

TEAM NAME	<b>ANSWER KEY</b>		
DATE		PROCTOR'S NAME	

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**Team Round (Free Response)**

January 9 - January 15, 2023  
Maximum: 2 hours

Additional Materials: Answer Sheet, [USNCO Reference Sheet](#)

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**READ THESE INSTRUCTIONS FIRST**

Write in a black or dark blue pen, or a pencil.

Do not use staples, paper clips, glue or correction fluid.

Write your team name, date, captain's CIN, and your proctor's name in the spaces at the top of this page.

Write your answers on the answer sheet provided.

**Read the instructions on the answer sheet very carefully.**

All results must be written in the appropriate answer boxes with pen or pencil on the answer sheets.

The use of an approved scientific calculator is expected, where appropriate.

At the end of the examination, fasten all your work securely together with a paperclip.

The number of marks is given in the table at the top of each question.

## Problems & Grading Information

Problem no.	Title	Author	Total score	% of total score
1	Sulfonamides, a powerful synthetic building block	Lim Dillion	51	16.7
2	Electrochemical Catalysis	Lim Dillion	27	16.7
3	Where inorganic meets organic	Lim Dillion	36	16.7
4	"So, my NMR looks a little funny..." 😊	Lim Dillion	24	16.7
5	Ester Hydrolysis	Lim Dillion	26	16.7
6	Quantum Harmonic Oscillator and Isotopes	Nathanael Reza Putra Widjaja	24	16.7

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Problem 1 16.7% of total	Question	1-1	1-2	1-3	1-4	1-5	1-6	1-7	1-8	1-9	Total
	Points	3	4	14	7	7	2	5	5	4	51

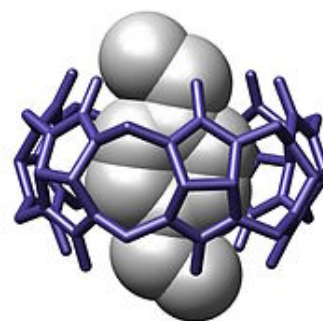
## Problem 1: Sulfonamides, a powerful synthetic building block

by Lim Dillion, Singapore

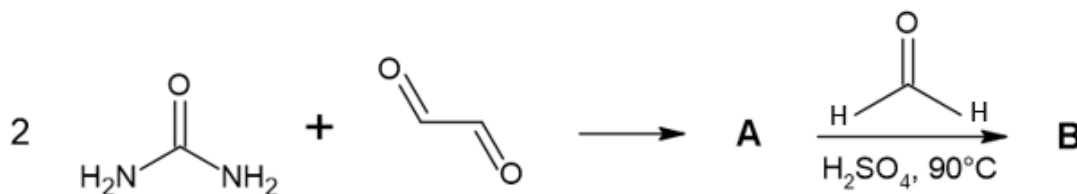
Pharmaceutical drugs are undoubtedly an important area of chemistry research. The aim of pharmaceutical chemists is to obtain new molecules that serve as the baseline for the discovery of new pharmaceuticals or optimise already known drug structures, thereby expanding the current known range of drugs. As a result, pharmaceutical chemists concern themselves primarily with two things:

1. Drug synthesis
2. Drug delivery vehicles

Particularly for drug delivery, there has been recent attention placed on macrocycles as potential hosts for drugs, having increased drug solubility, masking unpleasant tastes, controlled and sustained drug release, improved chemical and physical drug stability as well as potential light activation of prodrugs. A likely candidate for such applications are a family of compounds, cucurbiturils (which, incidentally look like pumpkins, which were the "representative" molecule for ACOT!)



The synthesis of cucurbiturils, fortunately, is extremely easy. The scheme below outlines the synthesis of cucurbit[7]-urils, indicating a macrocycle with 7 repeating units.

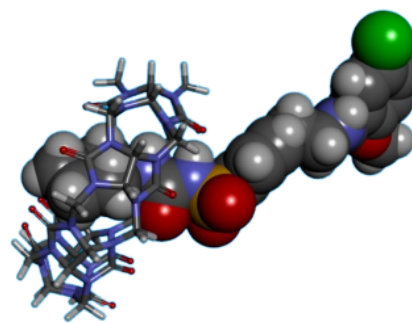


Hints:

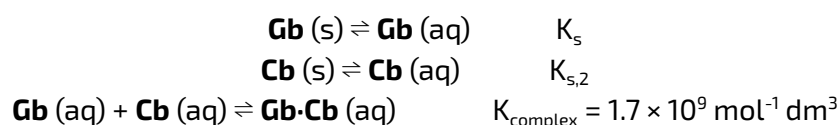
- The first step involves the elimination of water molecules.
- Compound **A** is not polymeric.
- Compound **B** only has 14 oxygen atoms in the whole compound.

- 1.1) Draw the structures of compounds **A** and **B**. You can use the bracket notation  $[\text{R}]_n$  to indicate a polymer of R with  $n$  repeating units.

With cucurbit[7]-urils (molar mass = 1163.00 g mol<sup>-1</sup>), a popular choice of drug for delivery is glibenclamide (molar mass = 494.00 g mol<sup>-1</sup>), an antidiabetic medication used to treat type 2 diabetes, as shown on the right in the picture.

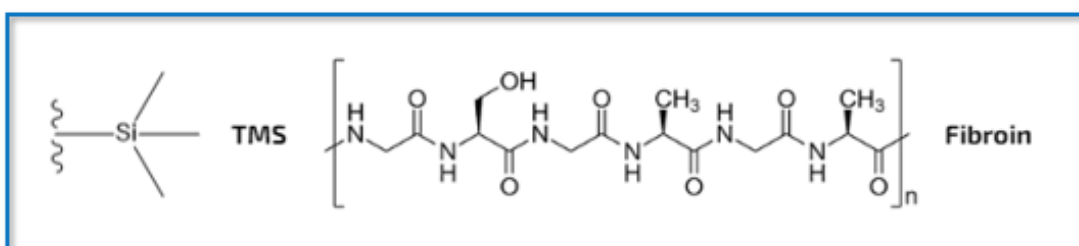
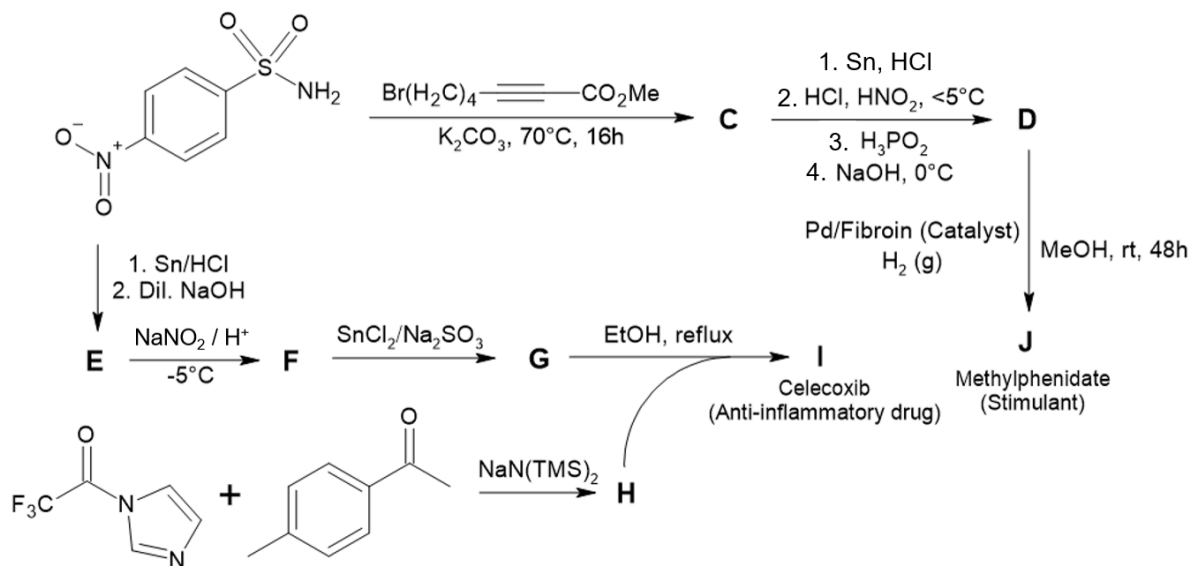


By itself, glibenclamide has a very low solubility in water (4 mg dm<sup>-3</sup>). Cucurbit[7]-uril also has a very low solubility in water (20 μmol L<sup>-1</sup>). However, it is able to form a complex with cucurbit[7]-uril, forming a complex ion that enables it to dissolve in water as shown below. Abbreviating glibenclamide as **Gb**, and cucurbit[7]-urils as **Cb**, the following equilibria are obtained:



- 1.2) Using the information above, compute the solubility of the glibenclamide-cucurbit[7]-uril complex in g dm<sup>-3</sup>.

Glibenclamide fundamentally has an aryl sulfonamide structure. Aryl sulfonamides are useful precursors for pharmaceutical chemistry, and are usually used as a precursor for the synthesis of many drugs. The synthesis of methylphenidate and celecoxib, two other drugs with similar structures, are shown below from a common starting material.



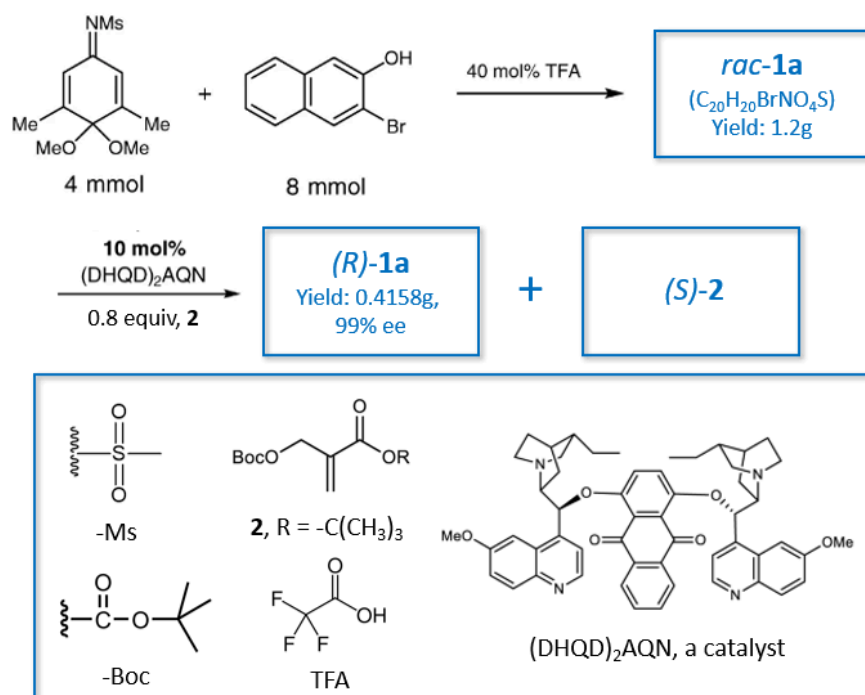
### Hints:

- The synthesis of **C** involves the expulsion of SO<sub>2</sub> gas and a rearrangement reaction.
- The synthesis of **C** also generates a cyclic compound (which has a ring which is not the phenyl ring), C<sub>14</sub>H<sub>16</sub>N<sub>2</sub>O<sub>4</sub>.
- Pd/Fibroin acts as a chemoselective catalyst which causes H<sub>2</sub> to not react with esters, carboxylic acids, ketones and aromatic rings.
- **J** has chemical formula C<sub>14</sub>H<sub>19</sub>NO<sub>2</sub>.
- Reacting **G** and **H** forms a 1,5-dialkylpyrazole moiety through condensation.
- Compound **I** has the chemical formula C<sub>17</sub>H<sub>14</sub>F<sub>3</sub>N<sub>3</sub>O<sub>2</sub>S.

1.3) Suggest the structures of compounds **C** to **J**.

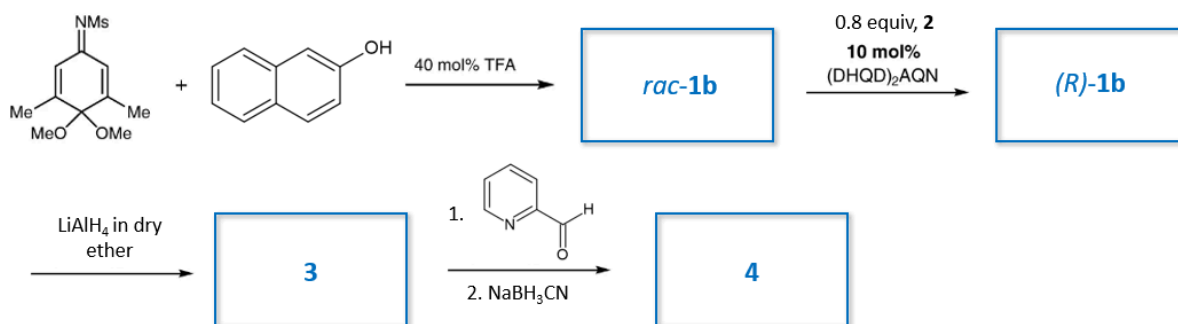
1.4) Suggest the mechanism for the conversion of the aryl sulfonamide to **C**.

In recent years, beyond simple aryl sulfonamides like those above, the discovery of new bioactive biaryl compounds also represents a highly active area of research. Of these, axially chiral aryl sulfonamides have attracted great interest as well. A notable paper is that of Lu *et al.*, which reported using kinetic resolution to gain access to these axially chiral aryl sulfonamides.

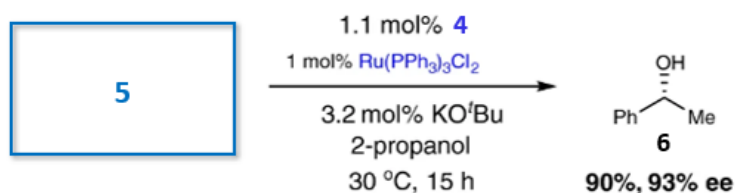


- 1.5) Suggest the structures of **rac-1a**, **(R)-1a** and **(S)-2**. Stereochemical details **are required**. (*rac* = racemic, *R* and *S* are the respective stereodescriptors of **1a** and **2** respectively)
- 1.6) In the reaction above, 1.2g of **rac-1a** was initially produced, then 0.4158g of **(R)-1a** was produced in the second step. Using the information above, compute the percentage yield of the first step and the percentage yield of the second step respectively.

A compound structurally similar to compound **1a**, compound **1b** has found use as a catalyst as well. Abbreviations are the same as those above.

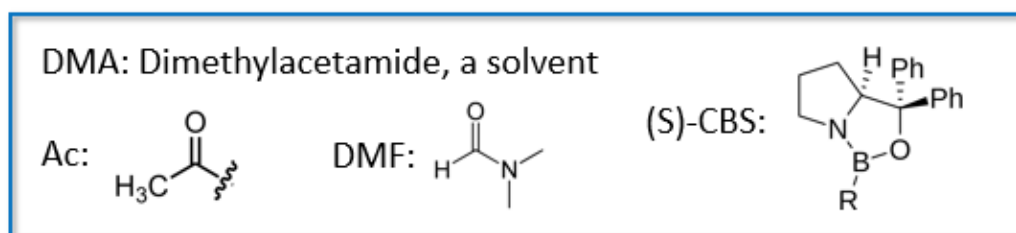
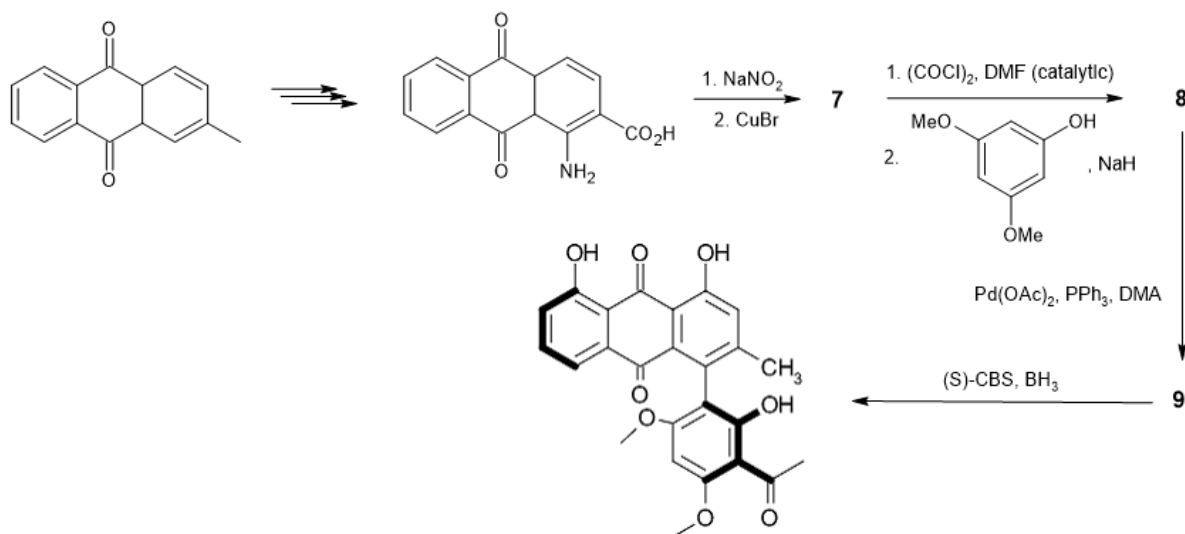


Compound **4** can then be used for the enantioselective asymmetric reduction of compound **5**, yielding compound **6**.



- 1.7) Suggest the structures of **rac-1b**, **(R)-1b**, **3** - **5**. Stereochemical details **are required**, where applicable.

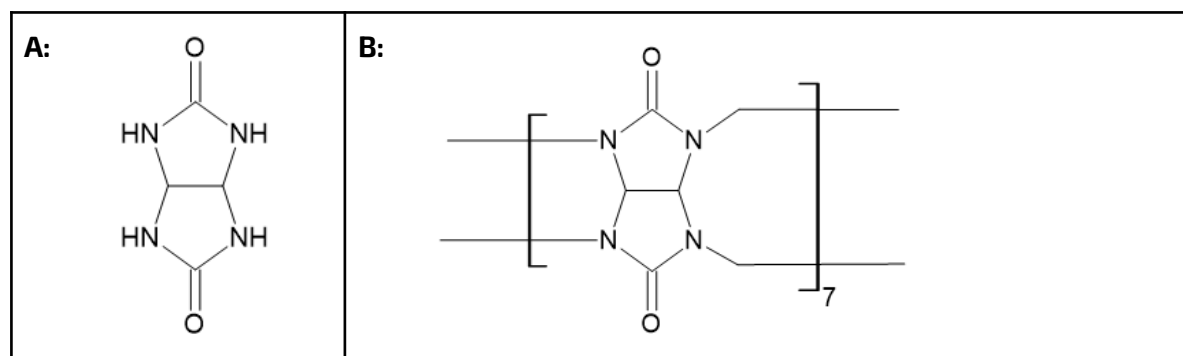
One of the applications of the above biaryl systems in synthesis of drugs is the African folk medicine, Knipholone. A partial synthesis of it is shown below:



- 1.8) Suggest the structures of **7** to **9**. Stereochemistry is **not** required.
- 1.9) Suggest the mechanism for the transformation of **7** to **8**.

## Problem 1: Solution

- 1.1) Draw the structures of compounds **A** and **B**. You can use the bracket notation  $[R]_n$  to indicate a polymer of R with  $n$  repeating units.



### Explanation (Not required):

The first reaction is simply a nucleophilic addition of the urea molecules to the dialdehyde, giving **A**.

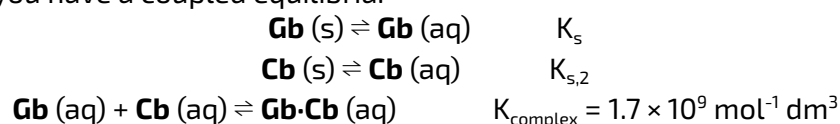
The second reaction is a condensation reaction. Taking the hint that there are only 14 oxygen atoms, the formaldehyde molecules only contribute carbon atoms.

**1 point for correct structure of A.**

**2 points for correct structure of B. [1.5 points if they draw  $[R]_n$  instead of  $[R]_7$ , no penalty if they draw out the full structure without bracket notation]**

- 1.2) Using the information above, compute the solubility of the glibenclamide-cucurbit[7]-uril complex in  $\text{g dm}^{-3}$ .

Notice that you have a coupled equilibria:



Writing out the expression for  $K_s$ ,  $K_s = [\text{Gb (aq)}]$ .

Convert its solubility to  $\text{mol dm}^{-3}$ ,  $K_s = 4 \text{ mg dm}^{-3} = (4 \times 10^{-3} / 494) \text{ mol dm}^{-3} = 8.0972 \times 10^{-6} \text{ mol dm}^{-3}$ .

Similarly,  $K_{s,2} = 20 \text{ } \mu\text{mol dm}^{-3} = 2 \times 10^{-5} \text{ mol dm}^{-3}$

Then,  $[\text{Gb-Cb (aq)}] = K_{\text{complex}} K_s K_{s,2} = 0.275304 \text{ mol dm}^{-3}$ .

Converting this to  $\text{g dm}^{-3}$ , one will obtain the solubility of the complex in water as:

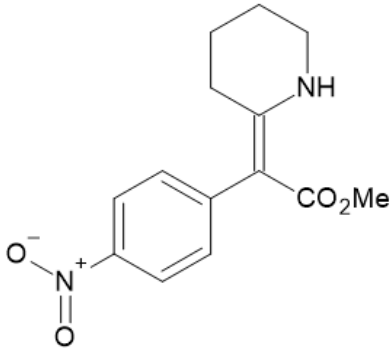
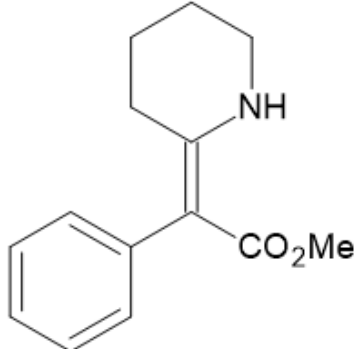
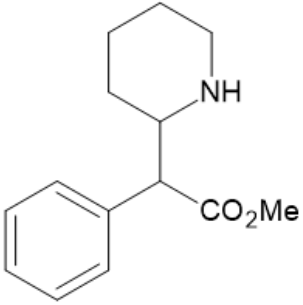
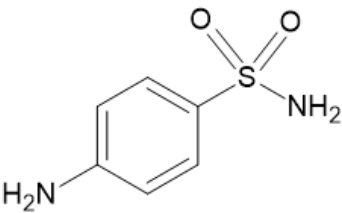
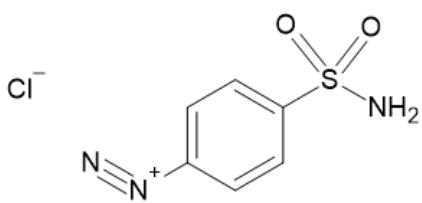
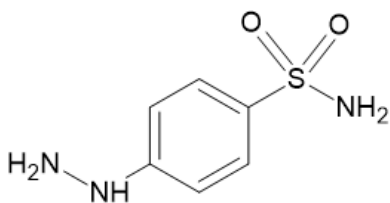
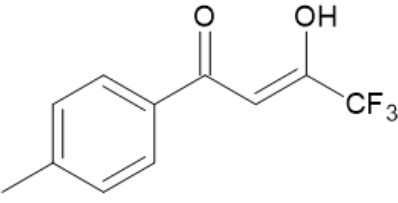
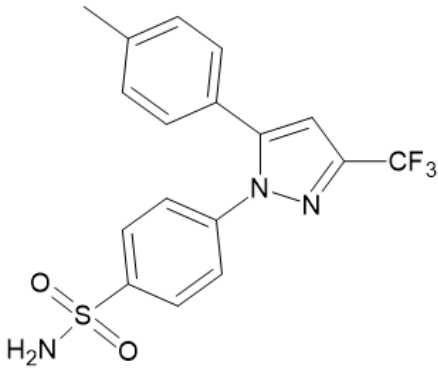
Solubility =  $0.275304 \text{ mol dm}^{-3} \times (1163 + 494) = 456 \text{ g dm}^{-3}$ .

**1 point each for computing  $K_s$  and  $K_{s,2}$  (Total 2 points).**

**1 point for computing the  $[\text{Gb-Cb (aq)}]$ .**

**1 point for converting this to solubility in  $\text{g dm}^{-3}$  correctly.**

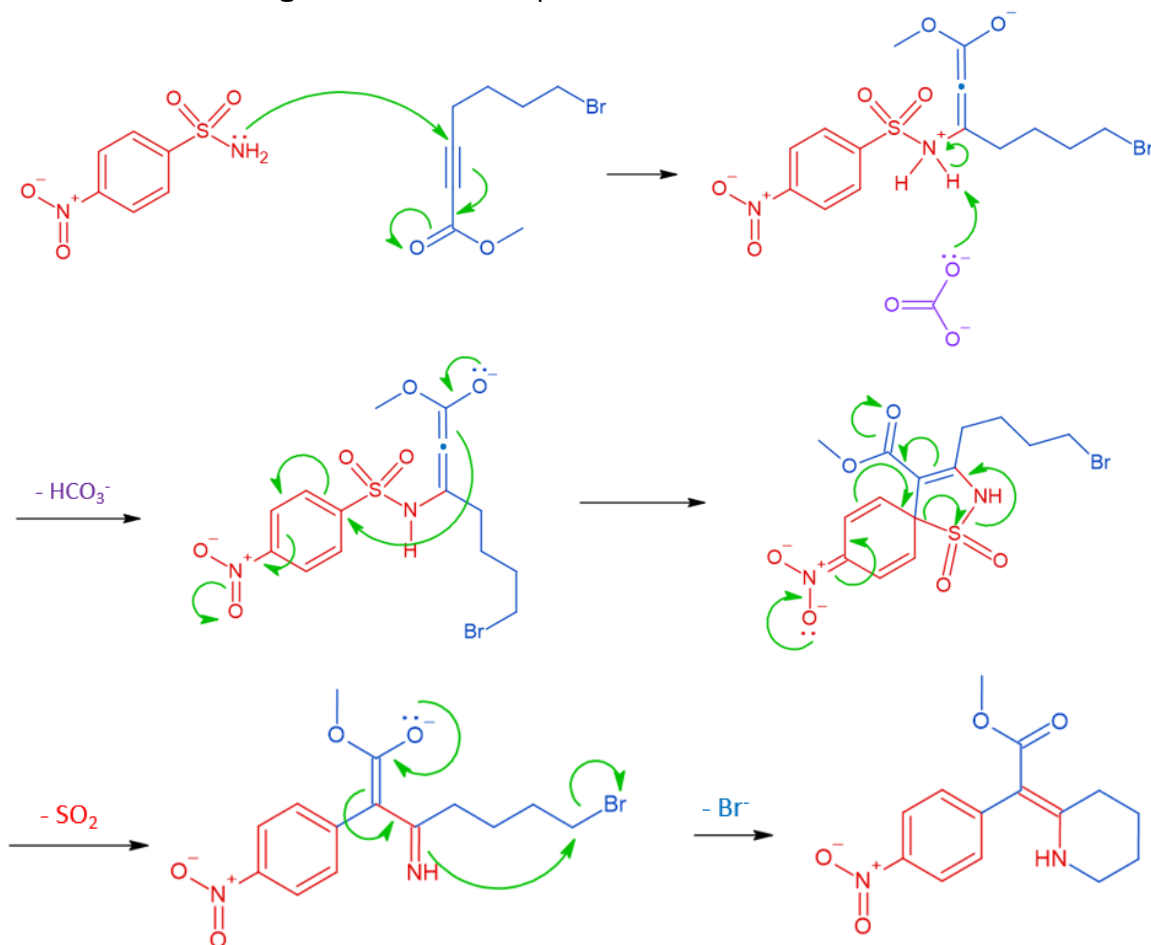
1.3) Suggest the structures of compounds **C** to **J**.

<p><b>C:</b></p> 	<p><b>D:</b></p> 
<p><b>J:</b></p> 	<p><b>E:</b></p> 
<p><b>F:</b></p> 	<p><b>G:</b></p>  <p>(Accept the hydrazine hydrochloride form as well)</p>
<p><b>H:</b></p>  <p>(Accept the keto form)</p>	<p><b>I:</b></p> 
<p><b>1 point for each structure from D, E, F, G, J. (Total 5 points)</b>  <b>2 points for each structure from C, H. (Total 4 points)</b>  <b>5 points for correct structure of I.</b></p>	



1.4) Suggest the mechanism for the conversion of the aryl sulfonamide to **C**.

Truce-Smiles Rearrangement and Nucleophilic Substitution



**7 points in total:**

1 point for addition to alkyne, forming the allene

0.5 points for correct deprotonation of sulfonamide

1.5 points for formation of the correct 5-membered intermediate through an electrophilic substitution mechanism

1 point for restoring aromaticity of the phenyl ring

2 points for correct decomposition, with elimination of  $\text{SO}_2$ , forming the ester enolate

1 point for imine reaction with the alkyl bromide in an intramolecular nucleophilic substitution reaction

No penalty if the side products (i.e.  $\text{HCO}_3^-$ ,  $\text{SO}_2$  and  $\text{Br}^-$ ) are not shown, though it is good practice to show them

-0.5 points if base used is not specified (e.g.  $\text{B}^-$ ) or wrong base is used (e.g. water instead of the carbonate ion),

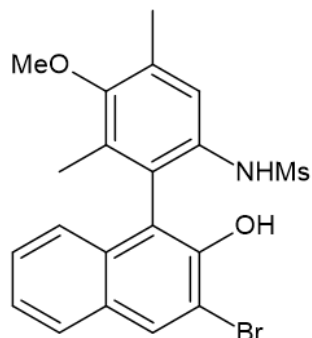
-0.5 points if the mechanism involves a tautomerisation to an amine before a intramolecular nucleophilic substitution mechanism is drawn,

-0.5 points if electrons are not pushed to an electron sink (e.g. not pushing to the nitro group for the electrophilic substitution, instead leaving it as a carbanion)

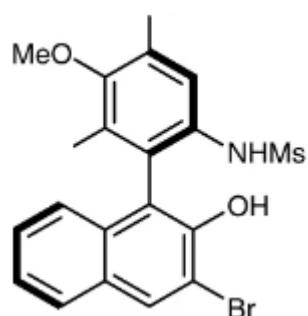
-0.5 points for every general minor error in mechanism (e.g. missing H, missing charges),  
 -1 point for every general major error in mechanism (e.g. direction of arrow is wrong, expanded octet for period 2 elements)

- 1.5) Suggest the structures of *rac*-**1a**, (*R*)-**1a** and (*S*)-**2**. Stereochemical details **are required**. (*rac* = racemic, *R* and *S* are the respective stereodescriptors of **1a** and **2** respectively)

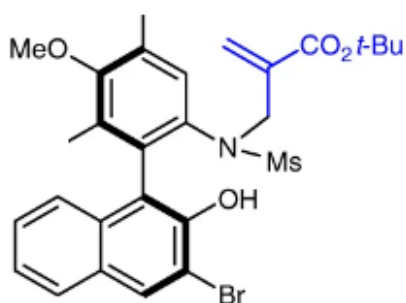
*rac*-**1a**:



(*R*)-**1a**:



(*S*)-**2**:



**1 point for structure *rac*-1a.**

0 points awarded if stereochemistry is drawn, because **1a** is racemic.

**3 points each for structures (*R*)-1a and (*S*)-2. (Total 6 points)**

1 point for the above if correct structure, but wrong or no stereochemistry is shown

No penalty if Ms, <sup>t</sup>Bu are abbreviated as shown above, as long as the connectivity of atoms are clear.

- 1.6) In the reaction above, 1.2g of *rac*-**1a** was initially produced, then 0.4158g of (*R*)-**1a** was produced in the second step. Using the information above, compute the percentage yield of *rac*-**1a** in the first step and the percentage yield of **both** atropisomers of **1a** in the second step respectively.

Molar mass of **1a** is 450.35 g mol<sup>-1</sup>.

Hence, the number of moles of *rac*-**1a** formed is 1.2 / 450.34 = 0.00266465 mol.

Since the two reactants react in a 1:1 molar ratio, the first reactant is the limiting reagent.

$$\text{Hence, percentage yield of step 1} = \frac{0.00266465}{0.00400} \cdot 100\% = \boxed{66.6\%}$$

Notice that the atropisomeric and racemic form of **1a** have the same molar masses.

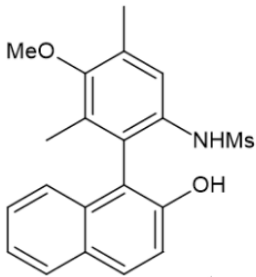
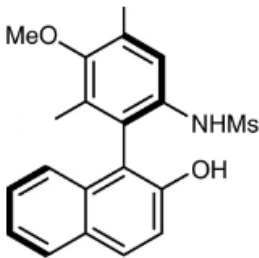
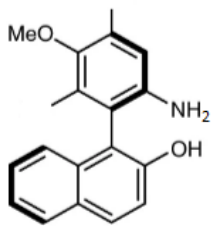
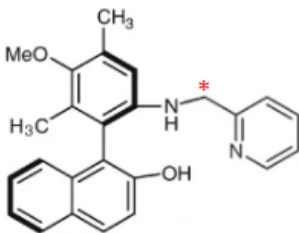
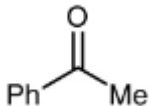
Total mass of **1a** formed = 0.4158 × 100/99 = 0.42g

$$\text{Hence, percentage yield of step 2} = \frac{0.42}{1.2} \cdot 100\% = \boxed{35.0\%}$$

**0.25 points each for computation of molar mass of 1a, number of moles of rac-1a, identification of limiting reagent, and total mass of 1a formed. (Total 1 point, steps identified above in blue)**

**0.5 points each for correct percentage yield with correct computation. (Total 1 point, boxed up)**

- 1.7) Suggest the structures of *rac*-**1b**, (*R*)-**1b**, **3** - **5**. Stereochemical details **are required**, where applicable.

<p><i>rac</i>-<b>1b</b>:</p> 	<p>(<i>R</i>)-<b>1b</b>:</p> 
<p><b>3</b>:</p> 	<p><b>4</b>:</p> 
<p><b>5</b>:</p> 	

**0.5 points for structures *rac*-1a and (*R*)-1b. (Total 1 point)**

Error carry forward given if something analogous to that in the previous part of the question is drawn. Only the Br atom should be removed.

**1 point for correct amine deprotection, leading to structure 3.**

0 points if stereochemistry changed, new stereocenter, wrong product, etc.

**2 points for correct structure 4.**

1 point if wrong position of substitution relative to pyridine.

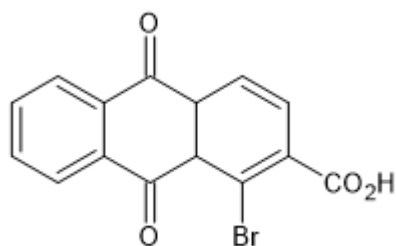
0.5 points if the bridging carbon atom (highlighted by the red asterisk) is missing in the new amine formed.

**1 point for structure 5.**

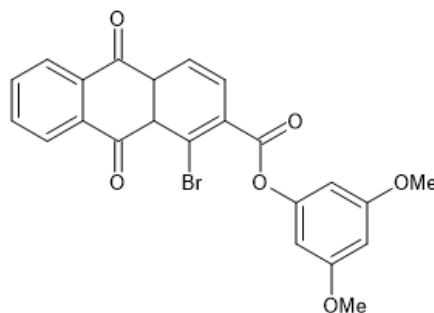
No partial credit (1 or 0 points only).

1.8) Suggest the structures of **7** to **9**. Stereochemistry is **not** required.

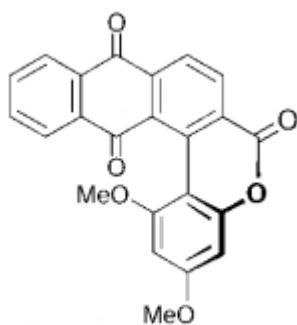
**7:**



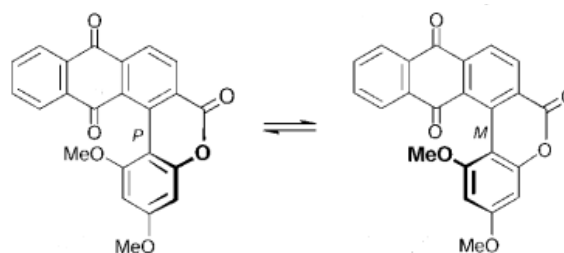
**8:**



**9:**



Stereochemistry is not required for **9**, but it is drawn in to illustrate the atropisomer that leads to the desired product. However, note that **9** is **not** configurationally stable. That is,



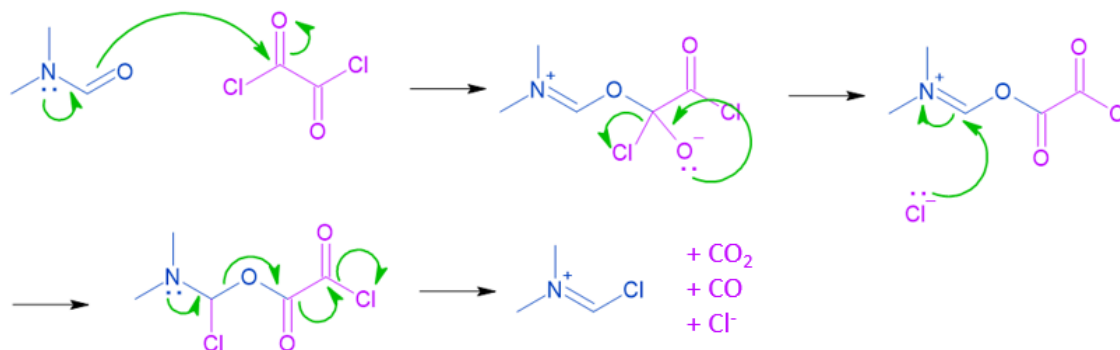
**1 point for structure 7.**

**2 points each for structures 8 and 9. (Total 4 points)**

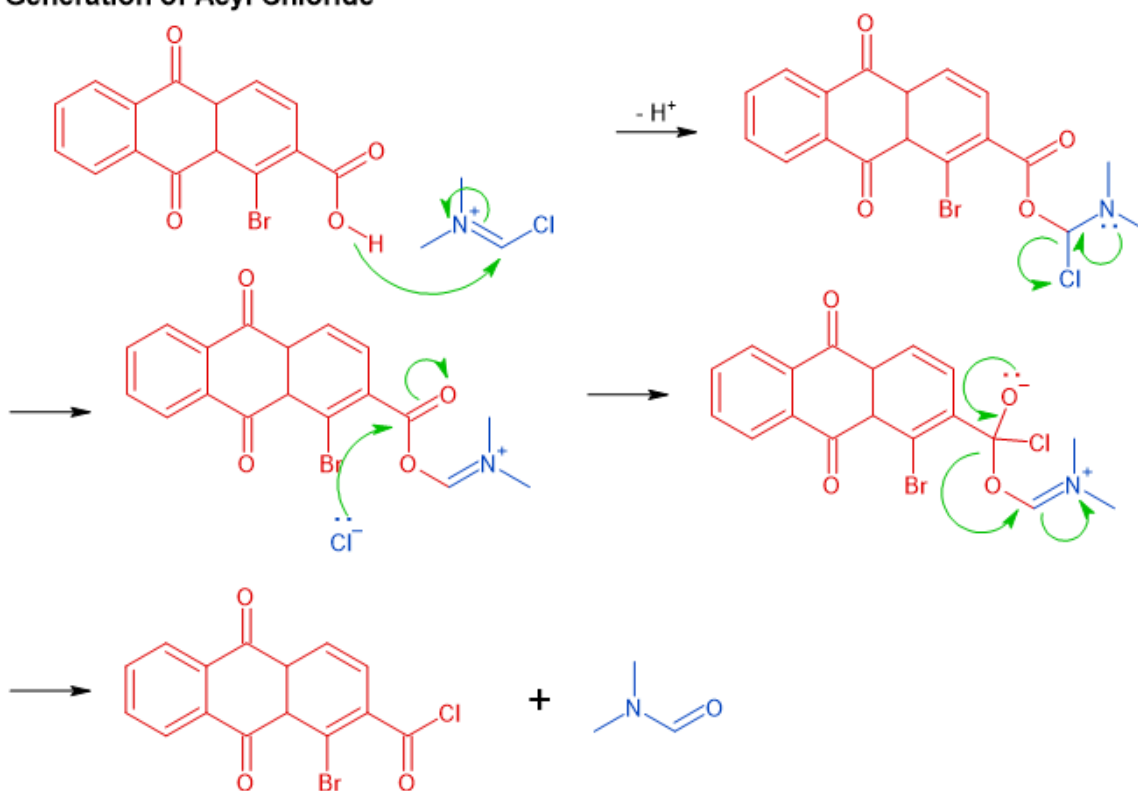
1.9) Suggest the mechanism for the transformation of **7** to **8**.

"Vilsmeier-Haack"-like Reaction and Nucleophilic Acyl Substitution

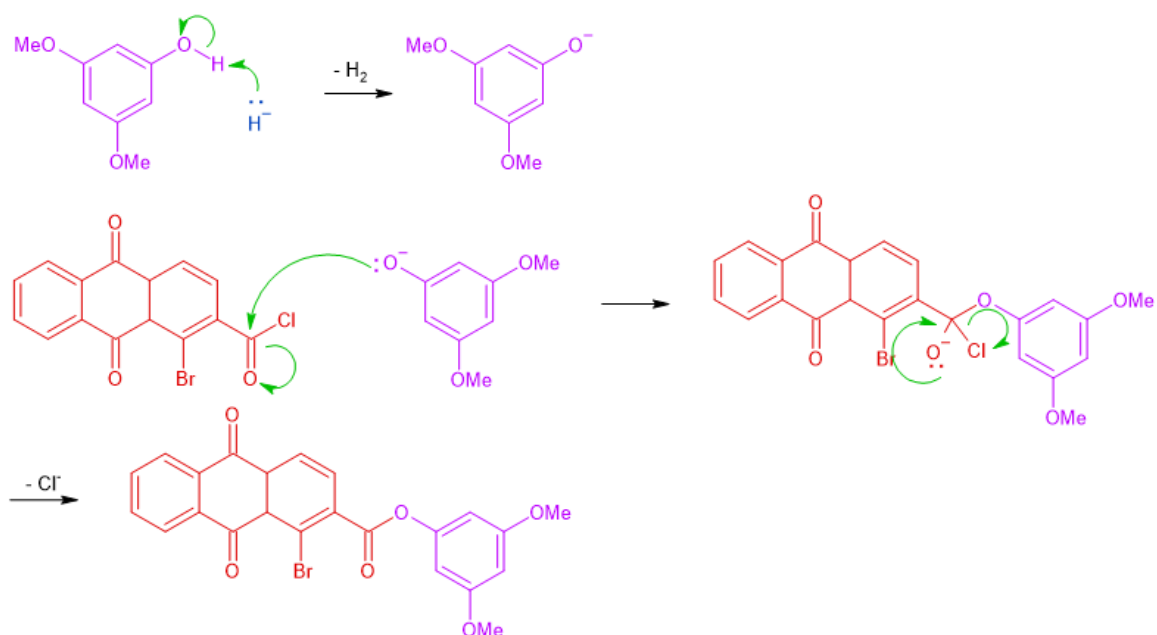
**Generation of Vilsmeier Reagent**



**Generation of Acyl Chloride**



#### Formation of ester



#### 4 points in total:

0.5 points for correct nucleophilic acyl substitution mechanism in the Vilsmeier reagent formation

1 point for correct attack of iminium ion with chloride then a decomposition, forming the Vilsmeier reagent

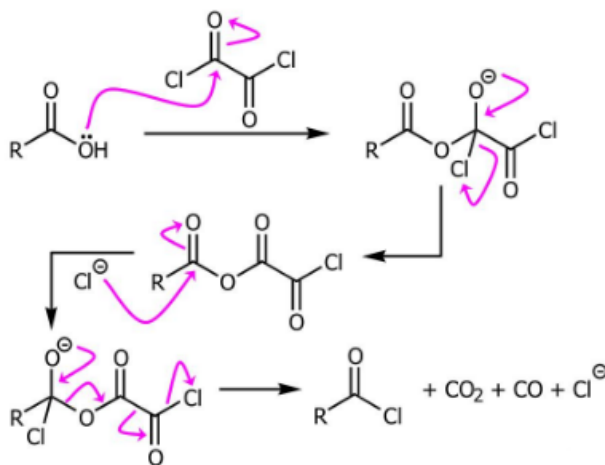
0.5 points for correct nucleophilic addition mechanism in the generation of acyl chloride

1 point for correct nucleophilic acyl substitution to yield the acyl chloride, explicitly showing the regeneration of DMF

0.5 points for deprotonation of phenol using hydride ion

0.5 points for correct nucleophilic acyl substitution mechanism to yield the final ester

**Capped at 2 points if the Vilsmeier reagent is not formed before the nucleophilic addition is conducted, as the alternative proceeds much more slowly, i.e. the mechanism shown below (credit for image):**



No penalty if the side products are not shown, though it is good practice to show them

-0.5 points if base used is not specified (e.g.  $B^-$ ) or wrong base is used (e.g. water instead of the hydride ion),

-0.5 points if electrons are not pushed to an electron sink (e.g. not pushing to the carbonyl oxygen or iminium nitrogen in the nucleophilic acyl substitution / addition mechanisms)

-0.5 points for every general minor error in mechanism (e.g. missing H, missing charges),

-1 point for every general major error in mechanism (e.g. direction of arrow is wrong, expanded octet for period 2 elements)

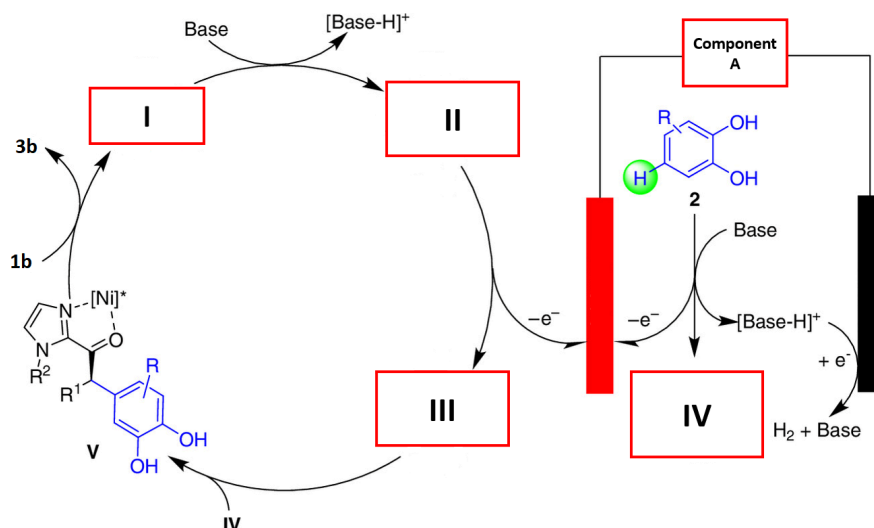
Problem 2 16.7% of total	Question	2-1	2-2	2-3	2-4	2-5	2-6	2-7	Total
	Points	3	4	1	8	3	2	6	27

## Problem 2: Electrochemical Catalysis

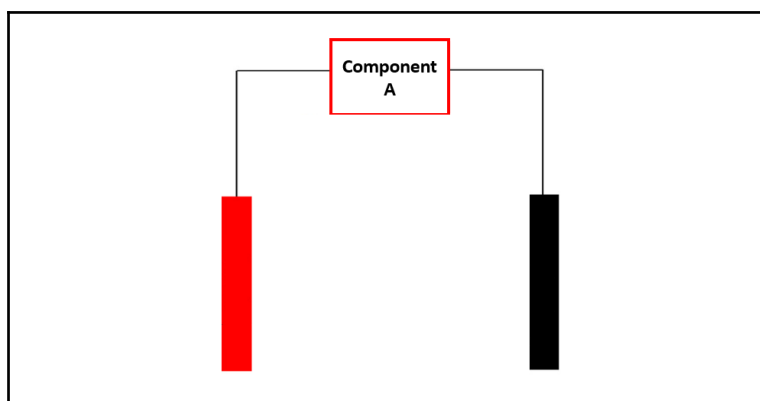
by Lim Dillion, Singapore

A research conducted by Zhang, Liang and Guo in 2021 involved the use of asymmetric electrochemical arylation in the total synthesis of (+)-Amurensinine.

The synthesis of (+)-Amurensinine involved the use of an electrochemical setup for the conversion of **1b** and **2a** to **3b**. The mechanism is shown below:



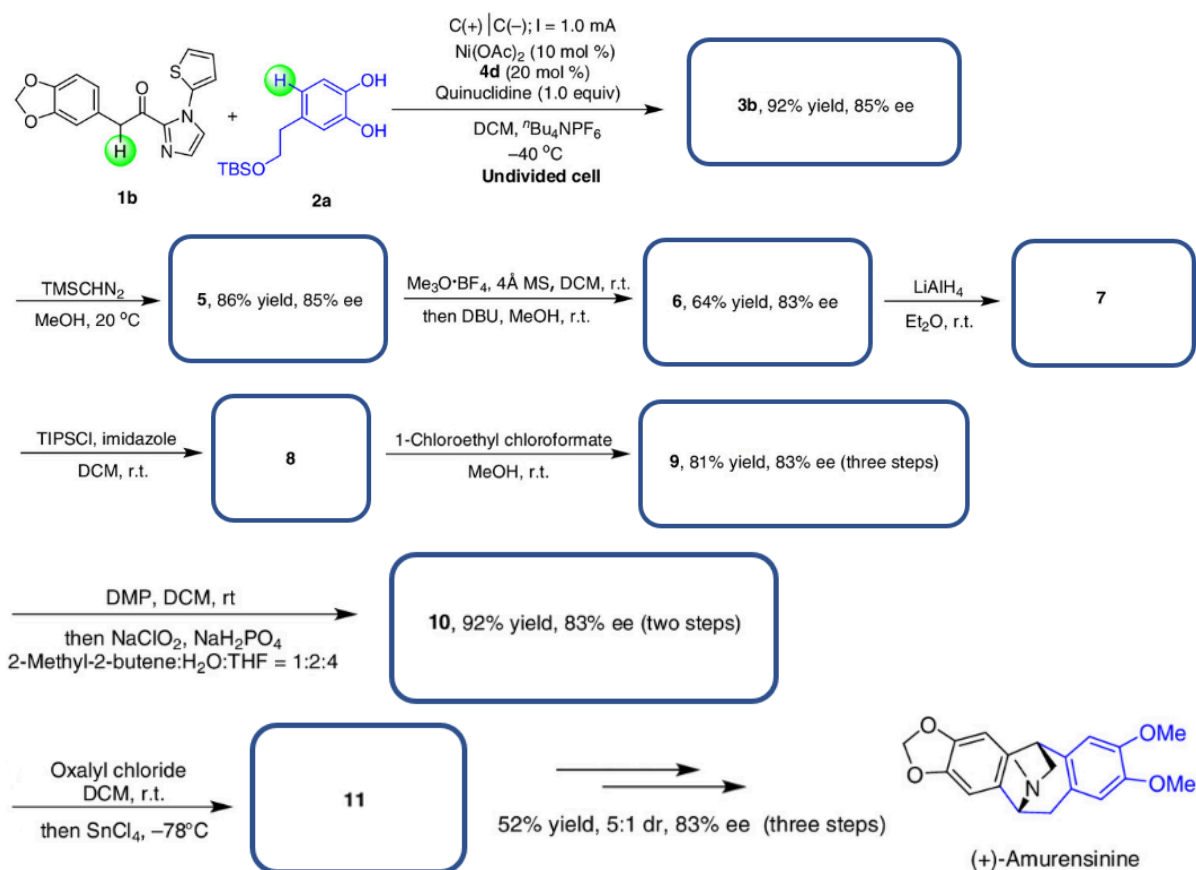
- 2.1) Copy the abbreviated electrochemical setup below and **draw in component A, indicating any polarity of the component and the electrodes clearly**. You may label the electrodes as red and black, or just ignore the colour completely. A copy has been provided in the answer sheet as well.



- 2.2) Deduce the structures of species **I** to **IV**. Note that these chemical species may not be neutrally charged.
- 2.3) Suggest **one** benefit of the electrochemical method of synthesising product **3b**, as opposed to normal cross-coupling methods.



The rest of the total synthesis is shown below:

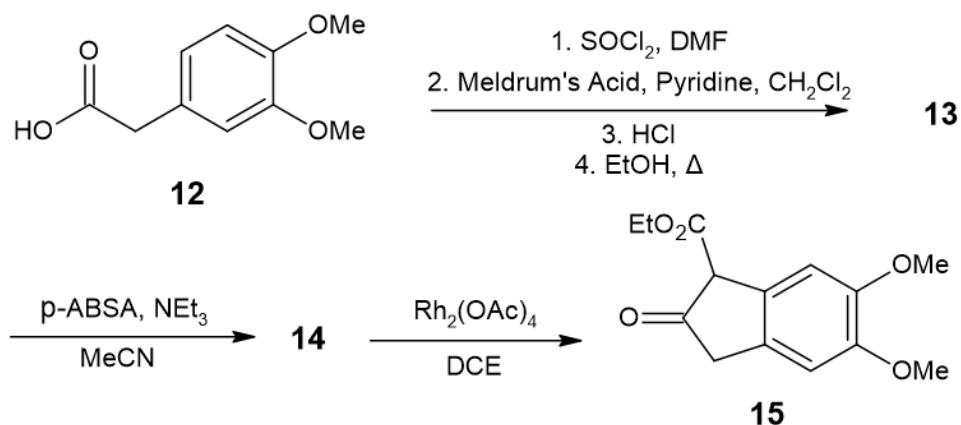


#### List of abbreviations:

-Ac	-TMS	DBU	TIPSCl
Imidazole	1-chloroethyl chloroformate	DMP (Dess-Martin periodinane)	Oxalyl chloride
		Molecular sieves, speeds up the reaction	<b>ee:</b> enantiomeric excess <b>dr:</b> diastereomeric ratio <b>DCM:</b> dichloromethane (solvent) <b>r.t.:</b> room temperature
Quinuclidine	<b>4d</b> (Ar = 2,4,6-Cl <sub>3</sub> -Ph) <b>4d</b> is a catalyst	4Å MS	

- 2.4) Deduce the structures of **3b** and **5 - 11**. Stereochemistry is **not** required.  
 2.5) Compute the overall yield of (+)-Amuresinine.

The non-electrochemical synthesis of (+)-Amuresinine by Stolz *et al.* in 2006 includes the following synthesis of intermediate **15**:

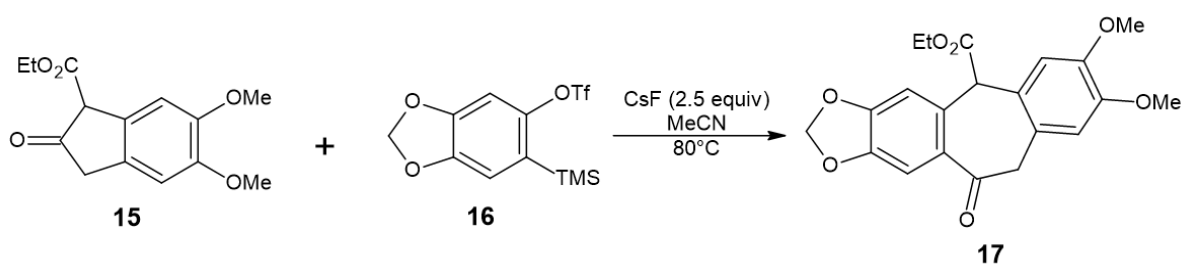


**List of abbreviations:**

-Ac	Meldrum's Acid	p-ABSA	DCE

- 2.6) Deduce the structures of **13** and **14**.

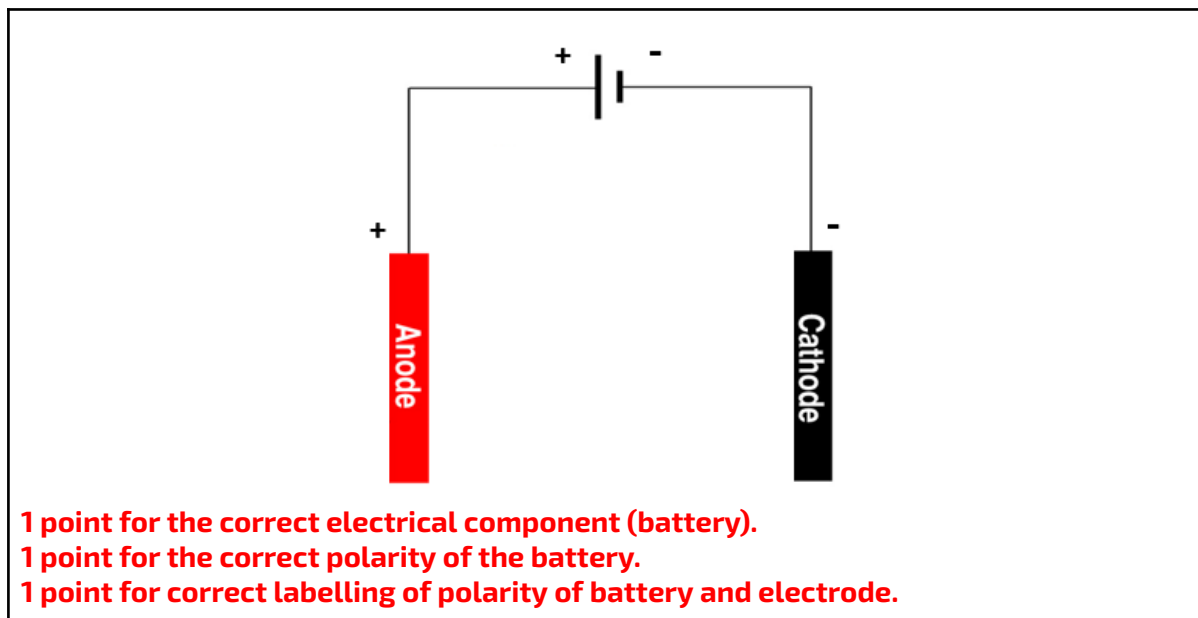
Structure **15** is an important intermediate in setting up the main carbocyclic core of (+)-Amuresinine. The following transformation sets up the main carbocyclic core:



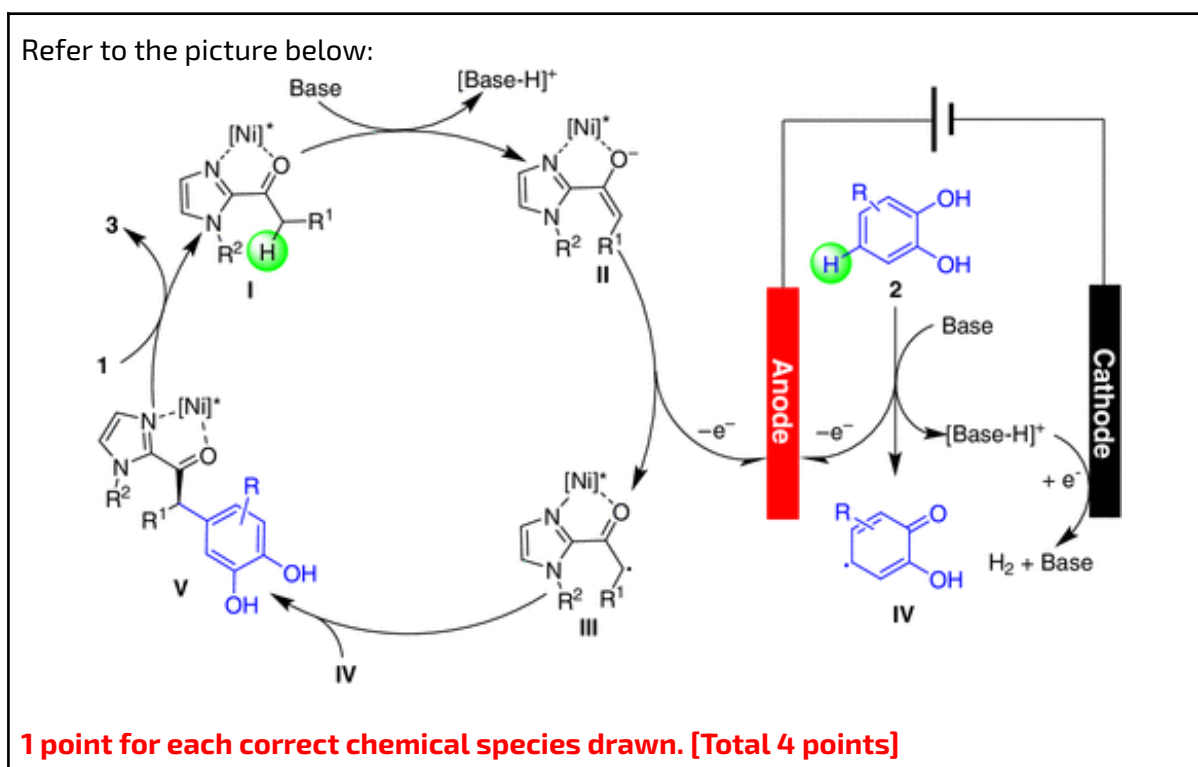
- 2.7) Draw the mechanism of the formation of **17**.

## Problem 2: Solution

- 2.1) Copy the abbreviated electrochemical setup below and **draw in component A, indicating any polarity of the component and the electrodes clearly**. You may label the electrodes as red and black, or just ignore the colour completely. A copy has been provided in the answer sheet as well.



- 2.2) Deduce the structures of species **I** to **IV**. Note that these chemical species may not be neutrally charged.



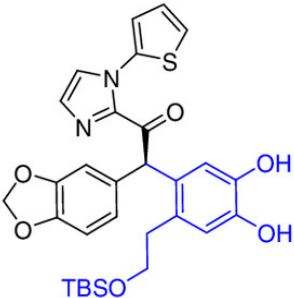
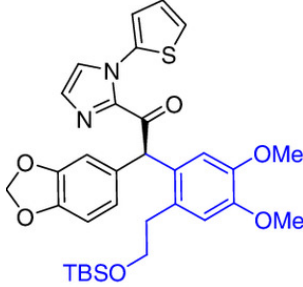
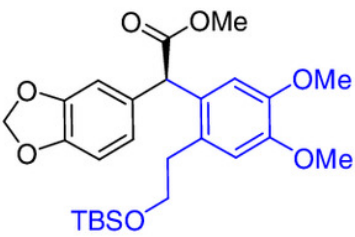
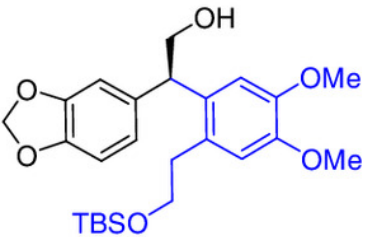
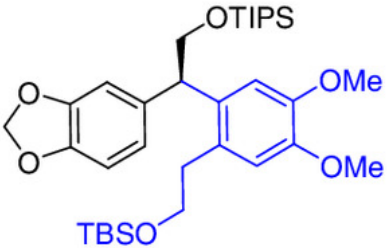
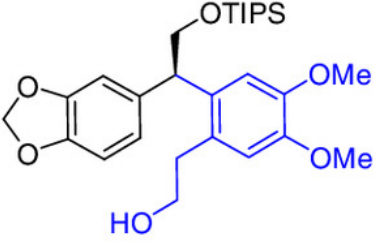
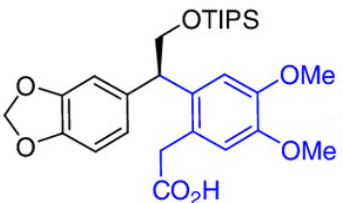
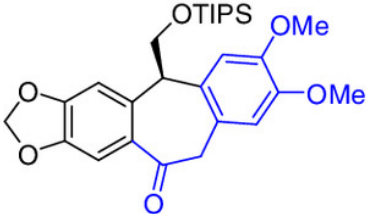
- 2.3) Suggest **one** benefit of the electrochemical method of synthesising product **3b**, as opposed to normal cross-coupling methods.

Accept any of the following answers:

- The reaction is faster than a normal cross-coupling method because the reaction is catalysed.
- The reaction is more chemoselective than a normal reaction.
- The reaction does not require stoichiometric quantities of chemical oxidants or reductants.
- Or any alternative answer that makes sense.

**1 point for correct benefit stated.**

- 2.4) Deduce the structures of **3b** and **5 - 11**. Stereochemistry is **not** required.

<p><b>3b:</b></p> 	<p><b>5:</b></p> 
<p><b>6:</b></p> 	<p><b>7:</b></p> 
<p><b>8:</b></p> 	<p><b>9:</b></p> 
<p><b>10:</b></p> 	<p><b>11:</b></p> 
<p><b>1 point for each correct structure. (Total 8 points)</b></p>	

2.5) Compute the overall yield of (+)-Amuresinine.

Total yield of Amuresinine =  $0.92 \times 0.86 \times 0.64 \times 0.81 \times 0.92 \times 0.52 = 0.19622$   
 Total yield of (+)-Amuresinine =  $0.19622 \times 0.83 + (1-0.83)/2$  (enantiomer)  $\times 5/6$  (diastereomer) = 0.1496

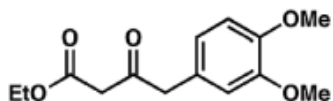
Overall yield is **15.0%**.

**1 point for correct overall yield of Amuresinine.**

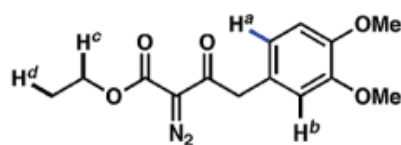
**2 points for correct overall yield of the enantiomer of Amuresinine. [-1 point if ee was used, yielding 13.6%; -1 point if 1/5 was used for diastereomeric ratio, yielding 3.26%]**

2.6) Deduce the structures of **13** and **14**.

**13:**



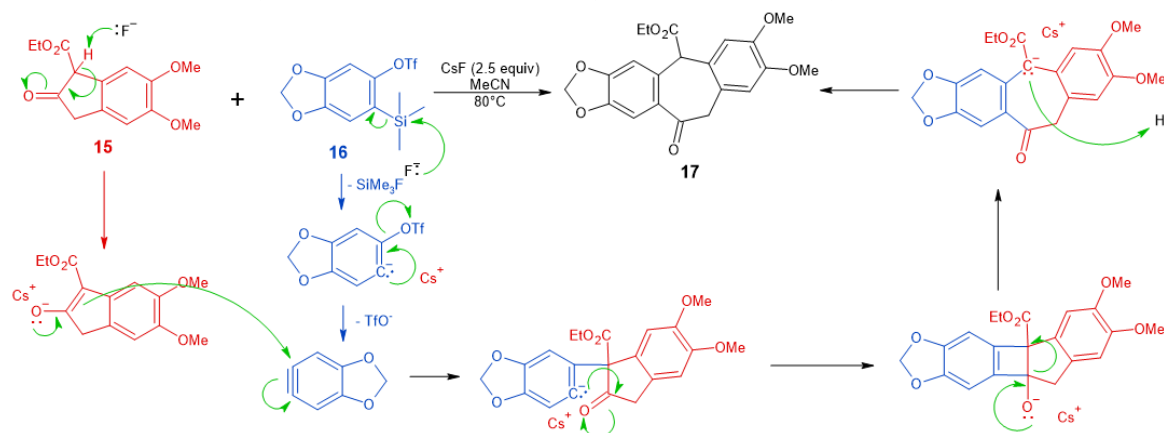
**14:**



**1 point for each correct structure. (Total 2 points)**

2.7) Draw the mechanism of the formation of **17**.

Generation of Kobayashi reagent, followed by addition to benzyne



A higher resolution picture can be found at [https://prnt.sc/A\\_R1UjoOb58G](https://prnt.sc/A_R1UjoOb58G).

**6 points in total:**

1 point for forming the enolate of **15**.

2 points for forming the Kobayashi reagent. [No penalty if concerted mechanism]

2 points for the addition to the benzyne. [No penalty if concerted [2+2] cycloaddition]

1 point for final ring expansion and protonation.

No penalty if the side products (i.e.  $\text{TMSF}$ ,  $\text{TfO}^-$ ) are not shown, though it is good practice to show them

-0.5 points if base used is not specified (e.g.  $\text{B}^-$ ) or wrong base is used (e.g. water instead of the fluoride ion),

-0.5 points for every general minor error in mechanism (e.g. missing H, missing charges),

-1 point for every general major error in mechanism (e.g. direction of arrow is wrong, expanded octet for period 2 elements)

Problem 3 16.7% of total	Question	3-1	3-2	3-3	3-4	3-5	3-6	3-7	Total
	Points	14	2	3	9	1	1	6	36

## Problem 3: Where inorganic meets organic

by Lim Dillion, Singapore

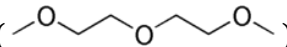
### Note:

Let  $\omega(\mathbf{W})$  refer to the percentage by mass of element **W**.

Compounds **A1** to **A6** below all contain element **X**.

Compounds **B1** to **B6** and **C1** to **C5** below all contain element **Y**.

Organic chemistry is usually associated with hydrocarbons and common heteroatoms like oxygen, sulfur and nitrogen. However, a very common method of making functionalized organic molecules involves another element, **X**.

**X**, in particular, forms compounds that are of great theoretical interest. Ternary compound **A1** (a very common reagent in organic chemistry,  $\omega(\mathbf{X}) = 28.6\%$ ) reacts with compound **A2** (which contains 5 types of elements,  $\omega(\mathbf{X}) = 7.61\%$ ) in diglyme () at 100°C to give a ternary compound **A3** ( $\omega(\mathbf{X}) = 51.1\%$ ). Compound **A2** exists in equilibrium with compound **A4** ( $\omega(\mathbf{X}) = 15.9\%$ ) and diethyl ether ( $\text{Et}_2\text{O}$ ).

Further heating of the solution for 36 hours under reflux gives compound **A5** as the main product ( $\omega(\mathbf{X}) = 69.075\%$ ). After separation of the side products, addition of CsOH precipitates ionic compound **A6** as the final product of theoretical interest.

- 3.1) Deduce compounds **A1** to **A6**, and element **X**. Show all working **clearly**, as points are awarded for your working and process of deduction.
- 3.2) Draw the 3-dimensional structure of the anion of **A6**.

An X-ray diffraction was conducted on compound **A6**, giving the following bond lengths:

Bond	Bond length / ppm
<b>X - X</b>	178
<b>X - Z</b> , where <b>Z</b> is the other element in the anion of <b>A6</b>	112

- 3.3) It is known that the 3-dimensional structure of the anion of **A6** is that of a regular solid. Find the surface area of the volume enclosed by the anion of **A6** based on the above data.

Metal **Y** is often found as the ionic compound **C1**, which forms metal **Y** upon prolonged heating under  $H_2$ , with two gaseous side products with molar masses 17 and 37  $g\ mol^{-1}$  (to the nearest whole number). Metal **Y** is then reacted with  $Cl_2$  at 300 - 400  $^{\circ}C$  to form compound **C2** ( $\omega(Y) = 64.38\%$ ).

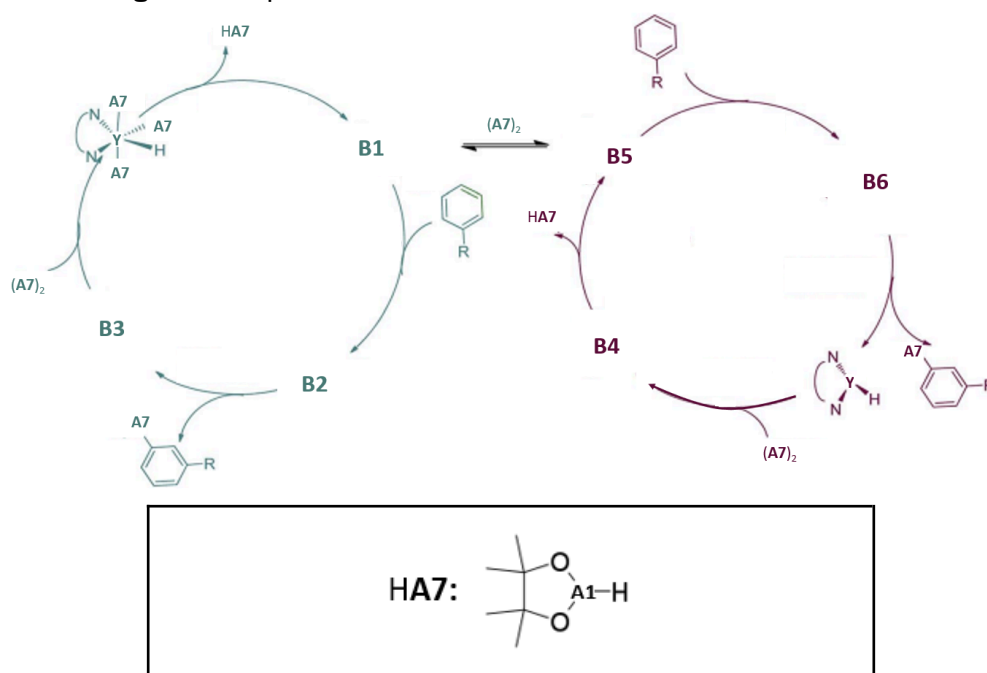
A famous compound of metal **Y** is *Vaska's complex*, **C3** ( $\omega(Y) = 24.6\%$ ). It can be prepared by the reaction of triphenylphosphine,  $PPh_3$ , and *hydrated* compound **C2** in dimethylformamide, DMF ( $Me_2NC(=O)H$ ) or 2-methoxyethanol ( $HOCH_2CH_2OCH_3$ ). Regardless of the choice of solvent, both DMF and 2-methoxyethanol decompose in the reaction to provide a ligand. Compound **C3** is known to bind to  $O_2$  reversibly, forming a di-oxygen ligand that binds side-on, forming compound **C4**. Compound **C3** also reacts with  $MeI$ , forming compound **C5**.

- 3.4) Deduce compounds **C1**, **C2**, and element **Y**. Draw compounds **C3** to **C5**. Show all working **clearly**, as points are awarded for your working and process of deduction.

Upon conducting infra-red spectroscopy on compound **C3**, a stretching mode was observed at  $1967\ cm^{-1}$ . Compound **C4** instead showed a shift at  $2015\ cm^{-1}$ , and compound **C5** at  $2047\ cm^{-1}$ .

- 3.5) Which bond gives rise to the stretching mode observed?  
 3.6) State the factor that affects the frequency of the stretching mode observed for compound **C4** and **C5**.

A complex containing metal **Y** is used as a catalyst for the insertion of groups containing element **X** into organic compounds. The mechanism of insertion is shown below:



- 3.7) Deduce compounds **B1** to **B6**.



### Problem 3: Solution

- 3.1) Deduce compounds **A1** to **A6**, and element **X**. Show all working **clearly**, as points are awarded for your working and process of deduction.

Notice that: Compound **A2** (which contains 5 types of elements,  $\omega(\mathbf{X}) = 7.61\%$ ) exists in equilibrium with compound **A4** ( $\omega(\mathbf{X}) = 15.9\%$ ) and diethyl ether ( $\text{Et}_2\text{O}$ ).

Notice that  $\text{Et}_2\text{O}$  has 3 elements (C, H, O). Hence, **A4** is likely binary. Hence, let **A2** be  $\mathbf{X}_a\mathbf{M}_b \cdot (\text{Et}_2\text{O})_c$ .

Let  $a = 1$ ,  $c = 1$ . (That is, **A4** is  $\mathbf{XM}_b$ .) Let  $x = A_r(\mathbf{X})$  and  $m = A_r(\mathbf{M})$ .

We can set up the following system of simultaneous equations:

$$\frac{x}{x + mb} = 0.159 \Rightarrow x = 0.18906mb$$

$$\frac{x}{x + mb + (4 \times 12 + 10 + 16)} = 0.0761 \Rightarrow x = 0.08237mb + 6.095$$

$$0.18906mb = 0.08237mb + 6.095 \Rightarrow m = \frac{57.128}{b}$$

Now, notice that we do not need to do guess and check on **X** (since  $mb$  is a constant).

We can compute  $mb = 57.128$ , that is,  $x = 10.801$ , corresponding to B (boron).

$b$	$m$	Identity of M
1	57.128	-
2	28.564	-
3	19.043	F
4	14.282	-
5	11.426	-
6	9.521	-

Hence, **M** is likely F (fluorine) and **X** is likely B (boron).

Hence, we can deduce that **A2** is  $\text{BF}_3 \cdot \text{Et}_2\text{O}$  and **A4** is  $\text{BF}_3$ .

It is also clear that **A1** is likely  $\text{NaBH}_4$ , verified by  $\omega(\mathbf{X}) = 28.6\%$ .

Now, we can guess that **A3** likely has Na, B and H as the elements based on the reaction between **A1** and **A2**, since  $\text{BF}_3 \cdot \text{Et}_2\text{O}$  is simply a source of  $\text{BF}_3$ . Hence, based on  $\omega(\mathbf{X}) = 51.1\%$ , we can conduct a guess and check to determine their coefficients. Assuming that **A3** is  $\text{Na}[\text{B}_x\text{H}_y]$ , we can come up with the following equation:

$$\frac{10.8x}{23.0 + 10.8x + y} = 0.511 \Rightarrow x = 0.09675831y + 2.22544118$$

<b>y</b>	<b>x</b>	<b>Integer?</b>
1	2.322	No
2	2.419	No
3	2.516	No
4	2.612	No
5	2.709	No
6	2.806	No
7	2.903	No
8	3.000	Yes
9	3.096	No

Hence, it is likely that **x** = 3, **y** = 8. That is, **A3** is Na[B<sub>3</sub>H<sub>8</sub>].

**A5** is likely consisting of the same elements. Hence, based on  $\omega(\mathbf{X}) = 69.1\%$ , we can conduct a guess and check to determine their coefficients. Assuming that **A3** is Na[B<sub>x</sub>H<sub>y</sub>], we can come up with the following equation:

$$\frac{10.8x}{23.0 + 10.8x + y} = 0.691 \Rightarrow x = 0.20705981y + 4.78308162$$

<b>y</b>	<b>x</b>	<b>Integer?</b>
1	4.984	Maybe
2	5.191	No
3	5.398	No
4	5.605	No
5	5.812	No
6	6.018	Maybe
7	6.233	No

However, the compound being NaBH is fairly ridiculous, thus it is likely that the empirical formula is NaB<sub>6</sub>H<sub>6</sub>, hence the molecular formula Na<sub>2</sub>[B<sub>12</sub>H<sub>12</sub>], containing the famous [B<sub>12</sub>H<sub>12</sub>]<sup>2-</sup> anion. Hence, **A5** is Na<sub>2</sub>[B<sub>12</sub>H<sub>12</sub>].

Adding CsOH simply yields a double displacement reaction. Therefore, **A6** is Cs<sub>2</sub>[B<sub>12</sub>H<sub>12</sub>].

Summary of answers:

<b>X</b>	B (boron)	<b>A4</b>	$\text{BF}_3$
<b>A1</b>	$\text{NaBH}_4$	<b>A5</b>	$\text{Na}_2[\text{B}_{12}\text{H}_{12}]$
<b>A2</b>	$\text{BF}_3 \cdot \text{Et}_2\text{O} / \text{BF}_3 \cdot (\text{C}_2\text{H}_5)_2\text{O}$	<b>A6</b>	$\text{Cs}_2[\text{B}_{12}\text{H}_{12}]$
<b>A3</b>	$\text{Na}[\text{B}_3\text{H}_8]$		

**1 point for each correct compound from X, A1 to A6. (Total 7 points)**

**2 points for showing work of deducing  $\text{BF}_3 \cdot \text{Et}_2\text{O}$ .**

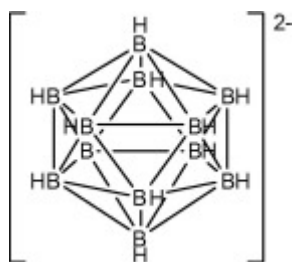
**1 point for showing work of deducing  $\text{Na}[\text{B}_3\text{H}_8]$ .**

**2 points for showing work of deducing  $\text{Na}_2[\text{B}_{12}\text{H}_{12}]$  (including rationale of rejecting  $\text{NaBH}$ , and deducing  $\text{B}_{12}\text{H}_{12}^{2-}$  instead of  $\text{B}_6\text{H}_6^-$ ).**

**1 point for showing work of deducing  $\text{NaBH}_4$ .**

**1 point for indicating double displacement leading to A6.**

3.2) Draw the 3-dimensional structure of the anion of **A6**.



**0.5 points for correct charge.**

**0.5 points for having 12 BH vertices.**

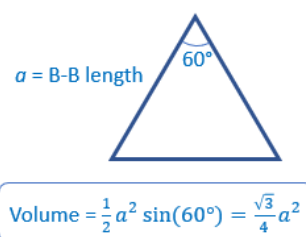
**0.5 points for having 30 B - B edges.**

**0.5 points for correct overall structure.**

- 3.3) It is known that the 3-dimensional structure of the anion of **A6** is that of a regular solid. Find the surface area of the volume enclosed by the anion of **A6** based on the above data.

First, notice that the 3-dimensional structure of the anion is an icosahedron. Since the icosahedron has 20 faces, then the total surface area =  $20 \times (\text{area of a face})$ .

Now, since the face of the icosahedron is an equilateral triangle, the area of a face =  $0.5a^2 \sin(60^\circ)$ , where  $a$  is the length of an edge.



Hence, the total surface area =  $20 \times (\sqrt{3} / 4) \times 178^2 = 2.74 \times 10^5 \text{ pm}^2$ .

**1 point for correct deduction of there being 20 faces.**

**1 point for correct deduction of the area of a face.**

**1 point for correct final answer.**

- 3.4) Deduce compounds **C1**, **C2**, and element **Y**. Draw compounds **C3** to **C5**. Show all working **clearly**, as points are awarded for your working and process of deduction.

The easiest way to approach this problem is the following statement:

Metal **Y** is then reacted with  $\text{Cl}_2$  at  $300 - 400^\circ\text{C}$  to form compound **C2** ( $\omega(\text{Y}) = 64.38\%$ ).

Compound **C2** is clearly a binary chloride. Let compound **C2** be  $\text{YCl}_x$ . Let  $y = A_r(\text{Y})$ .

Then we can obtain the following equation:

$$\frac{y}{y + 35.5x} = 0.6438 \Rightarrow y = 64.16311061x$$

Then we can conduct guess-and-check based on the above equation:

$x$	$y$	Identity of Y
1	64.163	-
2	128.326	-
3	192.489	Ir
4	256.652	-

Hence, **C2** is likely  $\text{IrCl}_3$ . So **Y** is Ir (iridium).

Now, from the statement: with two gaseous side products with molar masses 17 and  $37 \text{ g mol}^{-1}$ , we can deduce that the side products are  $\text{NH}_3$  and  $\text{HCl}$ .

It is therefore clear that **C1** should be ammonium hexachloroiridate,  $(\text{NH}_4)_2[\text{IrCl}_6]$ , similar in form to ammonium hexachloroplatinate.

For your information: It decomposes as follows:  $(\text{NH}_4)_2[\text{IrCl}_6] + 2 \text{H}_2 \rightarrow \text{Ir} + 6 \text{HCl} + 2 \text{NH}_3$ .

Now, consider the following statement:

This yellow compound can be prepared by the reaction of triphenylphosphine,  $\text{PPh}_3$ , and hydrated compound **C2** in dimethylformamide (DMF), together with aniline.

Hence, compound **C3** is formed from the reaction of  $\text{IrCl}_3(\text{H}_2\text{O})_3$ , DMF or 2-methoxyethanol. It is clear from the choice of both solvents that the likely ligand inserted is carbon monoxide (CO), and other ligands are  $\text{PPh}_3$  and Cl. Since one of the ligands are clearly repeated for a square planar / tetrahedral complex, and multiple ligands repeated for an octahedral complex, let us consider the possible permutations:

For the easier case of 4 ligands:

Repeated Ligand	$\omega(\text{Y})$
CO	37.3%
$\text{PPh}_3$	24.6%
Cl	36.8%

It is hence clear that  $\text{PPh}_3$  is the repeated ligand, and there is hence no need to consider the case of 6 ligands. Nevertheless, doing so will yield no change in result.

Hence, **C3** is  $\text{IrCl}(\text{CO})(\text{PPh}_3)_2$ . The complex is drawn out below, in *summary of answers*. **C4** and **C5** are simply where  $\text{O}_2$  and MeI add as ligands respectively.

Summary of answers:

<b>Y</b>	Ir (iridium)	<b>C3</b>	
<b>C1</b>	$(\text{NH}_4)_2[\text{IrCl}_6]$	<b>C4</b>	
<b>C2</b>	$\text{IrCl}_3$	<b>C5</b>	

**1 point for each correct compound from Y, C1 to A5. (Total 6 points)**

**1 point for showing work of deducing  $\text{IrCl}_3$ .**

**1 point for using the molar masses of gases to deduce the gases itself, and C1.**

**1 point for showing work of deducing C3 by using mass data.**

3.5) Which bond gives rise to the stretching mode observed?

$\text{C}\equiv\text{O}$  triple bond

1 point for the correct bond indicated.

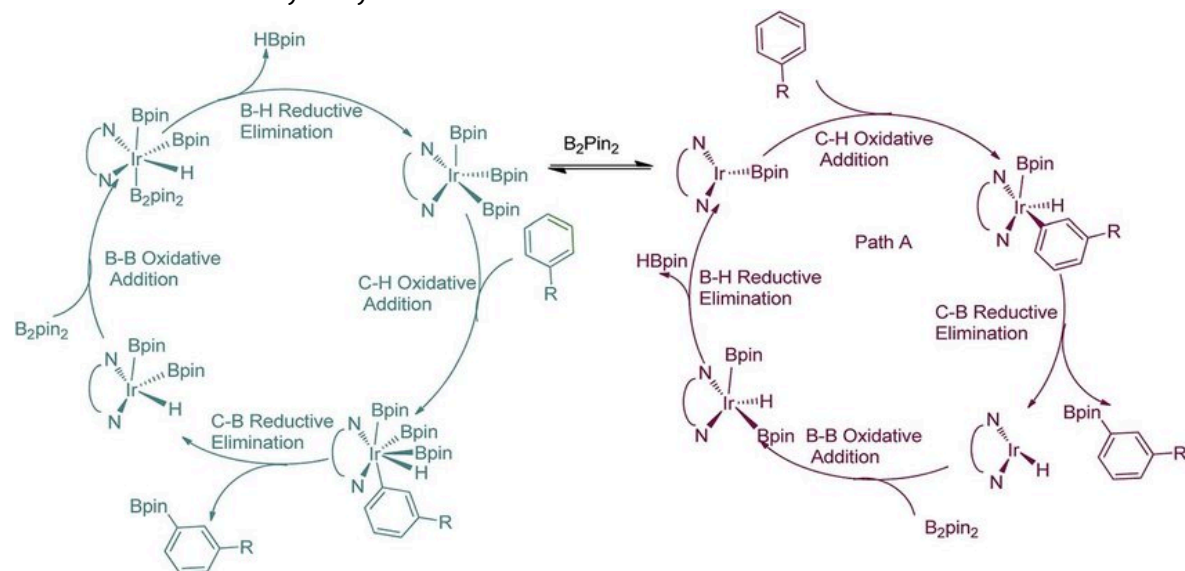
3.6) State the factor that affects the frequency of the stretching mode observed for compound **C4** and **C5**.

The amount of  $\pi$ -back bonding allowed by the newly associated ligands.

1 point for the correct factor indicated.

3.7) Deduce compounds **B1** to **B6**.

Simply go around the whole catalytic cycle, and deduce the compounds accordingly. See the filled in catalytic cycle below for answers:



1 point for each correct compound drawn. (Total 6 points)

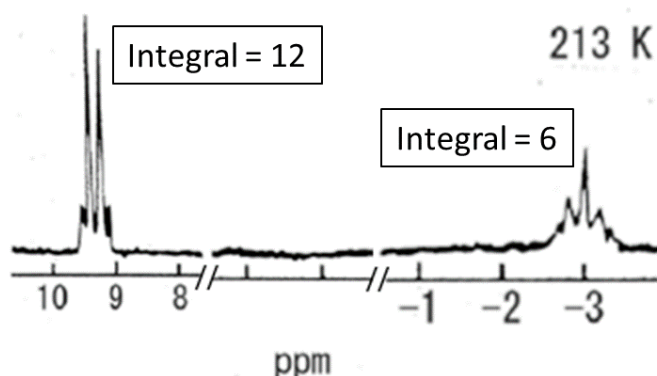
Problem 4 16.7% of total	Question	4-1	4-2	4-3	4-4	4-5	4-6	Total
	Points	6	1	6	7	2	2	24

## Problem 4: "So, my NMR looks a little funny..." 🙄

by Lim Dillion, Singapore

In nuclear magnetic resonance (NMR) spectroscopy, a common reference for  $\delta = 0.00$  ppm is tetramethylsilane. This usually yields NMR spectra with peaks all being in the positive region. Occasionally, however, some peaks may be found in the negative region.

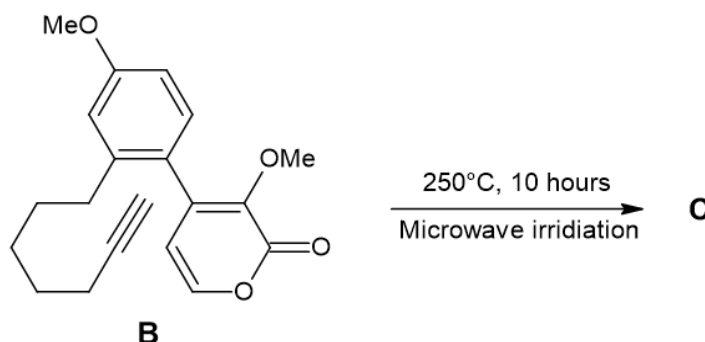
A very common example of this is compound **A**. Compound **A** has its  $[M+]$  peak at  $m/z = 234$ , and the  $[M+1]$  peak has a relative intensity of 20% compared to the  $[M+]$  peak. Compound **A** also exhibits 2 peaks in its  $^1\text{H}$  NMR at 213K, as shown below:



- 4.1) Deduce the structure of compound **A**. Explain your answer fully using relevant spectroscopic data.
- 4.2) Explain why the protons responsible for the peak with the negative NMR shift in the spectrum above have this unconventional value.
- 4.3) At 110°C, however, the two peaks in the NMR spectrum above coalesce to a singlet peak at  $\delta = 5.45$  ppm. Explain this result.

Another more interesting example of this phenomenon is compound **C**.

Compound **C** is synthesized from compound **B**. The reaction scheme is shown below:



Mass spectroscopy of **C** yielded the molecular ion peak at  $m/z = 282$ . The ratio of intensity of peaks at  $m/z = 282$  and  $283$  is  $52 : 10.9$ . The  $^1\text{H}$  NMR spectrum of **C** is also summarised below:

$\delta / \text{ppm}$	Integral	Multiplicity
-0.5	2	Quintet
0.9	2	Quintet
1.2	2	Quintet
2.1	2	Triplet
2.3	2	Triplet
3.7	3	Singlet
3.8	3	Singlet
6.9 - 7.5	6	Multiplet

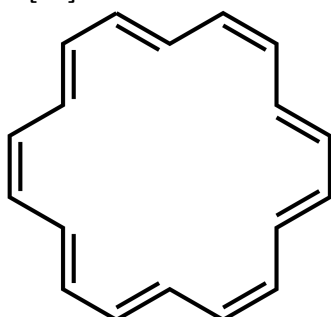
- 4.4) Deduce the structure of **C**. Explain your answer fully using relevant spectroscopic data. Using your structure, briefly explain whether **C** is optically active.
- 4.5) Propose a mechanism for the conversion of **B** to **C**.
- 4.6) Using your answer in 4.5, give **two** reasons why the reaction proceeds largely to completion.



## Problem 4: Solution

- 4.1) Deduce the structure of compound **A**. Explain your answer fully using relevant spectroscopic data.

**A:** [18]annulene



### Explanation:

From the mass spectrometry, we can obtain the approximate number of carbon atoms in the molecule, based on the abundance of  $^{12}\text{C}$  :  $^{13}\text{C}$ , which is approximately 100 : 1.1.

Number of carbon atoms =  $(100/1.1) \times 0.20 = 18.18$  (i.e. about 18 carbon atoms).

We also know the molecular ion peak is at  $m/z = 234$ . From this, we can determine whether heteroatoms exist in the molecule, since the NMR shows 18, or a multiple of 18 hydrogens.

Similarly, we can also determine if the number of carbon atoms is indeed 18, or the neighbouring numbers.

Assuming no heteroatoms, the number of supposed hydrogens =  $234 - 18 \times 12 = 18$ .

Clearly, **A** has molecular formula  $\text{C}_{18}\text{H}_{18}$ , because any heteroatoms would yield a negative double bond equivalent.

Double bond equivalent (DBE) =  $18 + 1 - 18/2 = 10$ .

Now, notice from the NMR spectrum that the splitting is very complicated, but has very high integrals. This indicates that the molecule is very symmetrical.

$\delta$ / ppm	Integral	Deductions
-3.0	6	Highly shielded, likely due to anisotropic effect, so this is found in an aromatic ring system. Six equivalent protons.
9.2	12	Highly deshielded, protons are also found in the aromatic ring system. Twelve equivalent protons.

Judging by the high double bond equivalent, it is likely that the 6 protons are found within the ring, while the 12 protons are found outside the ring.

With this information, we can deduce that **A** is likely [18]annulene.

**2 points for correct structure of A.**

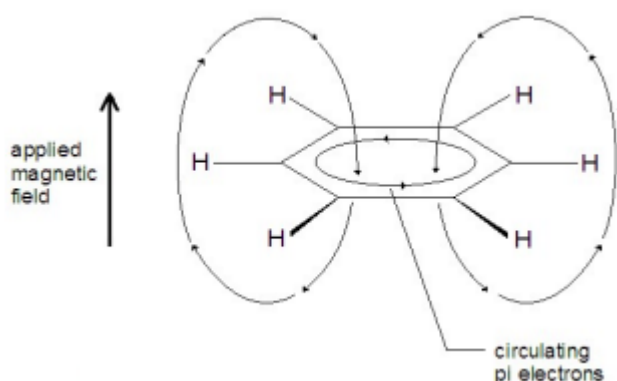
**1 point for correct deduction of number of carbon atoms using mass spectrometry data.**

**1 point for correct deduction of chemical formula using molecular ion peak mass.**

**1 point for correct deduction of the molecule being highly symmetrical based on the high integrals.**

**1 point for correct deduction of the fact that the protons are subject to an immense anisotropic effect, hence likely being an aromatic compound.**

- 4.2) Explain why the protons responsible for the peak with the negative NMR shift in the spectrum above have this unconventional value.



The diagram above is for benzene, but the same idea applies for [18]annulene.

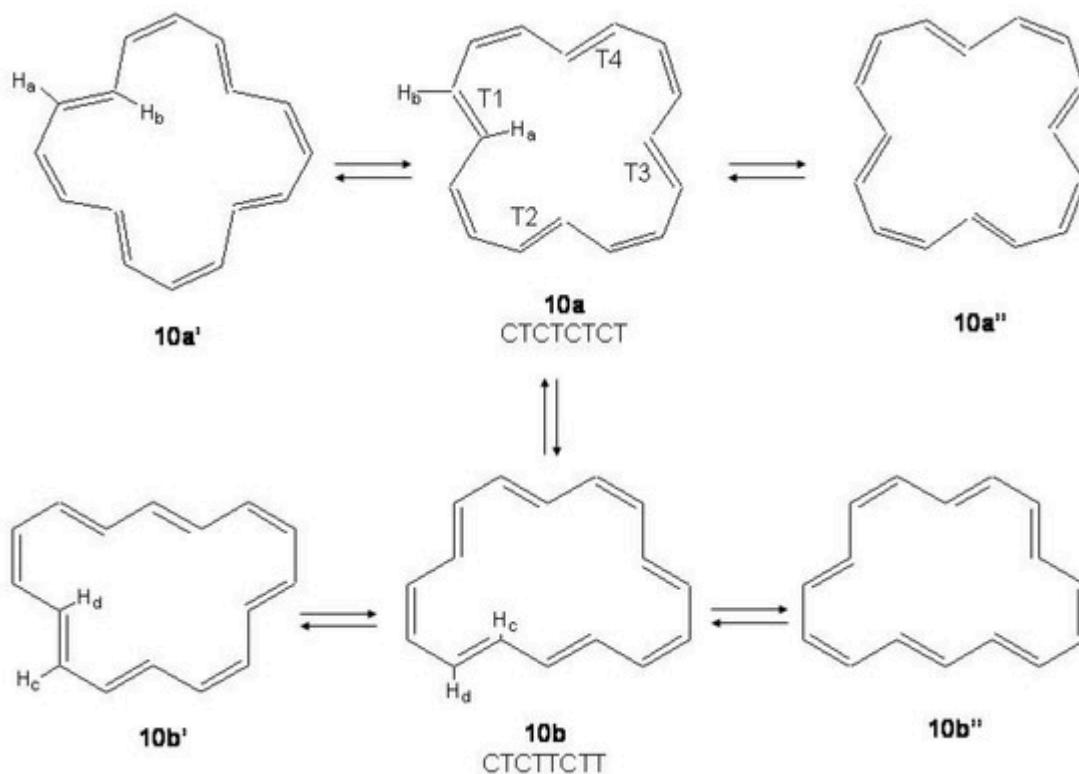
When a magnetic field is applied, the circulating  $\pi$  electrons of **A** generate a secondary magnetic field. The protons are located near the centre of the ring of **A** where the secondary magnetic field opposes the applied field. The protons experience a lower magnetic field hence greater shielding and thus have a negative chemical shift.

**1 point for correct explanation along the lines of anisotropy.**

- 4.3) At 110°C, however, the two peaks in the NMR spectrum above coalesce to a singlet peak at  $\delta = 5.45$  ppm. Explain this result.

A single signal at 5.45 ppm (the weighted average of the two individual signals) is observed at 120 °C. This is due to the rapid exchange of the exterior and interior hydrogens at that temperature due to the ring not being rigid.

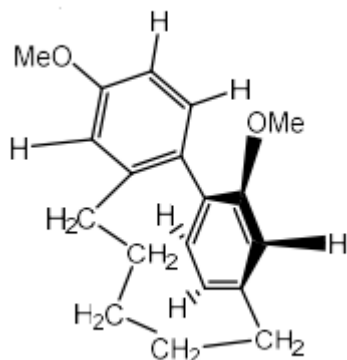
The diagram below is for [16]annulene, but the process of hydrogen exchange is similar for [18]annulene:



**1 point for correct explanation of bond flipping / hydrogen exchange due to it.**

- 4.4) Deduce the structure of **C**. Explain your answer fully using relevant spectroscopic data. Using your structure, briefly explain whether **C** is optically active.

**C:** A cyclophane



**Explanation:**

From the mass spectrometry, we can obtain the approximate number of carbon atoms in the molecule, based on the abundance of  $^{12}\text{C} : ^{13}\text{C}$ , which is approximately 100 : 1.1.  
 Number of carbon atoms =  $(100/1.1) \times (10.9/52) = 19.06$  (i.e. about 19 carbon atoms).

We also know the molecular ion peak is at  $m/z = 282$ . From counting the hydrogens in the  $^1\text{H}$  NMR, we can determine that there are 22 hydrogens, or a multiple of 22.

There must be 22 hydrogens because otherwise, **C** will have a negative DBE. Hence, the remaining molar mass must come from heteroatoms. The molar mass corresponds nicely to 2 oxygen atoms.

Hence, **C** has the molecular formula  $\text{C}_{19}\text{H}_{22}\text{O}_2$ .

Double bond equivalent =  $19 + 1 - 22/2 = 9$ .

$\delta$ / ppm	Integral	Multiplicity	Deductions
-0.5	2	Quintet	Highly shielded, likely to be $\text{CH}_2$ found in the ring current of a benzene ring, 2 $\text{CH}_2$ neighbours
0.9	2	Quintet	Likely to be $\text{CH}_2$ found away from the ring current, but far away from any aromatic ring as well, 2 $\text{CH}_2$ neighbours
1.2	2	Quintet	$\text{CH}_2$ with 2 $\text{CH}_2$ neighbours
2.1	2	Triplet	$\text{CH}_2$ with only 1 $\text{CH}_2$ neighbour
2.3	2	Triplet	

3.7	3	Singlet	Proton next to highly electronegative atom, likely OCH <sub>3</sub> group
3.8	3	Singlet	
6.9 - 7.5	6	Multiplet	Phenyl protons

From this, we can determine that the phenyl rings are trisubstituted, and since there are 2 -OCH<sub>3</sub> groups, **C** is also likely a very symmetrical molecule.

Since each phenyl ring contributes 4 DBE, there is either a double bond or a ring. Since there is no long-range coupling in the above NMR, it is likely to be a ring. Therefore, it is likely to be a bridged compound, **C** above.

**C** is likely to be optically active due to the phenyl rings providing considerable steric strain. They are hence likely to be perpendicular to each other, giving rise to axial chirality.

**1 point for correct structure of C.**

**1 point for correct deduction of number of carbon atoms using mass spectrometry data.**

**1 point for correct deduction of chemical formula using molecular ion peak mass and <sup>1</sup>H NMR data.**

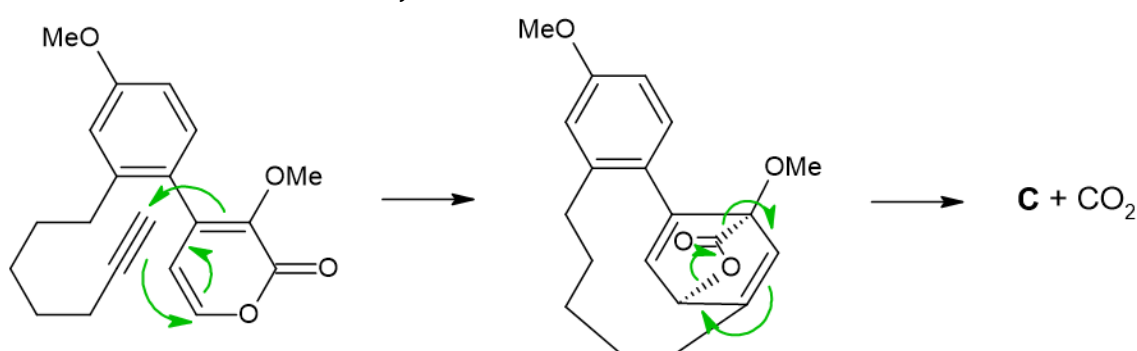
**1 point for correct deduction of substitution of C.**

**1 point for correct deduction of existence of bridge structure.**

**1 point for correct deduction of optical activity based on steric considerations.**

4.5) Propose a mechanism for the conversion of **B** to **C**.

Diels-Alder Reaction followed by Retro-Diels-Alder



**1 point for correct Diels-Alder reaction.**

**1 point for correct retro-Diels-Alder reaction.**

4.6) Using your answer in 4.5, give **two** reasons why the reaction proceeds largely to completion.

1. The expulsion of  $\text{CO}_2$  is a driving force in the reaction because the position of equilibrium of the second reaction lies very far to the right since  $\text{CO}_2$  is continuously removed from the system.
2. There is a formation of an aromatic ring in **C**, hence the product is more stable.
3. The bridgehead alkene in the intermediate is very unstable due to poor orbital overlap (see Bredt's Rule).

**1 point for any correct explanation from the above. (Total 2 points)**

Problem 5 16.7% of total	Question	5-1	5-2	5-3	5-4	5-5	5-6	5-7	5-8	Total
	Points	2	2	5	3	5	1	2	6	26

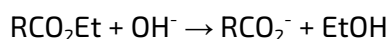
## Problem 5: Ester Hydrolysis

by Lim Dillion, Singapore

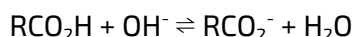
Ester hydrolysis is a widely studied mechanism, both by students and researchers alike. In this problem, we will examine the hydrolysis of esters.

When researchers examine reaction mechanisms, they frequently dabble in a field known as physical organic chemistry. In 1937, the chemistry Louis Plack Hammett observed that there existed a linear relationship between:

- the **rate** of base catalysed hydrolysis of a group of ethyl esters to form a series of carboxylic acids:



- the **equilibrium** position of the ionisation in water of the corresponding group of acids:



In simpler terms, he found that the rate of reaction,  $k_x$ , can be related to the equilibrium constant,  $K_x$  for the para- and meta-substituted benzoic acids:

$$\log k_x = \rho \log K_x + C$$

- By considering the reaction of the base case ( $R = \text{Ph}$ ), show that the equation above can be written in the form:

$$\log \left( \frac{k}{k_H} \right) = \rho \cdot \sigma$$

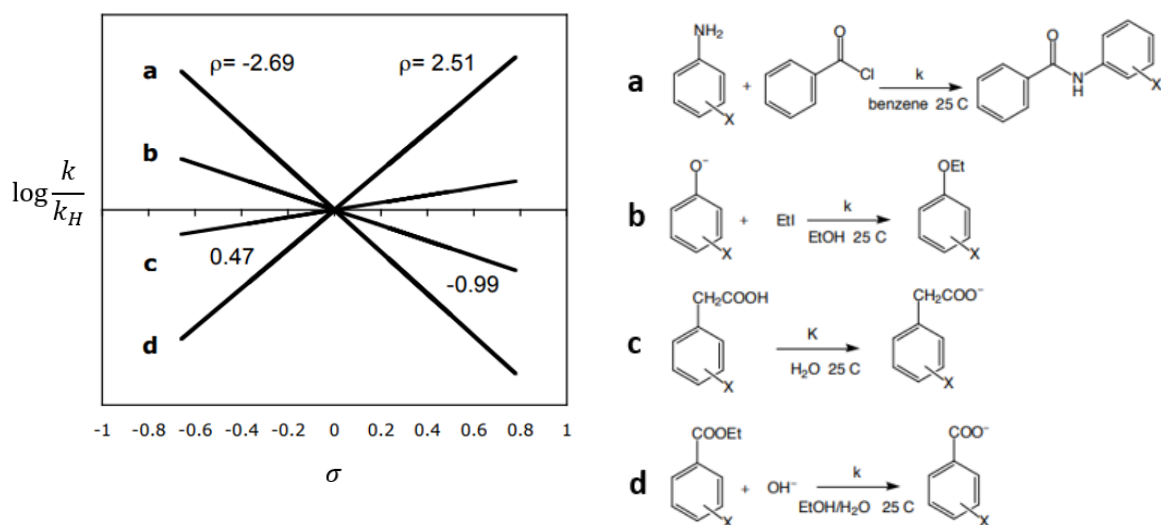
where  $k_H$  is the rate of reaction of the base case above. State **clearly** what  $\sigma$  represents mathematically.

The values of  $\sigma$  are given for some substituents below:

Substituent	- NO <sub>2</sub>	- CN	- Br	- F	- OH	- Me	- CMe <sub>3</sub>
$\sigma_{\text{meta}}$	+ 0.71	+ 0.56	+ 0.39	+ 0.34	+ 0.12	- 0.07	- 0.10
$\sigma_{\text{para}}$	+ 0.78	+ 0.66	+ 0.23	+ 0.06	- 0.37	- 0.17	- 0.20

- Explain why an -OH substituent exhibits a positive value of  $\sigma_{\text{meta}}$ , but negative value of  $\sigma_{\text{para}}$ .

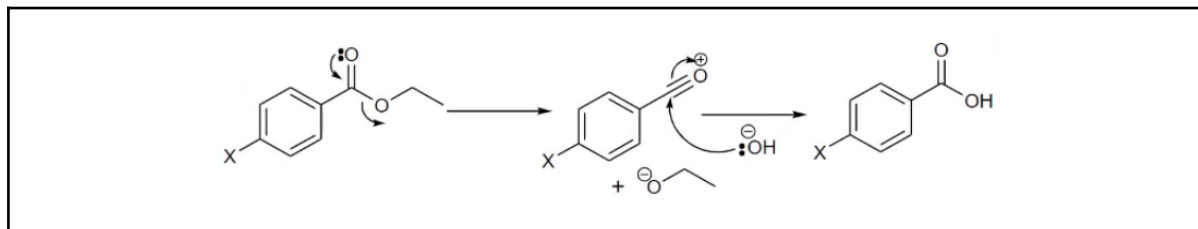
Hammett also found that many other reactions also showed straight-line correlations of their rate or equilibrium behaviour for a series of substituents with the equilibrium behaviour of benzoic acid. Some of these reactions are shown below:



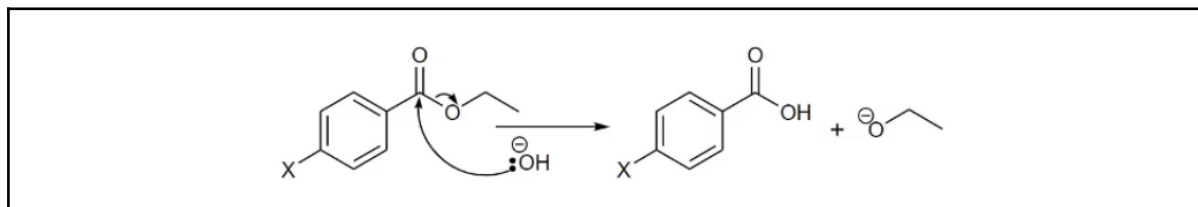
- 5.3) Based on the values of  $\rho$  given in the graphs above, explain what the physical significance of  $\rho$  is. Include in your answer **clearly**, what values of  $\rho < 0$ ,  $0 < \rho < 1$  and  $\rho > 1$  indicate about charge building up during the reaction.

For the base-catalysed hydrolysis of aryl ethyl esters (i.e. case **d** above), there are three commonly proposed mechanisms, illustrated below:

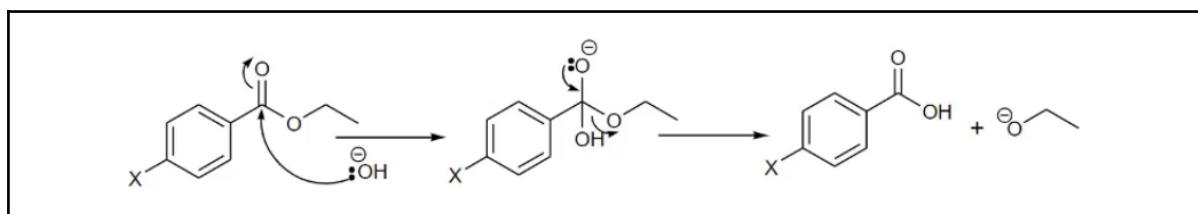
#### Postulated mechanism A



#### Postulated mechanism B



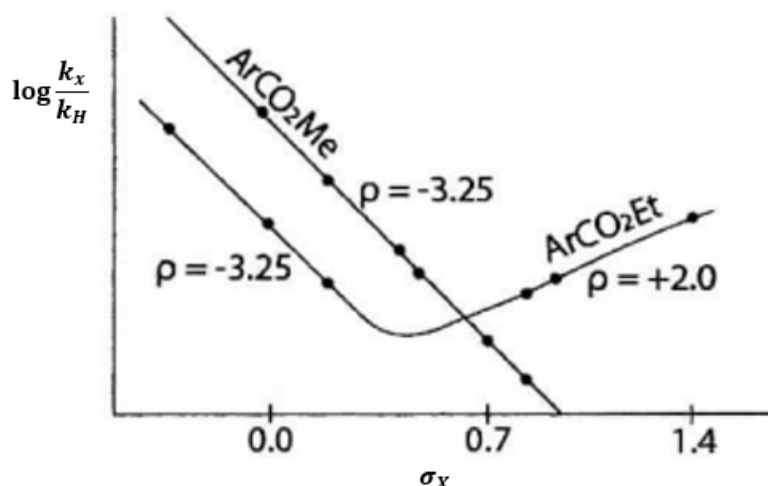
#### Postulated mechanism C





- 5.4) Explain **clearly**, with justification from the data above, which mechanism is most likely to be correct.

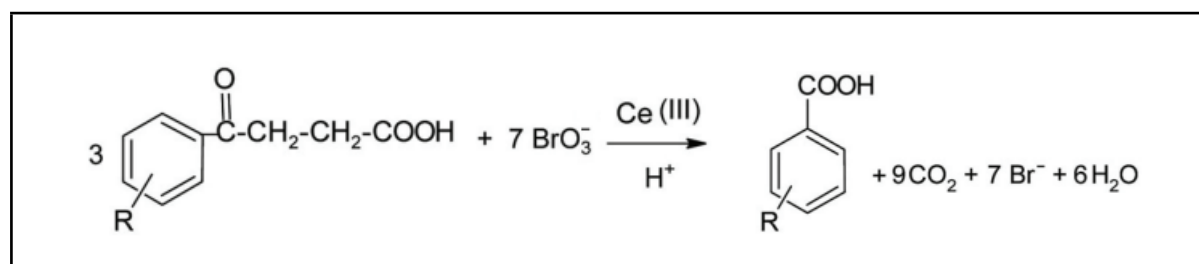
Hammett plots, as seen above, are generally linear. However, the most informative Hammett plots are those which are non-linear. We shall now examine some of these Hammett plots.



The above Hammett plot illustrates the acid-catalysed hydrolysis of aryl methyl esters and aryl ethyl esters. Aryl methyl esters exhibit an expected

- 5.5) By considering the significance of the sign of  $\rho$ , account for the change in the sign of  $\rho$  for different substituents when the aryl ethyl ester was hydrolysed. Include any relevant hydrolysis mechanisms.

An interesting use of this was in a research conducted by Babu, Manjari & Reddy in 2021. They examined the effect of changing substituents on the following reaction in order to propose the reaction mechanism of the oxidation of 4-oxoacids by bromate:

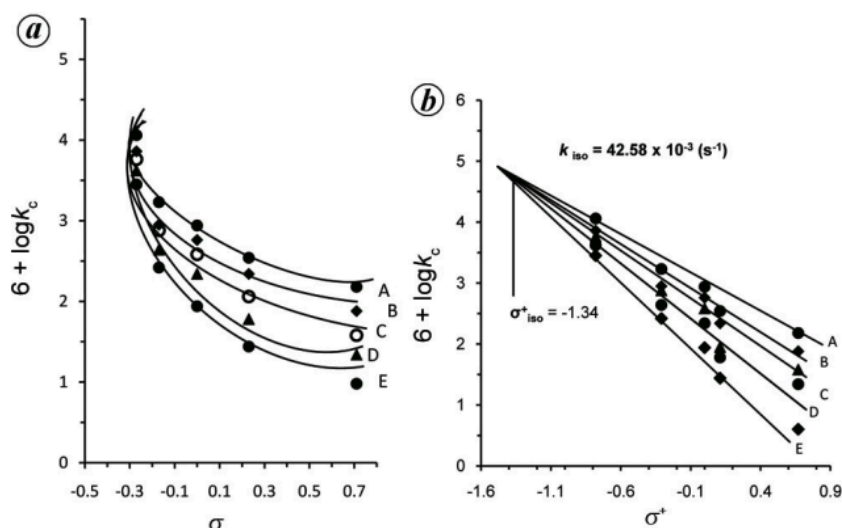


The researchers conducted an experiment examining the solvent isotope effect, done by conducting the reaction in H<sub>2</sub>O and D<sub>2</sub>O separately. The results of the experiment are as follows:

4-oxoacid substituent	$10^4 \times k \text{ (H}_2\text{O) (s}^{-1}\text{)}$	$10^4 \times k \text{ (D}_2\text{O) (s}^{-1}\text{)}$
-H	3.83	8.41
<i>p</i> -methyl	7.67	16.67
<i>p</i> -chloro	0.79	1.75
<i>m</i> -nitro	0.38	0.84

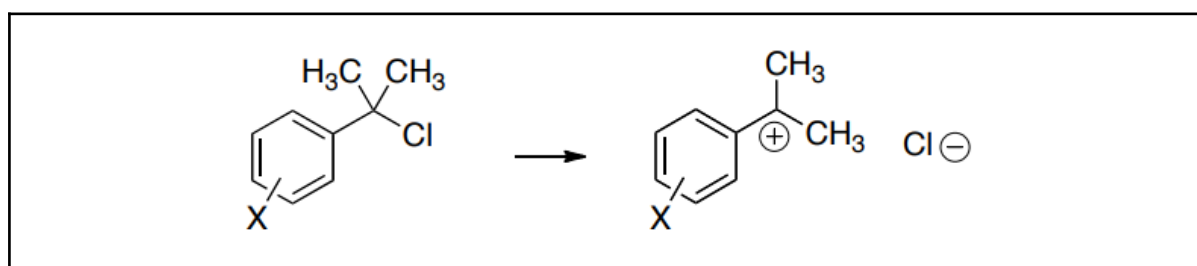
5.6) What can you say about the mechanism through which the oxidation occurs based on the data above?

Next, Hammett plots were plotted for the various substituents in order to further elucidate the reaction mechanism.



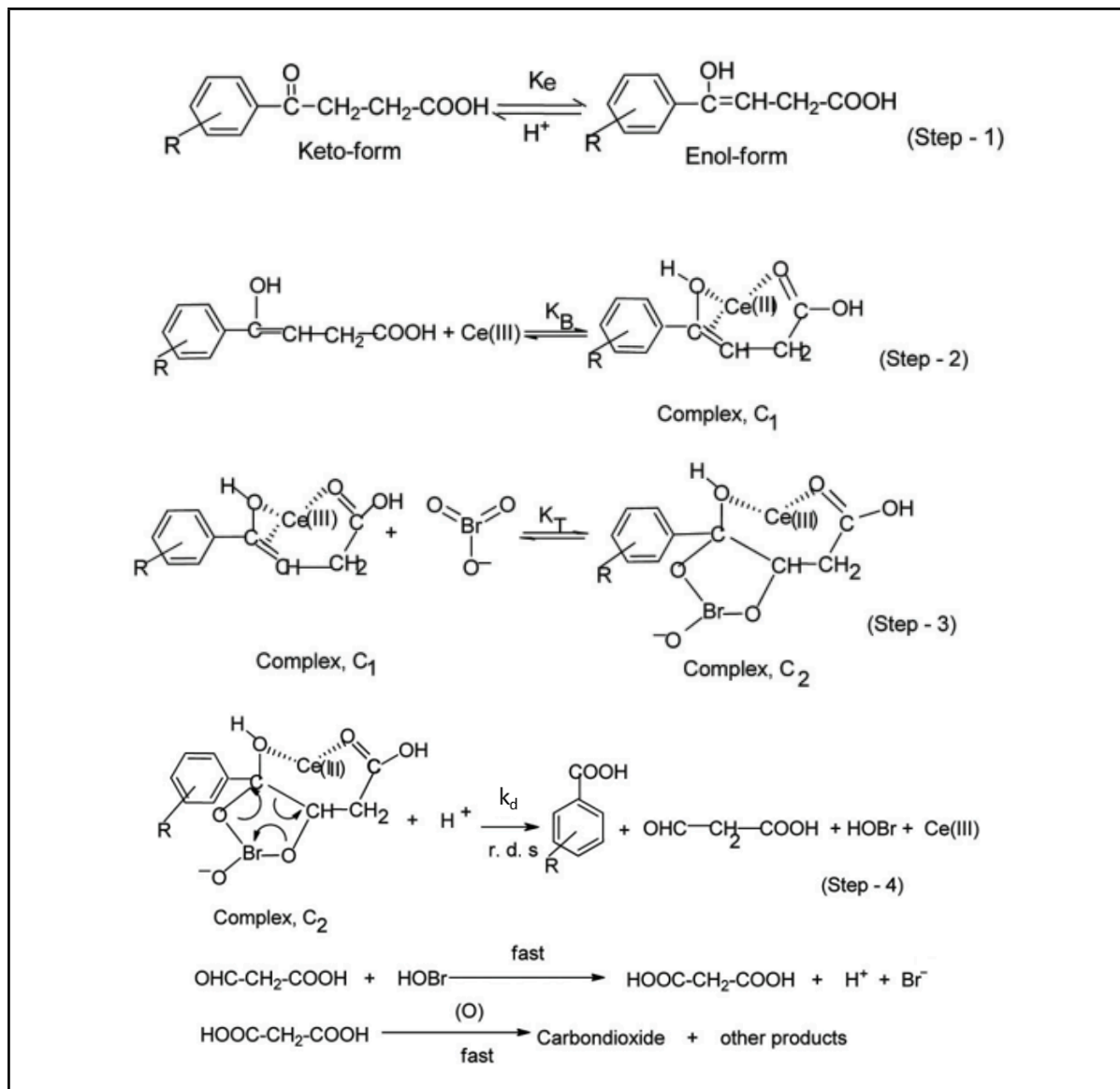
Hammett plots between (a)  $\log k_c$  and  $\sigma$  (b)  $\log k_c$  and  $\sigma^+$  at different temperatures. (A) 323 K, (B) 318 K, (C) 313 K, (D) 308 K and (E) 303 K in both (a) and (b).

The Hammett plot failed to show a good fit, but the modified Hammett plot, based on the following reaction as the reference reaction yields a better fit:



- 5.7) Suggest a reason why the normal Hammett plot fails to show linearity. What does this indicate about the nature of the transition state of this reaction?

Based on the above, the following mechanism was proposed:



- 5.8) Given that the total bromate concentration can be written as  $[\text{Br}]_0$ , deduce the rate law of the equation in terms of  $[\text{Br}]_0$ , [4-oxoacid],  $[\text{Ce(III)}]$ ,  $[\text{H}^+]$  and any relevant rate and equilibrium constants.



## Problem 5: Solution

- 5.1) By considering the reaction of the base case ( $R = \text{Ph}$ ), show that the equation above can be written in the form:

$$\log\left(\frac{k}{k_H}\right) = \rho \cdot \sigma$$

where  $k_H$  is the rate of reaction of the base case above. State **clearly** what  $\sigma$  represents mathematically.

Consider the following equations:

$$\log k_X = \rho \log K_X + C$$

$$\log k_H = \rho \log K_H + C$$

Subtracting the first from the second yields:

$$\log \frac{k_X}{k_H} = \rho \log \frac{K_X}{K_H}$$

The above can be written as  $\log\left(\frac{k}{k_H}\right) = \rho \cdot \sigma$ , where  $\sigma = \log \frac{K_X}{K_H}$ .

**1 point for correctly subtracting one from the other and using the law of logarithms to simplify.**

**1 point for a correct statement of what  $\sigma$  represents mathematically.**

- 5.2) Explain why an -OH substituent exhibits a positive value of  $\sigma_{\text{meta}}$ , but negative value of  $\sigma_{\text{para}}$ .

-OH substituents withdraw electron density from the phenyl ring when in the meta position by inductive effects, which stabilises the negative charge on the carboxylate oxygen atom by an electron-withdrawing inductive effect.

However, in the para position, it donates electron density via resonance / mesomeric effects, which will destabilise the negative charge on the carboxylate oxygen atom.

**1 point for explaining the sign on the meta position due to inductive effects.**

**1 point for explaining the sign on the para position due to mesomeric effects.**

- 5.3) Based on the values of  $\rho$  given in the graphs above, explain what the physical significance of  $\rho$  is. Include in your answer **clearly**, what values of  $\rho < 0$ ,  $0 < \rho < 1$  and  $\rho > 1$  indicate about charge building up during the reaction.

$\rho$  indicates how susceptible a reaction is to the electronic characteristics of the substituent, relative to benzoic acid.

$\rho < 0$	Negative $\rho$ is diagnostic of the <b>development of positive charge</b> at the reaction centre in the transition state of the rate-limiting step. The rate will be suppressed by electron-withdrawing substituents.
$\rho > 0$	Positive $\rho$ is diagnostic of the <b>development of negative charge</b> at the reaction centre in the transition state of the rate-limiting step. The rate will be accelerated by electron-withdrawing substituents.

$0 < \rho < 1$	The reaction is less sensitive to substituents than benzoic acid and negative charge is built.
$\rho > 1$	The reaction is more sensitive to substituents than benzoic acid and negative charge is built during the reaction.

**1 point for explaining significance of  $\rho$  as being the susceptibility of a reaction to electronic characteristics, or something to the extent of that.**

**2 points for explaining the development of opposite charges at the reaction center corresponding to the different signs of  $\rho$ .**

**2 points for explaining the sensitivity of reaction to substitutes for different magnitudes.**

- 5.4) Explain **clearly**, with justification from the data above, which mechanism is most likely to be correct.

Since  $\rho = 2.51$  for the reaction, significant negative charge is built up during the reaction. This corresponds to **postulated mechanism C**, because a localised negative charge is formed in the tetrahedral intermediate.

**1 point for citing the  $\rho$  value, or the significance of the  $\rho$  value.**

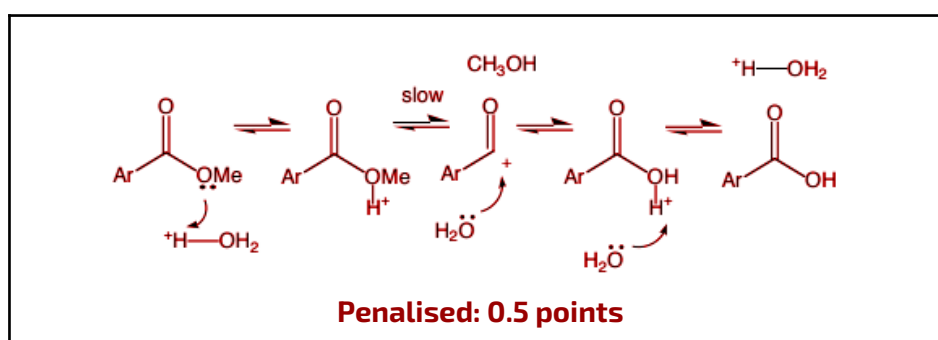
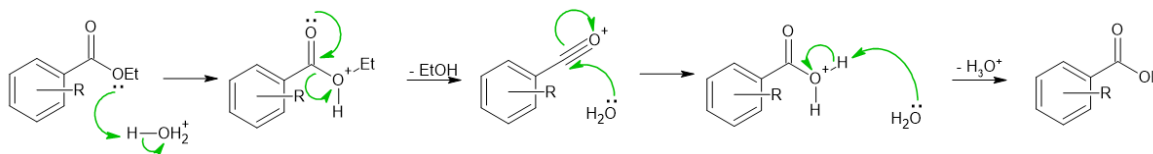
**1 point for correctly stating mechanism C.**

**1 point for explanation that a localised negative charge is formed. [0.5 points if merely a negative charge is formed is stated].**

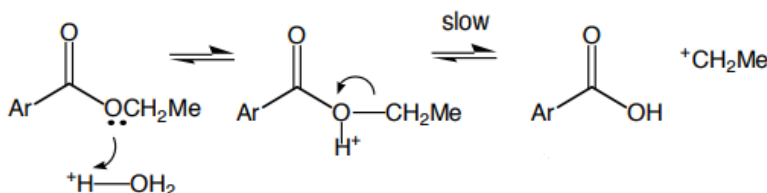
- 5.5) By considering the significance of the sign of  $\rho$ , account for the change in the sign of  $\rho$  for different substituents when the aryl ethyl ester was hydrolysed. Include any relevant hydrolysis mechanisms.

There is a change in the mechanism of hydrolysis.

For low values of  $\sigma$ , both the Me and Et esters pass through the following mechanism, where a positive charge is built up at the reaction centre during the rate-limiting step.



However, for high values of  $\sigma$ , the Et ester passes through the following mechanism, where the positive charge at the reaction centre is decreased during the rate-limiting step.



**1 point for stating change in mechanism of hydrolysis.**

**1 point for correctly stating the build-up of positive charge for low values of  $\sigma$ .**

**1 point for correct mechanism of hydrolysis through acylium intermediate. [0.5 points if the mechanism in red is shown instead, without the acylium intermediate]**

**1 point for correctly stating that positive charge at the reaction centre is decreased for low values of  $\sigma$ .**

**1 point for the correct mechanism of hydrolysis through the elimination of the ethyl cation group.**

- 5.6) What can you say about the mechanism through which the oxidation occurs based on the data above?

The mechanism is proton-catalysed.

**1 point for stating that the mechanism is proton-catalysed, involves an enolisation reaction that is not rate-determining / is fast or something to that effect.**

- 5.7) Suggest a reason why the normal Hammett plot fails to show linearity. What does this indicate about the nature of the transition state of this reaction?

The normal Hammett plot fails to show linearity because there is direct conjugation between the substituent and the reaction centre, due to which Hammett's sigma values are not applicable. The reactions have a charge that is directly adjacent to the aromatic ring, so the resonance effects dominate more than with the reference reaction.

This indicates that the transition state has a charged reaction centre directly next to the aromatic ring.

**1 point for stating that the deviation is due to resonance effects and explaining it.  
1 point for stating that the transition state has a charged reaction centre directly next to the aromatic ring / reaction centre has charge dispersed throughout the aromatic ring etc.**



- 5.8) Given that the total bromate concentration can be written as  $[Br]_0$ , deduce the rate law of the equation in terms of  $[Br]_0$ , [4-oxoacid],  $[Ce(III)]$ ,  $[H^+]$  and any relevant rate and equilibrium constants.

$$\text{Rate} = k_d [\text{complex C2}][H^+]$$

From the equilibrium steps in scheme 1, one can obtain the following:

$$[\text{Complex C1}] = K_B K_e [4\text{-oxoacid}][Ce(III)]$$

$$[\text{Complex C2}] = K_T K_B K_e [4\text{-oxoacid}][Ce(III)][BrO_3^-]$$

Hence, we obtain:

$$\text{Rate} = k_d K_T K_B K_e [4\text{-oxoacid}][Ce(III)][BrO_3^-][H^+]$$

Furthermore, notice that the total concentration of bromate can be obtained by considering the complexed and uncomplexed forms of bromate:

$$[Br]_0 = [BrO_3^-] + [\text{Complex C2}]$$

$$\text{Thus, } [Br]_0 = [BrO_3^-](1 + K_T K_B K_e [4\text{-oxoacid}][Ce(III)])$$

$$[BrO_3^-] = \frac{[Br]_0}{1 + K_T K_B K_e [4\text{-oxoacid}][Ce(III)]}$$

Therefore,

$$\text{rate} = \frac{k_d K_T K_B K_e [4\text{-oxoacid}][Ce(III)][Br]_0 [H^+]}{1 + K_T K_B K_e [4\text{-oxoacid}][Ce(III)]}$$

Consequently,

**2 points for obtaining the rate in terms of [4-oxoacid], [Ce(III)],  $[H^+]$  and  $[BrO_3^-]$ .**

**1 point for writing  $[Br]_0 = [BrO_3^-] + [\text{Complex C2}]$ , or something to that effect.**

**1 point for correct substitution based on the above computations.**

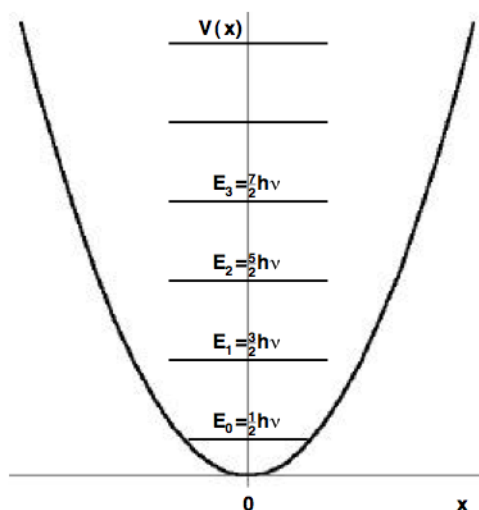
**1 point for correct rearrangement to obtain  $[BrO_3^-]$  as the subject of the equation.**

**1 point for correct final rate law.**

Problem 6 16.7% of total	Question	6-1	6-2	6-3	6-4	6-5	6-6	Total
	Points	4	4	3	3	6	4	24

## Problem 6: Quantum Harmonic Oscillator and Isotopes

by Nathanael Reza Putra Widjaja, Indonesia



The quantum harmonic oscillator is a decent start for investigating chemical bonding. The lowest energy that a harmonic oscillator can have is not zero, but rather the zero-point energy (ZPE) which is nonzero. The energies of a harmonic oscillator is given by  $E = (n + \frac{1}{2})hf$  where  $f$  is the frequency in Hz,  $E$  is the energy,  $h$  is Planck's constant, and  $n$  is the energy level. For the ZPE,  $n = 0$ .

- 6.1) Find the difference of the zero-point energies of C-H and C-D bonds if their bond frequency wavenumbers are  $3000\text{ cm}^{-1}$  and  $2200\text{ cm}^{-1}$ , respectively.  
(Hint: Remember that wavenumber =  $1/\text{wavelength}$ )

In some type of reaction, a C-H bond needs to break. It does so by first achieving the transition state.

- 6.2) Assuming the transition state energies for C-H and C-D bonds are the same, calculate the relative rates of bond-breaking ( $k_H/k_D$ ) for C-H and C-D at 298 K. Assume the pre-exponential factor in both cases to be equal.

An even nicer model is the Morse potential. The Morse potential energy function is given by

$$V(r) = D_e \left( 1 - e^{-a(r-r_{eq})} \right)^2$$

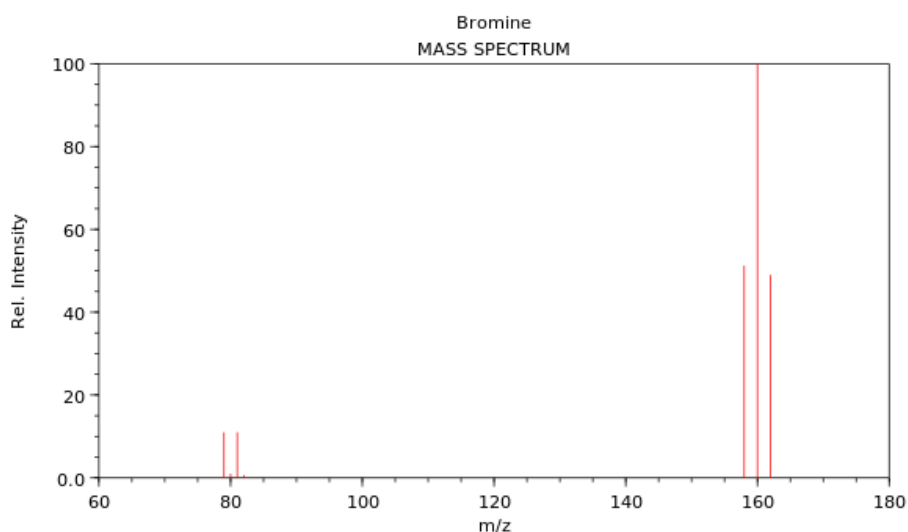
where  $D_e$  is the well-depth parameter,  $r_{eq}$  the equilibrium bond length,  $V$  the potential energy,  $r$  the internuclear distance, and  $a$  is a constant.

- 6.3) Sketch the shape of potential energy as a function of  $r$ . Show what  $D_e$  refers to in your diagram.
- 6.4) Calculate the true energy required to fully dissociate  $D_2$  in kJ/mol if the well depth parameter  $D_e$  is 457 kJ/mol and the bond stretching wavenumber for  $D_2$  is  $3115 \text{ cm}^{-1}$ .

Take element A which has 2 isotopes, say **1** and **2**, with different relative abundances. The element may form diatomic molecules  $^1A_2$ ,  $^2A_2$ , and  $^1A^2A$ . The distribution of the three are not equal, because the isotopes have different abundances.

Consider only carbon's most abundant isotope. It combines with chlorine ( $^{35}\text{Cl}$  76%,  $^{37}\text{Cl}$  24%).

- 6.5) In a sample of  $^{12}\text{CCl}_4$ , calculate the percentages of  $^{12}\text{C}^{35}\text{Cl}_3^{37}\text{Cl}$  and of  $^{12}\text{C}^{35}\text{Cl}_2^{37}\text{Cl}_2$ .



On the right side of this mass spectrometry reading of bromine ( $\text{Br}_2$ ) there are three peaks. The isotopic distribution for bromine is 50.69%  $^{79}\text{Br}$  and 49.31%  $^{81}\text{Br}$ .

- 6.6) Assign each peak to  $^{79}\text{Br}_2$ ,  $^{79}\text{Br}^{81}\text{Br}$ , and  $^{81}\text{Br}_2$ . Refer to the leftmost signal as **A**, middle as **B**, and rightmost signal as **C**.

## Problem 6: Solution

- 6.1) Find the difference of the zero-point energies of C-H and C-D bonds if their bond frequency wavenumbers are  $3000\text{ cm}^{-1}$  and  $2200\text{ cm}^{-1}$ , respectively.  
(Hint: Remember that wavenumber =  $1/\text{wavelength}$ )

The bond frequency for the C-H bond is  $3000\text{ cm}^{-1}$ . Converting to wavelength, that is :

$$3 \cdot 10^5 = 1/\lambda$$

Which gives  $\lambda = \frac{1}{3 \cdot 10^5}\text{ m}$ . Then, the frequency of this bond is  $f = c/\lambda = 9 \cdot 10^{13}\text{ Hz}$ .

Similarly, for the C-D bond we obtain  $f = 6.6 \cdot 10^{13}\text{ Hz}$ .

The difference of ZPEs can be written as :

$$\Delta ZPE = ZPE_H - ZPE_D = \frac{1}{2}h(f_H - f_D) = 7.95 \cdot 10^{-21}\text{ J}.$$

**Total 4 points**

**Obtaining  $f$  for C-H : 1 point**

**Obtaining  $f$  for C-D : 1 point**

**Finding  $\Delta ZPE$  : 2 points**

- 6.2) Assuming the transition state energies for C-H and C-D bonds are the same, calculate the relative rates of bond-breaking ( $k_H/k_D$ ) for C-H and C-D at 298 K. Assume the pre-exponential factor in both cases to be equal.

By Arrhenius,  $k = Ae^{-E_a/k_B T}$ .

$$\text{So, } k_H/k_D = e^{-E_{a,H}/k_B T} / e^{-E_{a,D}/k_B T} = e^{-(E_{a,H} - E_{a,D})/k_B T}.$$

Because we are assuming their transition states are the same,

$$E_{a,H} - E_{a,D} = -\Delta ZPE = -7.95 \cdot 10^{-21}\text{ J}.$$

$$\text{We obtain } k_H/k_D = e^{\Delta ZPE/k_B T} = 6.9.$$

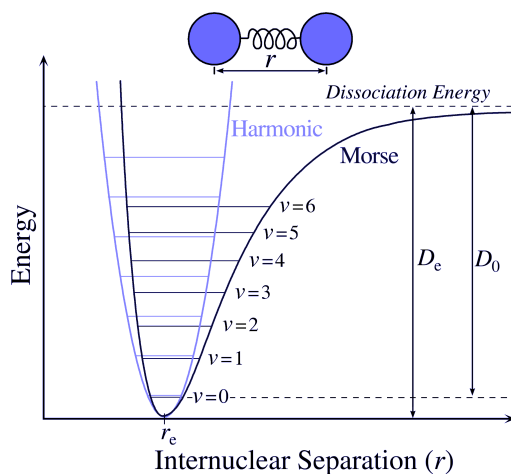
**Total 4 points**

**Arrhenius  $k_H/k_D$  : 1 point**

**Using  $\Delta E_a = \Delta ZPE$  : 2 points**

**Correct final answer : 1 point**

- 6.3) Sketch the shape of potential energy as a function of  $r$ . Show what  $D_e$  refers to in your diagram.



**Total 3 points**

**Clear diagram with desired shape : 2 points**

**Correct interpretation of  $D_e$  : 1 point**

- 6.4) Calculate the true energy required to fully dissociate  $D_2$  in kJ/mol if the well depth parameter  $D_e$  is 457 kJ/mol and the bond stretching wavenumber for  $D_2$  is  $3115\text{ cm}^{-1}$ .

The bond frequency for the D-D bond is  $3115\text{ cm}^{-1}$ . Converting to wavelength, that is :

$$3,115 \cdot 10^5 = 1/\lambda$$

Which gives  $\lambda = \frac{1}{3,115 \cdot 10^5}\text{ m}$ . Then, the frequency of this bond is  $f = c/\lambda = 9,345 \cdot 10^{13}\text{ Hz}$ .

The ZPE of  $D_2$  is therefore  $E_0 = \frac{1}{2}hf = 3.096 \cdot 10^{-20}\text{ J}$  which is equivalent to 18.64 kJ/mol.

The dissociation energy is therefore  $457 - 18.64 = 438.36\text{ kJ/mol}$ .

**Total 3 points:**

**1 point for finding  $f$**

**1 point for finding ZPE**

**1 point for correct final answer**

6.5) In a sample of  $^{12}\text{CCl}_4$ , calculate the percentages of  $^{12}\text{C}^{35}\text{Cl}_3^{37}\text{Cl}$  and of  $^{12}\text{C}^{35}\text{Cl}_2^{37}\text{Cl}_2$ .

1. For  $^{12}\text{C}^{35}\text{Cl}_3^{37}\text{Cl}$ , we wish to choose 1  $^{37}\text{Cl}$  and 3  $^{35}\text{Cl}$ . With binomial probability, it is evident that we are looking for  $P = \binom{4}{1} (0.76)^3 (0.24)^1 = 42\%$
2. For  $^{12}\text{C}^{35}\text{Cl}_2^{37}\text{Cl}_2$ , we wish to choose 2  $^{37}\text{Cl}$  and 2  $^{35}\text{Cl}$ . With binomial probability, we obtain what we are looking for  $P = \binom{4}{2} (0.76)^2 (0.24)^2 = 19.96\%$

**Total 6 points:**  
**3 points each**

6.6) Assign each peak to  $^{79}\text{Br}_2$ ,  $^{79}\text{Br}^{81}\text{Br}$ , and  $^{81}\text{Br}_2$ . Refer to the leftmost signal as **A**, middle as **B**, and rightmost signal as **C**.

Intuitively, there should be very little variation in height between the pairs 79-79 and 81-81. It makes sense that the smaller one would belong to the 81-81 pair since their abundance is less than that of the 79-79 pair. Hence, **C** is 81-81, **A** is 79-79, and **B** is 79-81.

Mathematically,

$$\mathbf{A}: 0.5069^2 = 25.69\%$$

$$\mathbf{B}: \binom{2}{1} (0.5069)(0.4931) = 49.99\%$$

$$\mathbf{C}: 0.4931^2 = 24.31\%$$

We see that the relative heights of the signals should be **A:B:C** = 1.06 : 2.05 : 1.

**Total: 4 points**  
**1.3 points for each**