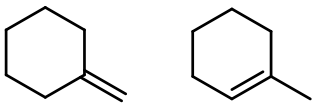
A **B** **C** **D** **E**

26. Which of the following structures have two chair conformations of equal energy ? (**select all that apply)**



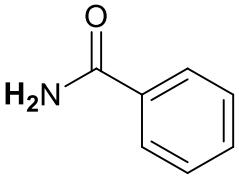
A **B** **C** **D** **E**

27. Which of the following terms **best** describes the relationship between the two molecules shown below ?



A configurational isomers
B conformational isomers
C enantiomers
D diastereomers
E regioisomers
AC stereoisomers

28. What is the **bond** angle of the **H-N-H bonds between the two hydrogen atoms** in the most stable conformation of the structure shown below ?



A 0° **D** 109.5°
B 60° **E** 120°
C 90° **AB** 180°

Cont'd -->

12% PART 5: SPECTROSCOPY

ANSWER ALL SIX (6) OF QUESTIONS 29 TO 34 (2 points each).

For each of questions 29-34 select the compound from the list provided that corresponds BEST with the spectroscopic data provided. The following common abbreviations have been used s = singlet, d = doublet, t = triplet, q = quartet, p = pentet, m = multiplet *etc*. .

29. **^{1}H NMR:** δ/ppm 0.9 (triplet, 3H), 1.4 (sextet, 2H), 1.6 (pentet, 2H), 2.35 (triplet, 2H), 12.0 (singlet, 1H, exchangeable)
^{13}C NMR: δ/ppm 14 ,22, 28, 35, 181 **IR:** 1712, 3510 (broad) cm^{-1}

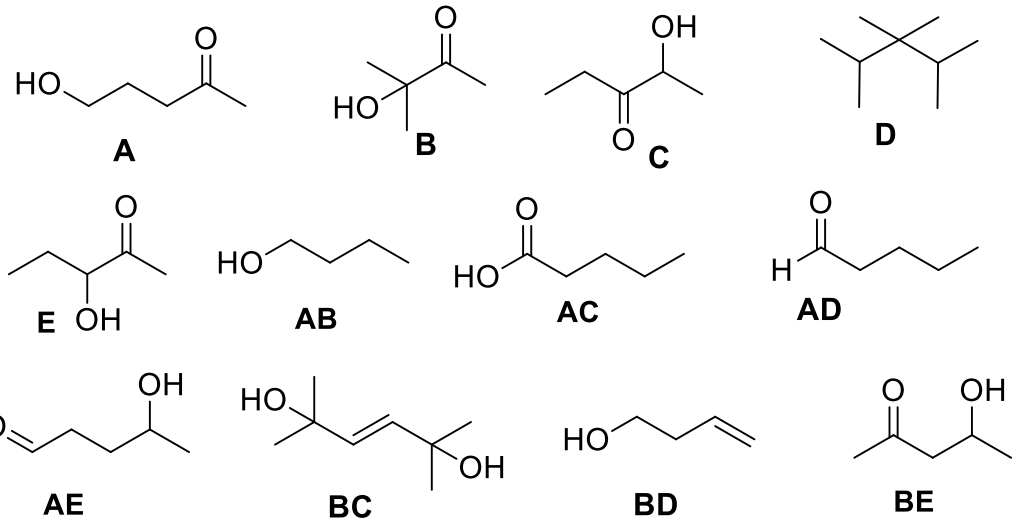
30. **^{1}H NMR:** δ/ppm 0.9 (triplet, 3H), 1.8 (pentet, 2H), 2.1 (singlet, 3H), 2,8 (singlet, 1H, exchangeable), 4.1 (triplet 1H)
^{13}C NMR: δ/ppm 9, 24, 26, 84, 219 **IR:** 1717, 3450 (broad) cm^{-1}

31. **^{1}H NMR:** δ/ppm 1.3 (singlet, 6H), 3.7 (singlet, 1H, exchangeable), 5.9 (singlet, 1H)
^{13}C NMR: δ/ppm 30, 73, 134 **IR:** 1653, 3550 (broad) cm^{-1}

32. **^{1}H NMR:** δ/ppm 0.7 (singlet , 3H), 0.8 (doublet, 6H), 1.2 (septet, 1H)
^{13}C NMR: δ/ppm 18, 20, 34, 29 **IR:** 2900 cm^{-1}

33. **^{1}H NMR:** δ/ppm 1.4 (singlet, 6H), 2.2 (singlet, 3H), 3.8 (singlet, 1H, exchangeable)
^{13}C NMR: δ/ppm 22, 26, 77, 218 **IR:** 1714, 3450 (broad) cm^{-1}

34. **^{1}H-NMR**: δ/ppm 1.2 (doublet, 3H) 2.1 (singlet, 3H), 2.7 (doublet, 2H), 3.6 (singlet, 1H, exchangeable,), 3.7 (sextet, 1H)
^{13}C-NMR: δ/ppm 23, 30, 55, 63, 208 **IR**: 1717, 3440 (broad) cm^{-1}



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12% **PART 6: MECHANISMS**

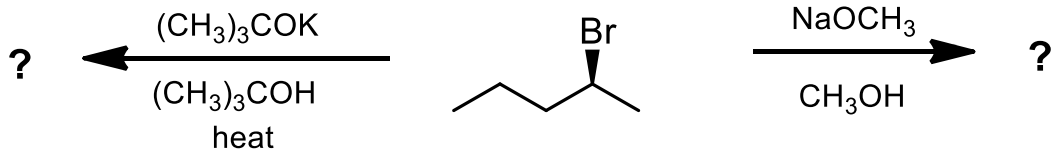
WRITE YOUR ANSWER IN THE APPROPRIATE BOX ON THE WRITTEN ANSWER SHEET PROVIDED.

ANSWER THREE (3) QUESTIONS, ONE FROM EACH OF PART 6.1, 6.2 and 6.3 (equally weighted).

Draw curly arrow mechanisms to explain / predict the following reactions. No other reagents are required.

6.1. Predict the product and provide the curly arrow mechanism for **one** of the following:

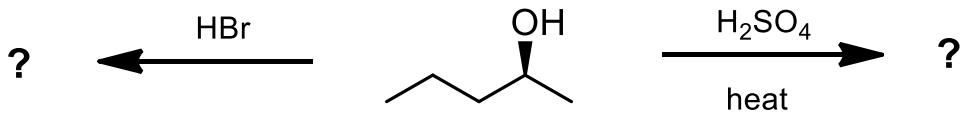
A **OR** **B**



AND

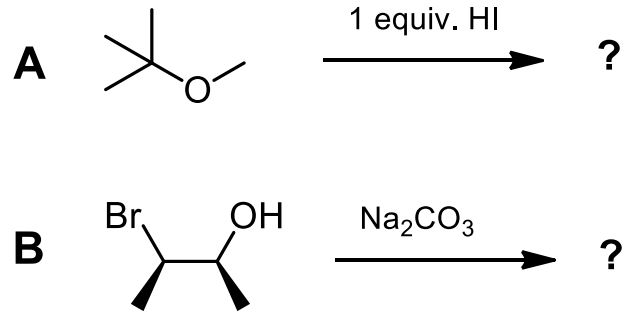
6.2. Predict the product and provide the curly arrow mechanism for **one** of the following:

A **OR** **B**



AND

6.3. Predict the product and provide the curly arrow mechanism for **one** of the following:



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10% PART 7: SYNTHESIS

WRITE YOUR ANSWER IN THE APPROPRIATE BOX ON THE WRITTEN ANSWER SHEET PROVIDED

DESIGN EFFICIENT SYNTHESES OF ANY TWO (equally weighted) of the following target molecules from the indicated starting material.

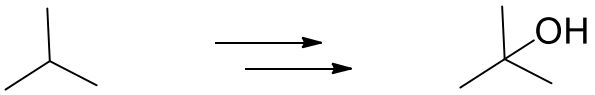
In addition, you are allowed to use **any hydrocarbon with three or fewer carbon atoms**, any solvents or inorganic reagents, and any organic reagents that do not contribute carbon atoms to the carbon skeleton in the product.

More than one step will be required for each synthesis.

SHOW YOUR ANSWER AS A STEPWISE REACTION SCHEME SHOWING THE REAGENT REQUIRED AND PRODUCT OF EACH STEP.

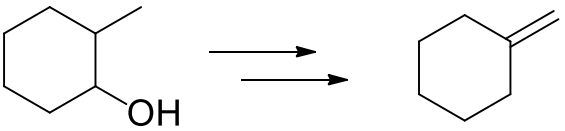
DO NOT SHOW MECHANISMS (i.e. curly arrows are NOT required)

A



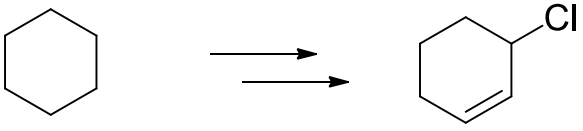
OR

B



OR

C



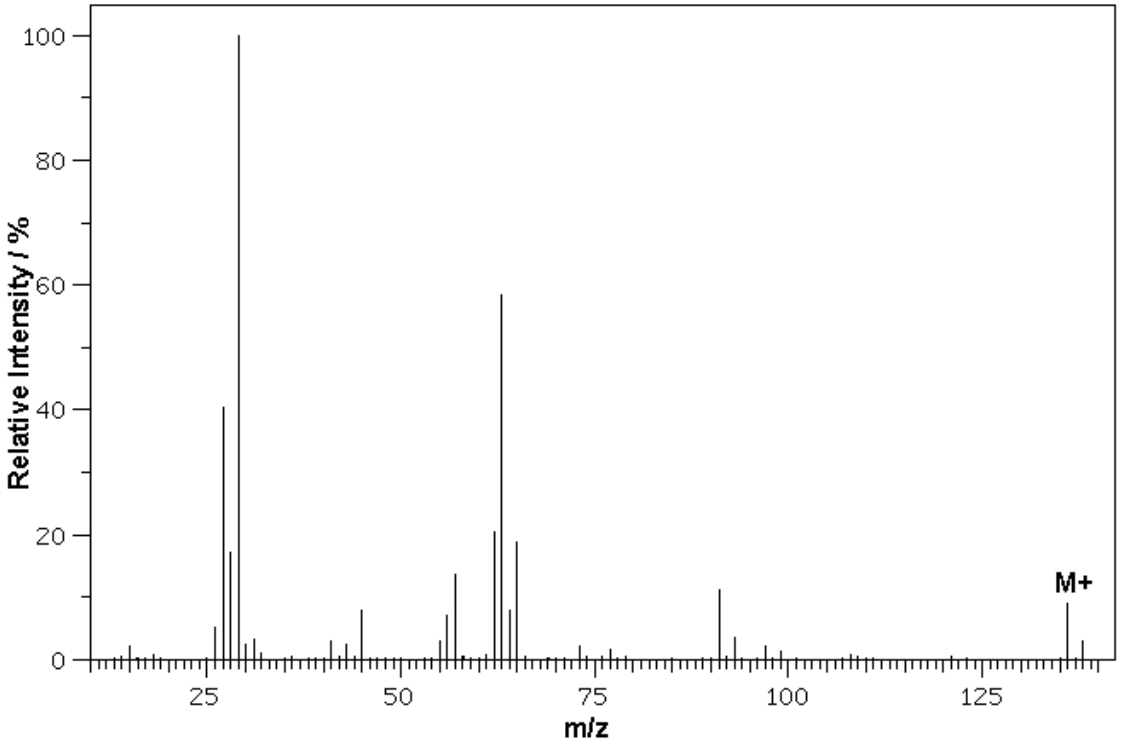
Cont'd -->

13% PART 8: SPECTROSCOPY

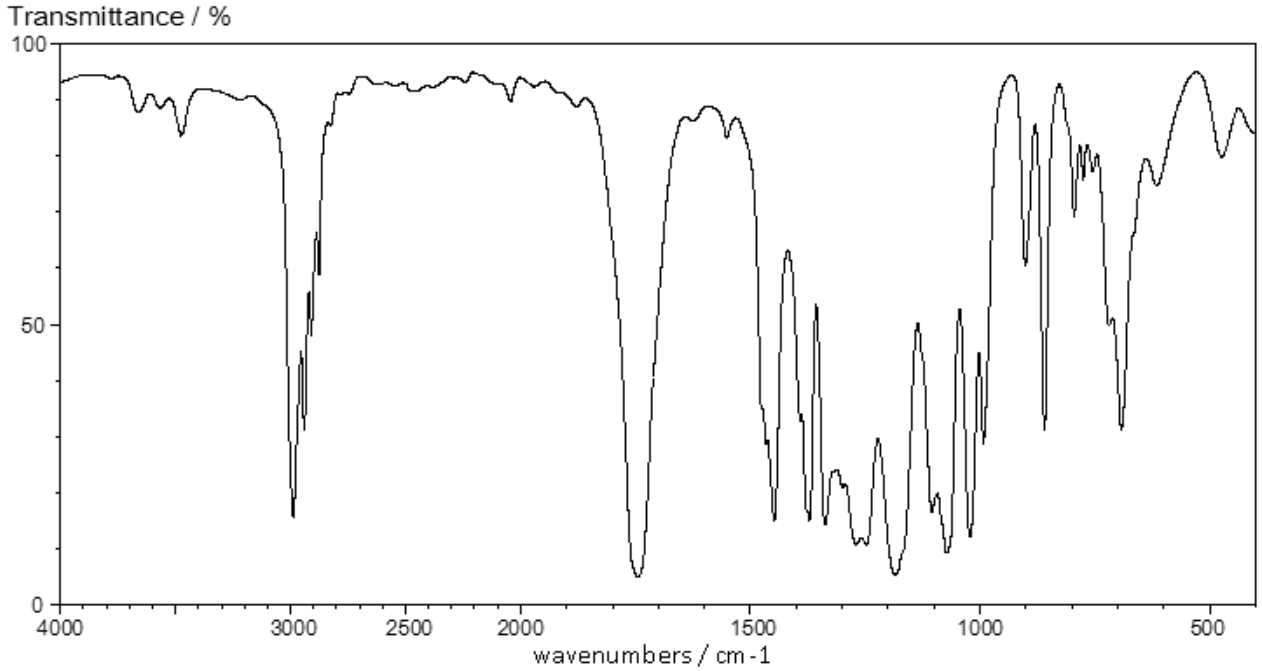
WRITE YOUR ANSWER IN THE APPROPRIATE BOX ON THE WRITTEN ANSWER SHEET PROVIDED Show your workings as PARTIAL marks may be given.

From the spectral data provided below, identify the structure of the "unknown" molecule.

Mass Spectrum:

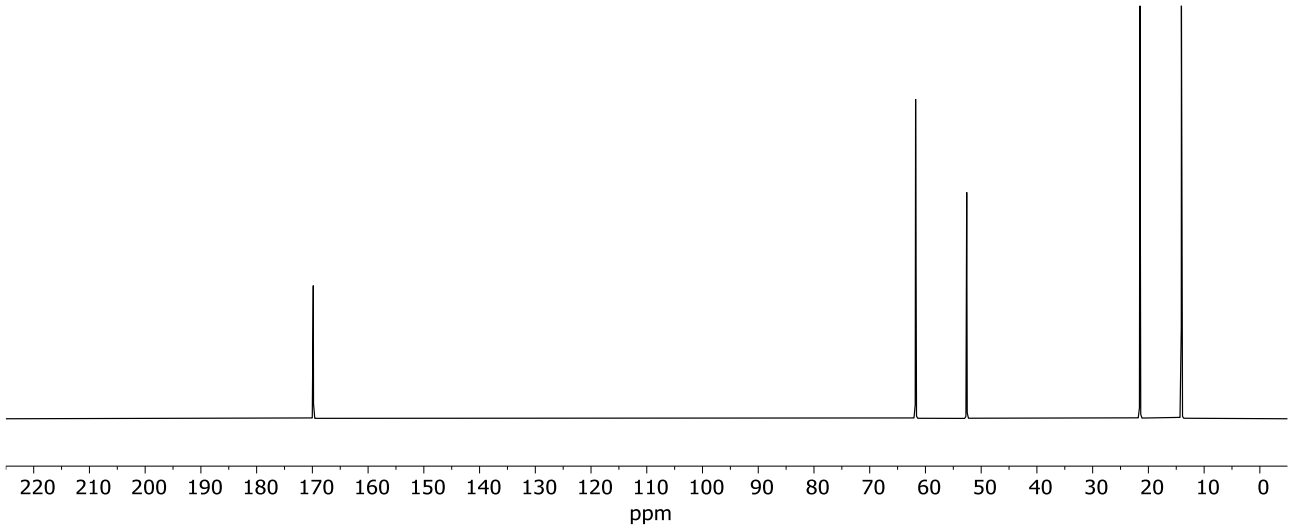


IR Spectrum:

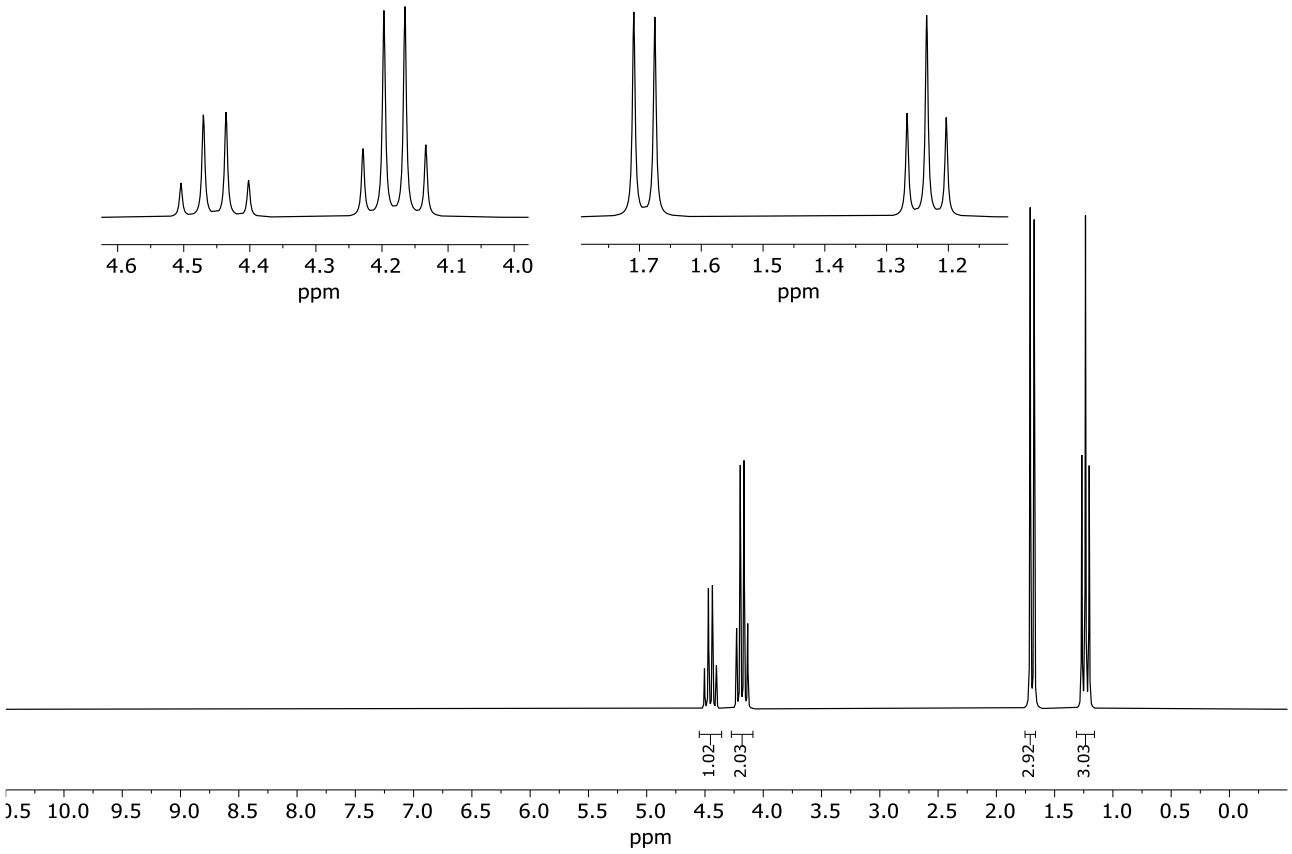


Cont'd -->

^{13}C-NMR:



^{1}H-NMR:



****** THE END ******

IRH /ASC 2025

Cont'd -->

SCRAP PAPER

Remember **ALL** final answers need to be entered in appropriate box on the answer sheet

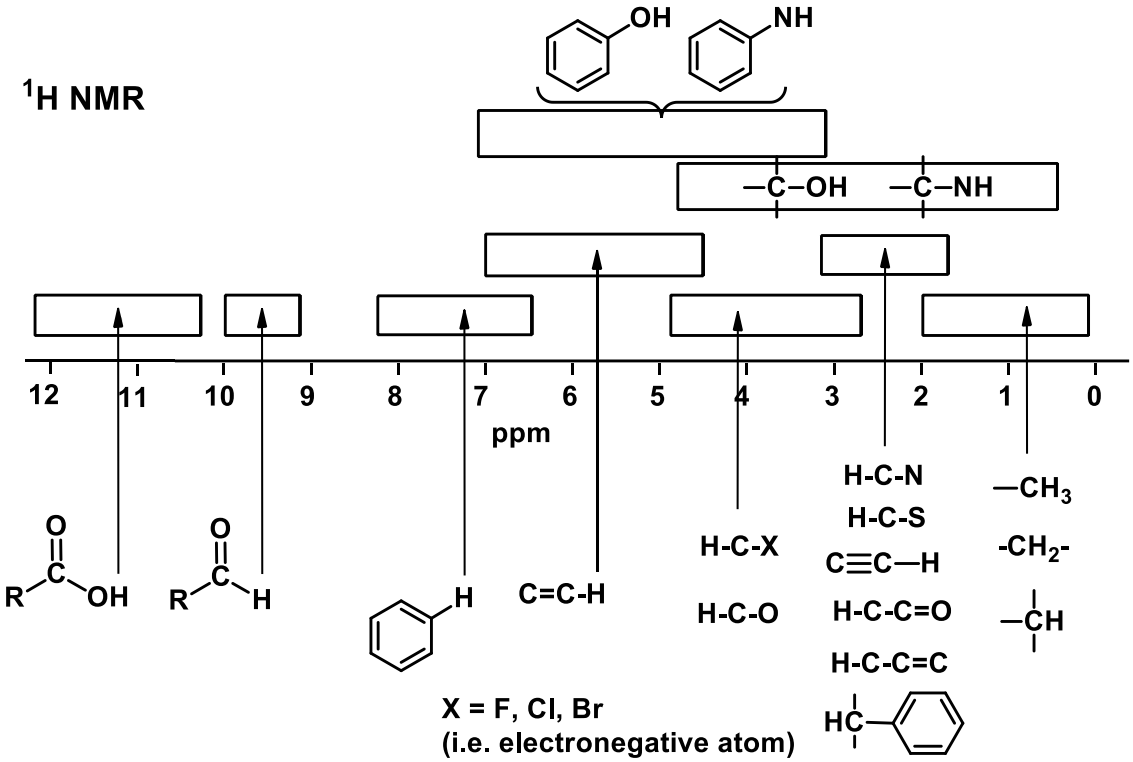
Cont'd -->

SCRAP PAPER

Remember **ALL** final answers need to be entered in appropriate box on the answer sheet

Cont'd -->

SPECTROSCOPIC TABLES



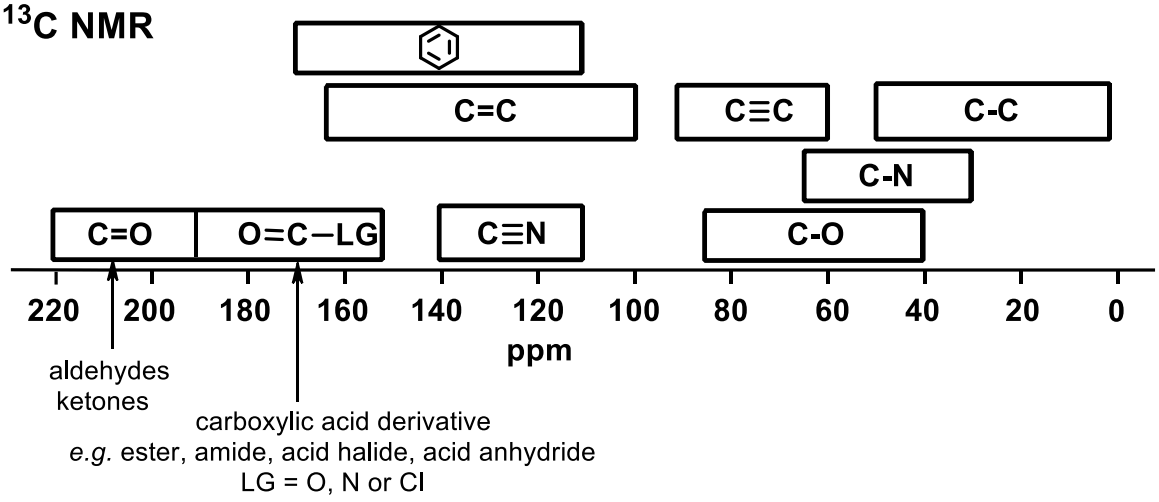
^{1}H NMR CHARACTERISTIC CHEMICAL SHIFTS / ppm

R =	methyl —CH_3	methylene -CH_2-	methyne —CH
R—C—	0.9	1.4	1.5
R, C=C	1.6	2.3	2.6
R—C(=O)—	2.1	2.4	2.5
R—N	2.2	2.5	2.9
R—Ph	2.3	2.7	3.0
R—Br	2.7	3.3	4.1
R—Cl	3.1	3.4	4.1
R—O—	3.3	3.4	3.7

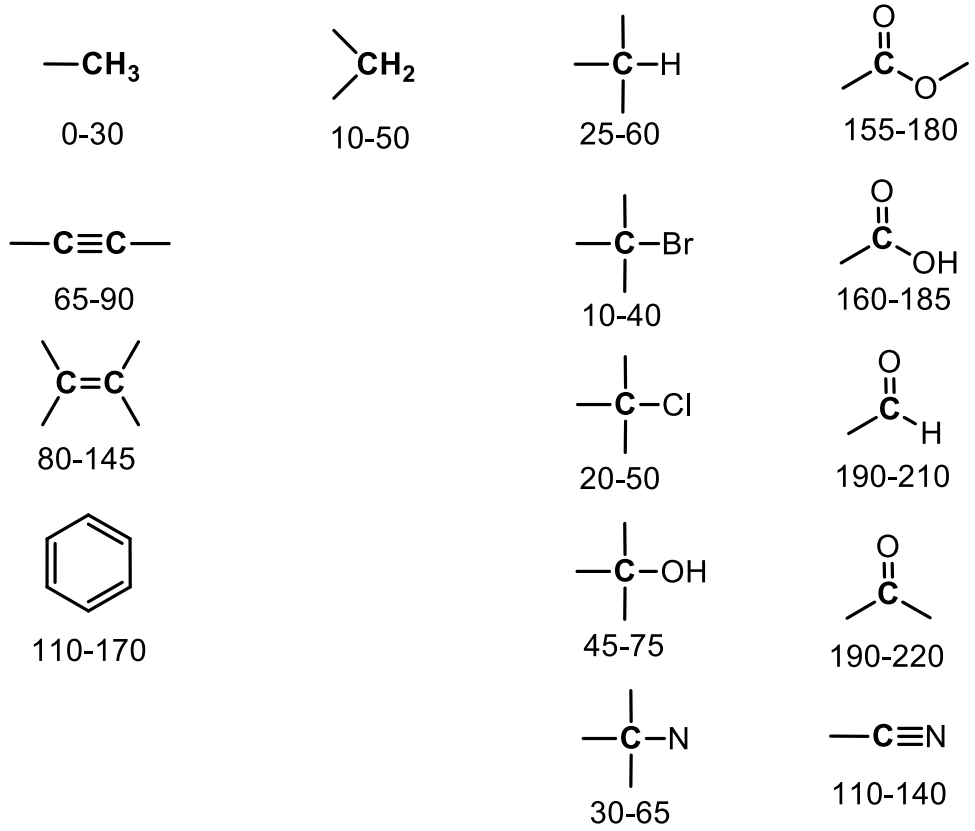
other	
sp^3C-OH	1-5
sp^3C-NH	1-3
C≡CH	2.5
C=C(H)	4.5-6.5
H—Ph	6.5-8
R—C(=O)—H	9-10
R—C(=O)—OH	9-12

Cont'd -->

^{13}C NMR



^{13}C NMR CHARACTERISTIC CHEMICAL SHIFTS / ppm



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INFRA-RED GROUP ABSORPTION FREQUENCIES

		TYPE OF VIBRATION	FREQUENCY (cm^{-1})	WAVELENGTH (μ)	INTENSITY (1)
C–H	Alkanes	(stretch)	3000-2850	3.33-3.51	s
	$-CH_3$	(bend)	1450 and 1375	6.90 and 7.27	m
	$-CH_2-$	(bend)	1465	6.83	m
	Alkenes	(stretch)	3100-3000	3.23-3.33	m
		(bend)	1700-1000	5.88-10.0	s
	Aromatics	(stretch)	3150-3050	3.17-3.28	s
		(out-of-plane bend)	1000-700	10.0-14.3	s
	Alkyne	(stretch)	ca. 3300	ca.3.03	s
	Aldehyde		2900-2800	3.45-3.57	w
			2800-2700	3.57-3.70	w
C–C	Alkane	not usually useful			
C=C	Alkene		1680-1600	5.95-6.25	m-w
	Aromatic		1600-1400	6.25-7.14	m-w
C≡C	Alkyne		2250-2100	4.44-4.76	m-w
C=O	Aldehyde		1740-1720	5.75-5.81	s
	Ketone		1725-1705	5.80-5.87	s
	Carboxylic acid		1725-1700	5.80-5.88	s
	Ester		1750-1730	5.71-5.78	s
	Amide		1700-1640	5.88-6.10	s
	Anhydride		ca. 1810	ca. 5.52	s
			ca. 1760	ca. 5.68	s
	Acyl chloride		1800	5.55	s
C–O	Alcohols, Ethers, Esters,				
	Carboxylic acids		1300-1000	7.69-10.0	s
O–H	Alcohols, Phenols				
	Free		3650-3600	2.74-2.78	m
	H-Bonded		3400-3200	2.94-3.12	m
	Carboxylic acids (2)		3300-2500	3.03-4.00	m
N–H	Primary and secondary amines		3500-3100	ca. 2.86	m
C≡N	Nitriles		2260-2240	4.42-4.46	m
N=O	Nitro ($R-NO_2$)		1600-1500	6.25-6.67	s
			1400-1300	7.14-7.69	s
C–X	Fluoride		1400-1000	7.14-10.0	s
	Chloride		800-600	12.5-16.7	s
	Bromide, Iodide		<600	>16.7	s

(1) s = strong, m = medium and w = weak

(2) note that the -OH absorption of solid carboxylic acids which run as a nujol mull can be difficult to see as they maybe very broad

Cont'd -->

PERIODIC TABLE

1 1A																	18 8A
1 **H** 1.008	**2** 2A											**13** 3A	**14** 4A	**15** 5A	**16** 6A	**17** 7A	2 **He** 4.003
3 **Li** 6.941	4 **Be** 9.012											5 **B** 10.81	6 **C** 12.01	7 **N** 14.01	8 **O** 16.00	9 **F** 19.00	10 **Ne** 20.18
11 **Na** 22.99	12 **Mg** 24.31	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	13 **Al** 26.98	14 **Si** 28.09	15 **P** 30.97	16 **S** 32.07	17 **Cl** 35.45	18 **Ar** 39.95
19 **K** 39.10	20 **Ca** 40.08	21 **Sc** 44.96	22 **Ti** 47.88	23 **V** 50.94	24 **Cr** 52.00	25 **Mn** 54.94	26 **Fe** 55.85	27 **Co** 58.93	28 **Ni** 58.69	29 **Cu** 63.55	30 **Zn** 65.38	31 **Ga** 69.72	32 **Ge** 72.59	33 **As** 74.92	34 **Se** 78.96	35 **Br** 79.90	36 **Kr** 83.80
37 **Rb** 85.47	38 **Sr** 87.62	39 **Y** 88.91	40 **Zr** 91.22	41 **Nb** 92.91	42 **Mo** 95.94	43 **Tc** (98)	44 **Ru** 101.1	45 **Rh** 102.9	46 **Pd** 106.4	47 **Ag** 107.9	48 **Cd** 112.4	49 **In** 114.8	50 **Sn** 118.7	51 **Sb** 121.8	52 **Te** 127.6	53 **I** 126.9	54 **Xe** 131.3
55 **Cs** 132.9	56 **Ba** 137.3	57* **La** 138.9	72 **Hf** 178.5	73 **Ta** 180.9	74 **W** 183.9	75 **Re** 186.2	76 **Os** 190.2	77 **Ir** 192.2	78 **Pt** 195.1	79 **Au** 197.0	80 **Hg** 200.6	81 **Tl** 204.4	82 **Pb** 207.2	83 **Bi** 209.0	84 **Po** (209)	85 **At** (210)	86 **Rn** (222)
87 **Fr** (223)	88 **Ra** 226.0	89** **Ac** (227)	104 **Rf** (261)	105 **Ha** (262)	106 **Sg** (263)	107 **Ns** (262)	108 **Hs** (265)	109 **Mt** (266)	110 **Uun** (269)	111 **Uuu** (272)							

Lanthanides *	58 **Ce** 140.1	59 **Pr** 140.9	60 **Nd** 144.2	61 **Pm** (145)	62 **Sm** 150.4	63 **Eu** 152.0	64 **Gd** 157.3	65 **Tb** 158.9	66 **Dy** 162.5	67 **Ho** 164.9	68 **Er** 167.3	69 **Tm** 168.9	70 **Yb** 173.0	71 **Lu** 175.0
Actinides **	90 **Th** 232.0	91 **Pa** 231.0	92 **U** 238.0	93 **Np** 237.0	94 **Pu** (244)	95 **Am** (243)	96 **Cm** (247)	97 **Bk** (247)	98 **Cf** (251)	99 **Es** (252)	100 **Fm** (257)	101 **Md** (258)	102 **No** (259)	103 **Lr** (260)