THE PREPARATORY PROBLEMS FROM THE INTERNATIONAL CHEMISTRY OLYMPIADS

Series 2

38th – 42nd IChOs
2006 – 2010

Edited by Anton Sirota

IChO International Information Centre

IUVENTA, Bratislava, 2017

THE PREPARATORY PROBLEMS FROM THE INTERNATIONAL CHEMISTRY OLYMPIADS, Series 2
The preparatory problems from the 38th – 42nd IChOs

Editor: Anton Sirota

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41st

IChO

International Chemistry Olympiad

PREPARATORY PROBLEMS

Edited by Anton Sirota

29 theoretical problems
5 practical problems

2009

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Fields of Advanced Difficulty

Theoretical

Kinetics: integrated first-order rate equation; analysis of moderately complex reactions mechanisms using the steady state approximation, the use of the Arrhenius equation, simple collision theory

Thermodynamics: electrochemical cells, the relationship between equilibrium constants, electromotive force and standard Gibbs energy, the variation of the equilibrium constant with temperature

Quantum mechanics: calculation of orbital and spin angular momentum, calculation of the magnetic moment using the spin-only formula

Spectroscopy: interpretation of relatively simple ^{13}C and ^{1}H NMR spectra; chemical shifts, multiplicities, coupling constants and integrals

Mass spectrometry: molecular ions and basic fragmentation

Practical

Synthetic techniques: filtration, recrystallisation, drying of precipitates, thin layer chromatography.
Use of a simple digital conductivity meter.

THE FORTY-FIRST INTERNATIONAL CHEMISTRY OLYMPIAD 18 – 27 JULY 2009, CAMBRIDGE, UNITED KINGDOM

PREPARATORY PROBLEMS

Contents

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PREPARATORY THEORETICAL PROBLEMS

THEORETICAL PROBLEM 1

Dating moon rock

The age of rocks collected from the moon on the Apollo 16 mission has been determined from the ^{87}Rb / ^{86}Sr and ^{87}Sr / ^{86}Sr ratios of different minerals found in the sample.

Mineral	**^{87}Rb / ^{86}Sr**	**^{87}Sr / ^{86}Sr**
A (Plagioclase)	0.004	0.699
B (Quintessence)	0.180	0.709

1.1 ^{87}Rb is a β^- emitter, write down the equation of nuclear decay. The half-life for this decay is 4.8×10^{10} years.

1.2 Calculate the age of the rock. You can assume that the initial ^{87}Sr / ^{86}Sr is the same in **A** and **B** and that ^{87}Sr and ^{86}Sr are stable.

SOLUTION OF PREPARATORY PROBLEM 1

1.1 $^{87}_{37}\text{Rb} \rightarrow {}^{87}_{38}\text{Sr} + {}^{0}_{-1}\beta$

1.2 $^{87}\text{Sr}_{now} = {}^{87}\text{Sr}_{t=0} + {}^{87}\text{Rb}_{t=0} - {}^{87}\text{Rb}_{now}$

$^{87}\text{Rb}_{now} = {}^{87}\text{Rb}_{t=0} \exp(-\lambda\, t)$

$$\left({}^{87}\text{Rb}_{t=0} / {}^{87}\text{Rb}_{now}\right) = \exp(\lambda t)$$

$$^{87}\text{Sr}_{now} = {}^{87}\text{Sr}_{t=0} + {}^{87}\text{Rb}_{now}\left(\exp(\lambda t) - 1\right)$$

$$\left({}^{87}\text{Sr}_{now} / {}^{86}\text{Sr}\right) = \left({}^{87}\text{Sr}_{t=0} / {}^{86}\text{Sr}\right) + \left({}^{87}\text{Rb}_{now} / {}^{86}\text{Sr}\right)\left(\exp(\lambda t) - 1\right)$$

$$y \quad = \quad c \quad + \quad x(m)$$

($^{87}\text{Sr}_{t=0}$ / ^{86}Sr) same for A and B using assumption given in question

$$m = \frac{0.709 - 0.699}{0.180 - 0.004} = 0.0568 = (\exp(\lambda\, t) - 1)$$

$$\lambda\, t = \frac{\ln 2 \times t}{t_{1/2}}$$

$t_{1/2} = 4.8\times10^{10}$ years

$$t = \frac{4.8\times10^{10} \times \ln 1.0568}{\ln 2} = 3.8\times10^{9} \text{ years}$$

THEORETICAL PROBLEM 2

Snorkelling

The pressure of a gas may be thought of as the force the gas exerts per unit area on the walls of its container, or on an imaginary surface of unit area placed somewhere within the gas. The force arises from collisions between the particles in the gas and the surface. In an ideal gas, the collision frequency (number of collisions per second) with a surface of unit area is given by:

$$Z_{\text{surface}} = \frac{p}{\sqrt{2\,\pi\, m\, k_B T}}$$

where p is the pressure and T the temperature of the gas, m is the mass of the gas particles, and k_B is the Boltzmann's constant (k_B = 1.38×10^{-23} J K^{-1}).

At sea level, atmospheric pressure is generally around 101.3 kPa, and the average temperature on a typical British summer day is 15℃.

2.1 Using the approximation that air consists of 79 % nitrogen and 21 % oxygen, calculate the weighted average mass of a molecule in the air.

2.2 Human lungs have a surface area of approximately 75 m^2. An average human breath takes around 5 seconds. Estimate the number of collisions with the surface of the lungs during a single breath on a typical British summer day. You should assume that the pressure in the lungs remains constant at atmospheric pressure; this is a reasonable approximation, as the pressure in the lungs changes by less than 1 % during each respiratory cycle.

The human lungs can operate against a pressure differential of up to one twentieth of atmospheric pressure. If a diver uses a snorkel for breathing, we can use this fact to determine how far below water the surface of the water she can swim.

The pressure experienced by the diver a distance d below the surface of the water is determined by the force per unit area exerted by the mass of water above her. The force exerted by gravity on a mass m is $F = m\,g$, where g = 9.8 m s^{-2} is the acceleration due to gravity.

2.3 Write down an expression for the mass of a volume of water with cross sectional area A and depth d.

2.4 Derive an expression for the force exerted on the diver by the volume of water in 2.3, and hence an expression for the difference in pressure she experiences at depth *d* relative to the pressure at the water's surface.

2.5 Calculate the maximum depth the diver can swim below the water surface, while still breathing successfully through a snorkel.

SOLUTION OF PREPARATORY PROBLEM 2

2.1 $m = 0.79 \times M(N_2) + 0.21 \times M(O_2) = 0.79 \times 28.02 \text{ g mol}^{-1} + 0.21 \times 32.00 \text{ g mol}^{-1} =$

$= 28.86 \text{ g mol}^{-1} = 4.79\times10^{-26} \text{ kg}$

2.2

$$Z = \frac{p}{\sqrt{2\,\pi\, m\, k\, T}} \times t = \frac{101\,300 \text{ N m}^{-2}}{\sqrt{2\,\pi \times 4.79\times10^{-26} \text{ kg} \times 1.3806\times10^{-23} \text{ J K}^{-1} \times 287 \text{ K}}} \times 5 \text{ s} = 1.47\times10^{28}$$

2.3 $m = \rho\, V = \rho\, A\, d$

$F = m\, g = \rho\, A\, d\, g$

2.4 $p = \dfrac{F}{A} = \rho\, d\, g$

$d_{\max} = \dfrac{p}{\rho\, g}$

$\rho = 1000 \text{ kg m}^{-3}$

2.5 $g = 9.8 \text{ m s}^{-2}$

$p = \dfrac{1}{20} \times p_{atm} = 5065 \text{ Pa}$

$d_{\max} = \dfrac{5065 \text{ Pa}}{1000 \text{ kg m}^{-3} \times 9.8 \text{ m s}^{-2}} = 0.52 \text{ m}$

THEORETICAL PROBLEM 3

Ideal and not-so-ideal gases

The force a gas exerts on the walls of its container arises from collisions between the particles in the gas and the surface. In a single collision, the magnitude of the impulsive of the force exerted on the surface is equal to the change in the momentum normal to the surface, $m\Delta v$. The force on the surface is then the impulse, multiplied by the rate at which the particles collide with the surface.

Since the motion of particles within a gas is random, the number of collisions occurring per unit time is a constant for a gas at constant temperature.

The temperature of a gas reflects the distribution of particle velocities within the gas. For a given gas, the particle speeds will be higher, on average, at higher temperatures.

3.1 Given the above information, and assuming the gas is initially at room temperature and atmospheric pressure, consider how carrying out the following actions would be likely to affect the pressure. Would the pressure double, halve, increase slightly, decrease slightly, or remain unchanged?

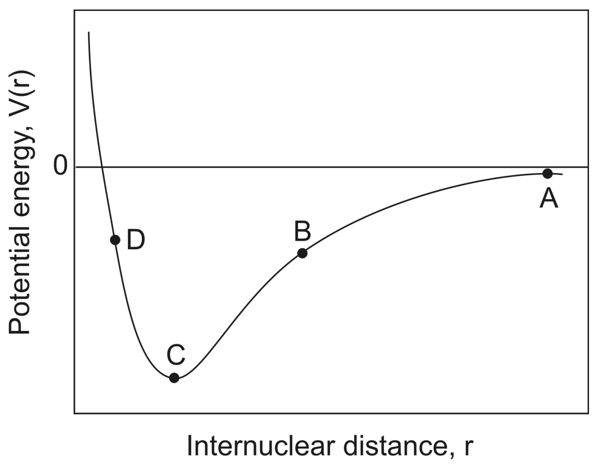
i) Doubling the number of particles in the gas.

ii) Doubling the volume of the container in which the gas is confined.

iii) Doubling the mass of the particles in the gas (assume that the particle velocities remain constant).

iv) Increasing the temperature by 10℃.

The ideal gas model assumes that there are no interactions between gas particles. Particles in a real gas do interact through a range of forces such as dipole–dipole forces, dipole–induced–dipole forces, and van der Waals interactions (induced–dipole–induced–dipole forces). A typical curve showing the potential energy of interaction between two particles is shown right:



The force between two particles in a gas at a given separation r may be calculated from the gradient of the potential energy curve i.e. $F = -\mathrm{d}V / \mathrm{d}r$.

3.2 What is the force at the four points marked **A**, **B**, **C** and **D** on the figure?

(attractive / repulsive / approximately zero)

The deviation from non-ideality in a gas is often quantified in terms of the compression ratio, *Z*.

$$Z = \frac{V_m}{V_m^0}$$

where V_m is the molar volume of the (real) gas, and V_m^0 is the molar volume of an ideal gas under the same conditions of temperature, pressure etc.

3.3 Match the following values of *Z* with the dominant type of interaction in the gas.

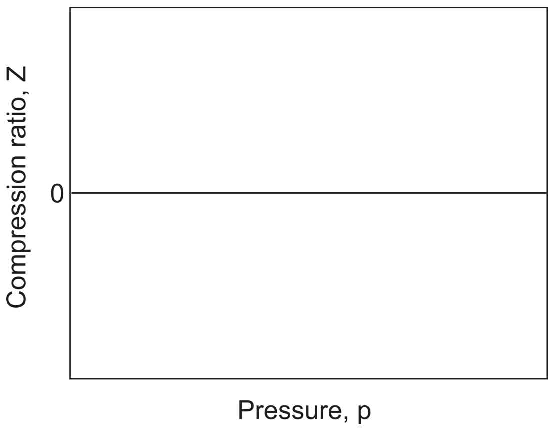
[$Z = 1$] [$Z < 1$] [$Z > 1$]

Attractive forces dominate

Repulsive forces dominate

No intermolecular forces, ideal gas behaviour

3.4 The compression ratio is pressure dependent. Consider the average separation between particles in a gas at different pressures (ranging from extremely low pressure to extremely high pressure), and the regions of the intermolecular potential that these separations correspond to. Sketch the way in which you think the compression ratio will vary with pressure on the set of axes below. [Note: do not worry about the actual numerical values of *Z*; the general shape of the pressure dependence curve is all that is required.]



SOLUTION OF PREPARATORY PROBLEM 3

3.1 **i)** pressure would double

ii) pressure would halve

iii) pressure would double

iv) pressure would increase slightly

3.2 A – approximately zero B – attractive

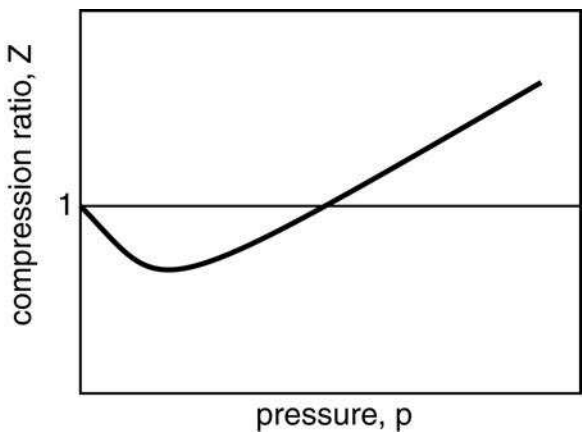
C – approximately zero D – repulsive

3.3 $Z = 1$ - no intermolecular forces, ideal gas behaviour

$Z < 1$ - attractive forces dominate

$Z > 1$ - repulsive forces dominate

3.4



THEORETICAL PROBLEM 4

Coal gasification

In the process of coal gasification coal is converted into a combustible mixture of carbon monoxide and hydrogen, called coal gas

$$H_2O(g) + C(s) \rightarrow CO(g) + H_2(g)$$

4.1 Calculate the standard enthalpy change for this reaction from the following chemical equations and standard enthalpy changes.

$2\ C(s) + O_2(g) \rightarrow 2\ CO(g)$ $\Delta_r H^\circ = -221.0$ kJ mol^{-1}

$2\ H_2(g) + O_2(g) \rightarrow 2\ H_2O(g)$ $\Delta_r H^\circ = -483.6$ kJ mol^{-1}

The coal gas can be used as a fuel :

$CO(g) + H_2(g) + O_2(g) \rightarrow CO_2(g) + H_2O(g)$

4.2 Given the additional information, calculate the enthalpy change for this combustion

$C(s) + O_2(g) \rightarrow CO_2(g)$ $\Delta_r H^\circ = -393.5$ kJ mol^{-1}

Coal gas can also undergo the process of *methanation*.

$3\ H_2(g) + CO(g) \rightarrow CH_4(g) + H_2O(g)$

4.3 Determine the standard enthalpy change for the methanation reaction using the additional data.

$CH_4(g) + 2\ O_2(g) \rightarrow CO_2(g) + 2\ H_2O(g)$ $\Delta_r H^\circ = -802.7$ kJ mol^{-1}

SOLUTION OF PREPARATORY PROBLEM 4

4.1 (1) $2\ C(s) + O_2(g) \rightarrow 2\ CO(g)$ $\Delta_r H^\circ = -221.0$ kJ mol^{-1}

(2) $2\ H_2(g) + O_2(g) \rightarrow 2\ H_2O(g)$ $\Delta_r H^\circ = -483.6$ kJ mol^{-1}

The overall reaction is ½ ($E_1 - E_2$) $\Delta_r H^\circ = +131.3$ kJ mol^{-1}.

4.2 (3) $CO(g) + H_2(g) + O_2(g) \rightarrow CO_2(g) + H_2O(g)$

(4) $C(s) + O_2(g) \rightarrow CO_2(g)$ $\Delta_r H° = –393.5\ \text{kJ mol}^{–1}$

$E_3 = E_4 + ½\ E_2 – ½\ E_1$ $\Delta_r H° = –524.8\ \text{kJ mol}^{–1}$.

4.3 (5) $3\ H_2(g) + CO(g) \rightarrow CH_4(g) + H_2O(g)$

(6) $CH_4(g) + 2\ O_2(g) \rightarrow CO_2(g) + 2\ H_2O(g)$ $\Delta_r H° = –802.7\ \text{kJ mol}^{–1}$

$E_5 = 3\ E_2 – ½\ E_1 – E_6$ $\Delta_r H° = –205.7\ \text{kJ mol}^{–1}$

THEORETICAL PROBLEM 5

The industrial preparation of hydrogen

Hydrogen gas may be prepared industrially by heating hydrocarbons, such as a methane, with steam:

$$CH_4(g) + H_2O(g) \longrightarrow 3\,H_2(g) + CO(g) \qquad \textbf{(A)}$$

5.1 Given the following thermodynamic data, calculate the $\Delta_rG°$ for reaction **A** at 298 K and hence a value for the equilibrium constant, K_p.

	$\Delta_fH°$(298) / kJ mol^{-1}	$S°$(298) / J K^{-1} mol^{-1}
$CH_4(g)$	–74.4	186.3
$H_2O(g)$	–241.8	188.8
$H_2(g)$		130.7
$CO(g)$	–110.5	197.7

5.2 How will the equilibrium constant vary with temperature?

The industrial preparation can be carried out at atmospheric pressure and high temperature, without a catalyst. Typically, 0.2 vol % of methane gas remains in the mixture at equilibrium.

5.3 Assuming the reaction started with equal volumes of methane and steam, calculate the value of K_p for the industrial process which gives 0.2 vol. % methane at equilibrium.

5.4 Use your answer from 5.3 together with the integrated form of the van't Hoff isochore to estimate the temperature used in industry for the preparation of hydrogen from methane.

SOLUTION OF PREPARATORY PROBLEM 5

5.1 $\Delta_r H° = -110.5 - (-74.4) - (-241.8) = 205.7 \text{ kJ mol}^{-1}$

$\Delta_r S° = 197.7 + 3 \times 130.7 - 186.3 - 188.8 = 214.7 \text{ J mol}^{-1} \text{ K}^{-1}$

$\Delta_r G° = \Delta_r H° - T\,\Delta_r S° = 205700 - 298 \times 214.7 = 141700 \text{ J mol}^{-1} = 141.7 \text{ kJ mol}^{-1}$

$\Delta_r G° = -RT \ln K_p$

$$K_p = \exp\left(-\frac{\Delta_r G^o}{R\,T}\right) = \frac{141700}{8.314 \times 298} = 1.44 \times 10^{-25}$$

5.2 As the reaction is endothermic increasing the temperature will result in shifting the equilibrium towards the products, i.e. increasing the equilibrium constant.

5.3 For ideal gases, vol % is the same as the mole fraction.

If 0.2 vol % CH_4 remains then there must be 0.2 vol % H_2O as well.

Remaining 99.6% correspondes to the products H_2 and CO in ratio 3 : 1. Therefore there is 24.9 % CO and 74.7 % H_2.

$$K_p = \frac{a(H_2)^3\, a(CO)}{a(H_2O)\, a(CH_4)} = \frac{\left(\dfrac{p(H_2)^3}{p^o}\right)\left(\dfrac{p(CO)}{p^o}\right)}{\left(\dfrac{p(H_2O)}{p^o}\right)\left(\dfrac{p(CH_4)}{p^o}\right)} = \frac{\left(x(H_2)\,\dfrac{p_{tot}}{p^o}\right)\left(x(CO)\,\dfrac{p_{tot}}{p^o}\right)}{\left(x(H_2O)\,\dfrac{p_{tot}}{p^o}\right)\left(x(CH_4)\,\dfrac{p_{tot}}{p^o}\right)} =$$

$$= \frac{x(H_2)^3\;\; x(CO)}{x(H_2O)\, x(CH_4)} \times \left(\frac{p_{tot}}{p^o}\right)^2$$

$$K_p = \frac{0.747^3 \times 0.249}{0.002 \times 0.002} \times \frac{101325^2}{100000^2} = 26640$$

5.4 $$\ln\frac{K_2}{K_1} = -\frac{\Delta_r H^o}{R}\left(\frac{1}{T_2} - \frac{1}{T_1}\right)$$

$$T_2 = \left(-\frac{R}{\Delta_r H^o} \ln\frac{K_2}{K_1} + \frac{1}{T_1}\right)^{-1} = 1580 \text{ K}$$

THEORETICAL PROBLEM 6

The bonds in dibenzyl

This question is a typical application of thermodynamic cycles to estimate a bond dissociation enthalpy.

The first step in the pyrolysis of toluene (methylbenzene) is the breaking of the $C_6H_5CH_2$–H bond. The activation enthalpy for this process, which is essentially the bond dissociation enthalpy, is found to be 378.4 kJ mol^{-1}.

6.1 Write a balanced equation for the complete combustion of toluene.

6.2 Standard enthalpies are given below, using the recommended IUPAC notation (i.e. f = formation, c = combustion, vap = vaporisation, at = atomisation)

$\Delta_f H^\circ(CO_2, g, 298K) = –393.5$ kJ mol^{-1}

$\Delta_f H^\circ(H_2O, l, 298K) = –285.8$ kJ mol^{-1}

$\Delta_c H^\circ(C_7H_8, l, 298K) = –3910.2$ kJ mol^{-1}

$\Delta_{vap} H^\circ(C_7H_8, l, 298K) = +38.0$ kJ mol^{-1}

$\Delta_{at} H^\circ(H_2, g, 298K) = +436.0$ kJ mol^{-1}.

i) Calculate $\Delta_f H^\circ(C_7H_8, l, 298K)$

ii) Estimate $\Delta_f H^\circ$ for the benzyl radical $C_6H_5CH_2\cdot$(g) at 298 K.

6.3 The standard entropy of vaporisation of toluene is 99.0 J K^{-1} mol^{-1}.

iii) Calculate $\Delta_{vap} G^\circ$ for toluene at 298 K.

iv) What is the reference state of toluene at 298 K?

v) Calculate the normal boiling point of toluene.

6.4 The standard enthalpy of formation of dibenzyl (1,2–diphenylethane) is 143.9 kJ mol^{-1}. Calculate the bond dissociation enthalpy for the central C–C bond in dibenzyl, $C_6H_5CH_2$–$CH_2C_6H_5$.

SOLUTION OF PREPARATORY PROBLEM 6

6.1 $C_7H_8 + 9\,O_2 \rightarrow 7\,CO_2 + 4\,H_2O$.

6.2 (all at 298 K)

i) $\Delta_c H°(C_7H_8,\,l) = 7\,\Delta_c H°(CO_2,\,g) + 4\,\Delta_f H°(H_2O,\,l) - \Delta_f H°(C_7H_8,\,l)$

$\Rightarrow\ \Delta_f H°(C_7H_8,\,l) = +12.2\ \text{kJ mol}^{-1}$

ii) $\Delta_f H°(Bz,\,g) =$

$= \Delta_f H°(C_7H_8,\,l) + \Delta_{vap} H°(C_7H_8) + \Delta_{bond} H°(Bz-H) - \frac{1}{2}\,\Delta_{at} H°(H_2,\,g)$

$= 210.6\ \text{kJ mol}^{-1}$.

6.3 **iii)** $\Delta_{vap} G° = \Delta_{vap} H° - T\Delta_{vap} S° = 8.50\ \text{kJ mol}^{-1}$

iv) liquid ($\Delta_{vap} G° > 0$)

v) $T_B = \dfrac{\Delta_{vap} H°}{\Delta_{vap} S°} = 384\ \text{K}$

6.4 $\Delta_{bond} H°(Bz-Bz) = 2\,\Delta_f H°(Bz,\,g) - \Delta_f H°(Bz-Bz,\,g) = 277.3\ \text{kJ mol}^{-1}$

THEORETICAL PROBLEM 7

Interstellar chemistry

A possible ion–molecule reaction mechanism for the synthesis of ammonia in interstellar gas clouds is shown below

$N^+ + H_2 \rightarrow NH^+ + H \qquad k_1$

$NH^+ + H_2 \rightarrow NH_2^+ + H \qquad k_2$

$NH_2^+ + H_2 \rightarrow NH_3^+ + H \qquad k_3$

$NH_3^+ + H_2 \rightarrow NH_4^+ + H \qquad k_4$

$NH_4^+ + e^- \rightarrow NH_3 + H \qquad k_5$

$NH_4^+ + e^- \rightarrow NH_2 + 2H \qquad k_6$

7.1 Use the steady state approximation to derive equations for the concentrations of the intermediates NH^+, NH_2^+, NH_3^+ and NH_4^+ in terms of the reactant concentrations $[N^+]$, $[H_2]$ and $[e^-]$. Treat the electrons as you would any other reactant.

7.2 Show that the overall rate of production of NH_3 is given by

$$\frac{d[NH_3]}{dt} = k_{2nd}[N^+][H_2]$$

where k_{2nd} is the second order rate constant for the reaction. Give an expression for k_{2nd} in terms of the rate constants for the elementary steps, k_1 to k_6.

7.3 What is the origin of the activation energy in a chemical reaction?

7.4 The rates of many ion-molecule reactions show virtually no dependence on temperature. What does this imply about their activation energy?

7.5 What relevance does this have to reactions occurring in the interstellar medium?

SOLUTION OF PREPARATORY PROBLEM 7

7.1 We can apply the SSA to NH^+, NH_2^+, NH_3^+ and NH_4^+.

$$\frac{d[NH^+]}{dt} = 0 = k_1\,[N^+][H_2] - k_2\,[NH^+][H_2]$$

$$[NH^+] = \frac{k_1\,[N^+]}{k_2}$$

$$\frac{d[NH_2^+]}{dt} = 0 = k_2\,[NH^+][H_2] - k_3[NH_2^+][H_2]$$

$$[NH_2^+] = \frac{k_2}{k_3}\,[NH^+] = \frac{k_2\,k_1}{k_3\,k_2}\,[N^+] = \frac{k_1}{k_3}\,[N^+]$$

$$\frac{d[NH_3^+]}{dt} = 0 = k_3\,[NH_2^+][H_2] - k_4[NH_3^+][H_2]$$

$$[NH_3^+] = \frac{k_3}{k_4}\,[NH_2^+] = \frac{k_1}{k_4}\,[N^+]$$

$$\frac{d[NH_4^+]}{dt} = 0 = k_4\,[NH_3^+][H_2] - k_5[NH_4^+][e^-] - k_6[NH_4^+][e^-]$$

$$[NH_4^+] = \frac{k_4\,[NH_3^+][H_2]}{(k_5 + k_6)\,[e^-]} = \frac{k_1\,[N^+][H_2]}{(k_5 + k_6)\,[e^-]}$$

7.2

$$\frac{d\,[NH_3]}{dt} = k_5\,[NH_4^+][e^-] = \frac{k_1\,k_5}{k_5 + k_6}\,[N^+][H_2] = k_{2nd}\,[N^+][H_2]$$

where $k_{2nd} = \dfrac{k_1\,k_5}{k_5 + k_6}$

7.3 Chemical reactions involve the making and breaking of bonds. The activation energy is related to the energy required to break the initial bond or provide a sufficient rearrangement of the reactant geometries to initiate reaction.

7.4 The temperature dependence of a rate constant k is described by the Arrhenius equation.

$$k(T) = A\,\exp(-\,E_a\,/\,RT)$$

Where A is the pre-exponential factor, E_a is the activation energy, R is the gas constant, and T the temperature. Virtually no temperature dependence therefore indicates that the activation energy is very close to zero.

7.5 Temperatures in the interstellar medium are extremely low. Only reactions with very low activation energies can occur.

THEORETICAL PROBLEM 8

Simple collision theory

For the elementary gas phase reaction H + $C_2H_4 \rightarrow C_2H_5$, the second-order rate constant varies with temperature in the following way:

***T* / K**	198	298	400	511	604
***k* × 10^{12} / cm^3 molecule^{-1} s^{-1}**	0.20	1.13	2.83	4.27	7.69

8.1 Use the data to calculate the activation energy, E_a, and the pre-exponential factor, A, for the reaction.

The simple collision theory of bimolecular reactions yields the following expression for the rate constant:

$$k = \sigma \sqrt{\frac{8 k_B T}{\pi \mu}} exp\left(-\frac{E_a}{RT} \right)$$

where μ is the reduced mass of the reactants and σ is the reaction cross section.

8.2 Interpret the role of the three factors in this expression; σ, the exponential, and the square-root term.

8.3 Use the answer to part **(a)** to estimate σ for the reaction at 400 K.

8.4 Compare the value obtained with an estimate of 4.0×10^{-19} m^2 for the collision cross section.

SOLUTION OF PREPARATORY PROBLEM 8

8.1 Assuming the reaction has an Arrhenius temperature dependence, a plot of ln k *vs* $1/T$ should be linear, with slope $-E_a / R$ and intercept ln A.

Plotting these data gives a straight line with a slope of –1042.9 K and an intercept of –23.991. We therefore have:

$E_a = -(R)(\text{slope}) = -8.314 \times (-1042.9) = 8663.118$ J mol^{-1} = 8.66 kJ mol^{-1}.

ln A = intercept = –23.991

so $A = \exp(-23.991) = 3.81\times10^{-11}$ cm^3 molecule^{-1} s^{-1}.

8.2 **i)** Explanation for the simple collision theory expression for the rate constant:

$$k = \sqrt{\frac{8k_B T}{\pi\mu}}\,\sigma\, exp\left(-\frac{E_0}{RT}\right)$$

The rate of a chemical reaction must obviously be proportional to the number of collisions between the reactants. The collision rate is given by

$$Z_{AB} = \sigma\, v_{rel}\, \eta_A\, \eta_B = \sigma\left(\frac{8\,kT}{\pi\,\mu}\right)^{1/2} n_A\, n_B$$

Here, vrel = (8kT/πμ)1/2 is the mean relative velocity of the collision partners and σ is the collision cross section (the effective size of one reactant as 'viewed' by the other). Often, σ is set equal to π(rA + rB)2, where rA and rB are the radii of reactants A and B. nA and nB are the number densities of the two reactants.

The exponential term, $\exp(-E_0/RT)$, reflects the fact that a collision will only lead to reaction if the collision energy exceeds the activation barrier.

The overall rate is therefore

$$rate = \sqrt{\frac{8k\,T}{\pi\mu}}\,\sigma\, exp\left(-\frac{E_0}{RT}\right) n_A\, n_B$$

and we can identify the rate constant as

$$k = \sqrt{\frac{8k\,T}{\pi\mu}}\,\sigma\, exp\left(-\frac{E_0}{RT}\right)$$

8.3 From part 8.1, we have $A = 3.81\times10^{-11}$ cm^3 molecule^{-1}s^{-1}. We can identify A from the simple collision theory expression as

$$A = \sqrt{\frac{8k\,T}{\pi\mu}}\,\sigma$$

so that $\sigma = \sqrt{\frac{\pi\mu}{8kT}}\,A$

The reduced mass of H and C_2H_4 is

$$\mu = \frac{m(\mathrm{H})\times m(\mathrm{C_2H_4})}{m(\mathrm{H}) + m(\mathrm{C_2H_4})} = \frac{1\times 28}{1+28} = 0.9655\ \mathrm{g\,mol^{-1}} = 1.603\times10^{-27}\ \mathrm{kg}$$

giving

$$\sigma = 3.775\times10^{-17}\left(\frac{1.603\times10^{-27}}{8\,k\,(400)}\,\pi\right)^{1/2} = 1.275\times10^{-20}\ \mathrm{m^2}$$

8.4 The calculated reaction cross section is around 30 times smaller than the collision cross section. This reflects the fact that not all collisions lead to reaction. Often the collision geometry and / or internal energy states of the collision partners are important in determining whether two molecules will react when they collide.

THEORETICAL PROBLEM 9

Hinshelwood

Sir C.N. Hinshelwood shared the 1956 Nobel prize in Chemistry for his work on the mechanisms of high temperature reactions.

The pyrolysis of ethanal proceeds by the following simplified mechanism:

Reaction	**rate constant**	**E_a / kJ mol^{-1}**
$CH_3CHO \rightarrow CH_3\cdot + HCO\cdot$	k_1	358
$CH_3\cdot + CH_3CHO \rightarrow CH_4 + CH_3CO\cdot$	k_2	8
$CH_3CO\cdot \rightarrow CH_3\cdot + CO$	k_3	59
$HCO\cdot \rightarrow H\cdot + CO$	k_4	65
$H\cdot + CH_3CHO \rightarrow H_2 + CH_3CO\cdot$	k_5	15
$2CH_3\cdot \rightarrow C_2H_6$	k_6	0

9.1 List each reaction as initiation, propagation or termination.

9.2 Use the steady-state approximation on the radical intermediates to find expressions for the steady-state concentrations of the HCO, H, CH_3 and CH_3CO radicals.

9.3 Find rate laws for the rate of loss of ethanal, and the rates of formation of methane, ethane, hydrogen and CO.

9.4 There are two pathways for the dissociation of ethanal. Write a balanced equation for each reaction and for each find the order with respect to ethanal, and the activation energy.

SOLUTION OF PREPARATORY PROBLEM 9

9.1

	Reactions
initiation	1
propagation	2, 3, 4, 5
termination	6

9.2 (1) $[HCO]' = k_1[AcH] - k_4[HCO] = 0 \Rightarrow\Rightarrow [HCO] = \frac{k_1}{k_4}[AcH]$

(2) $[H]' = k_4\,[HCO] - k_5[H][AcH] = 0 \;\Rightarrow\; [H] = \frac{k_4\,[HCO]}{k_5[AcH]} = \frac{k_1}{k_5}$ (from 1)

(3) $[Me]' = k_1\,[AcH] - k_2[Me][AcH] + k_3\,[Ac] - 2\,k_6[Me]^2 = 0$

(4) $[Ac]' = k_2\,[Me][AcH] - k_3[Ac] + k_5[H][AcH] = 0$

Add (3) + (4), and substitute from (2) and then from (1).

$0 = 2k\,[AcH] - 2k_6\,[Me]^2 \;\Rightarrow\; [Me] = \sqrt{\frac{k_1}{k_6}}\,[AcH]^{1/2}$

Finally from (4).

$$[Ac] = \frac{k_2[Me] + k_5[H]}{k_3}[AcH] = \frac{k_2}{k_3}\sqrt{\frac{k_1}{k_6}}\,[AcH]^{3/2} + \frac{k_1}{k_3}[AcH]$$

9.3 $-[Ac]' = k_1[AcH] + k_2\,[Me][AcH] + k_5[H][AcH] = 2\,k\,[AcH] + k_2\sqrt{\frac{k_1}{k_6}}\,[AcH]^{3/2}$

$[CH_4\,]' = k_2\,[Me][AcH] = k_2\sqrt{\frac{k_1}{k_6}}\,[AcH]^{3/2}$

$[C_2H_6]' = k_6[Me]^2 = k_1[AcH]$

$[H_2]' = k_5\,[H][AcH] = k_1[AcH]$

$[CO]' = k_3[Ac] + k_4[HCO] = 2\,k_1\,[AcH] + k_2\sqrt{\frac{k_1}{k_6}}\,[AcH]^{3/2}$

9.4 Find this by analysing the rates of formation of the different products: the formation of ethane and hydrogen is first order in ethanal with equal rates, and the formation of methane is order 3/2. Both routes form CO. The first order route forms CO at twice the rate of ethane and hydrogen, and the order 3/2 rate forms it at the same rate as methane.

To get the activation energies use the Arrhenius equation. Because the activation energy is the exponent, when the effective rate constant is a product of elementary rate constants, their activation energies must be added (with related rules for division and powers).

(i) $2\ CH_3CHO \rightarrow C_2H_6 + H_2 + 2CO$ order: 1 E_a = 358 kJ mol^{-1}

(ii) $CH_3CHO \rightarrow CH_4 + CO$ order: 3/2 E_a = 187 kJ mol^{-1}

THEORETICAL PROBLEM 10

Enzyme kinetics

Characterisation of enzyme kinetics can play an important role in drug discovery. A good understanding of how the enzyme behaves in the presence of its natural substrate is necessary before the effect of potential drugs can be evaluated. Enzymes are typically characterised by two parameters, V_{max} and K_m; these are determined by analysing the variation of the initial rate of reaction with substrate concentration.

Many enzymatic reactions can be modelled using the scheme:

$$\mathbf{E} + \mathbf{S} \rightarrow \mathbf{ES} \qquad \text{rate constant } k_1$$
$$\mathbf{ES} \rightarrow \mathbf{E} + \mathbf{S} \qquad \text{rate constant } k_{-1}$$
$$\mathbf{ES} \rightarrow \mathbf{E} + \mathbf{P} \qquad \text{rate constant } k_2$$

where **E** is the free enzyme, **S** is the substrate, **ES** is a complex formed between the enzyme and substrate and **P** is the product.

10.1 Assuming that the system is in steady state and that [**S**] >> [**E**] obtain an expression

i) for the rate of production of **ES** in terms of [**E**], [**S**], [**ES**] and the appropriate rate constants.

ii) for the rate of production of **P** in terms of [**ES**] and the appropriate rate constants.

When doing the experiment [**E**] is not known, however the total amount of enzyme present is constant throughout the reaction, therefore:

$$[\mathbf{E}]_0 = [\mathbf{E}] + [\mathbf{ES}]$$

where $[\mathbf{E}]_0$ is the initial enzyme concentration.

Also, in enzyme kinetics the Michaelis constant, K_m, is defined as:

$$K_m = (k_{-1} + k_2) / k_1$$

10.2 Obtain an expression for [**ES**] in terms of [**S**], $[\mathbf{E}]_0$ and K_m.

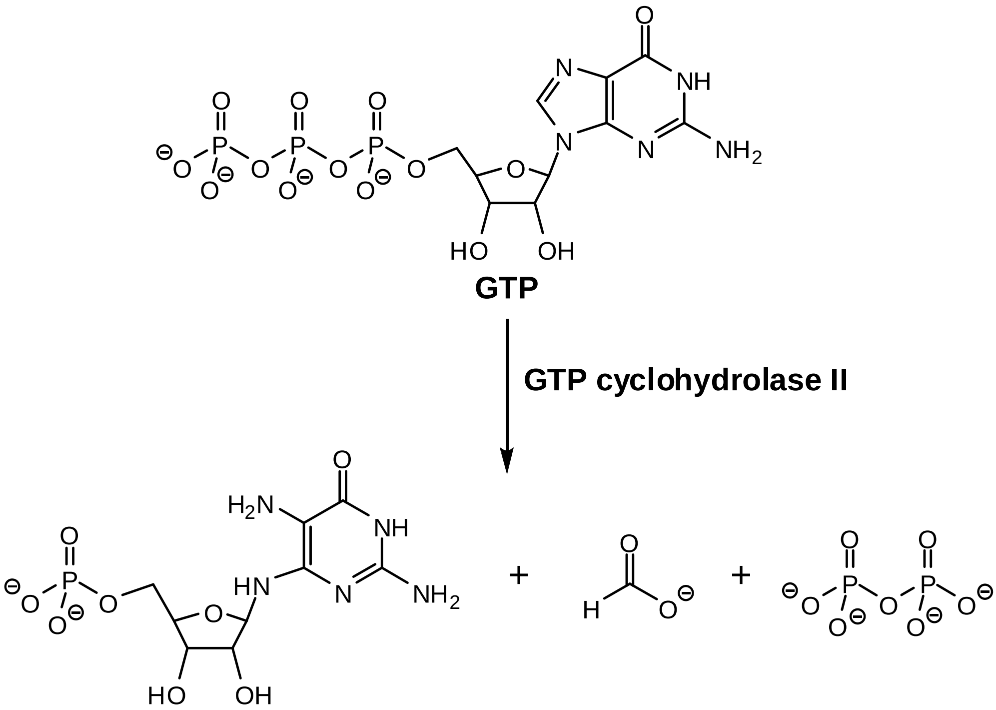
10.3 Hence obtain an expression for the rate of production of **P** in terms of $[\mathbf{E}]_0$, [**S**] and the appropriate constants.

The maximal rate of reaction, V_{max}, occurs when all of the enzyme molecules have substrate bound, i.e. when $[\mathbf{ES}] = [\mathbf{E}]_0$, therefore:

$$V_{max} = k_2 \times [\mathbf{E}]_0$$

10.4 Obtain an expression for the rate of production of **P** in terms of V_{max}, [**S**] and the appropriate constants.

The enzyme *GTP cyclohydrolase II* catalyses the first step in riboflavin biosynthesis in bacteria:



The absence of this enzyme in higher organisms makes GTP cyclohydrolase II a potential target for antimicrobial drugs.

Protein samples were rapidly mixed with different concentrations of GTP. The change in absorbance with time was measured at 299 nm in a 1 ml cell with a 1 cm pathlength. A solution with a concentration of 100 μmol dm^{-3} of the purified product gave an absorbance of 0.9 in a 1 cm pathlength cell at 299 nm.

Time (s)	**GTP concentration** (M = mol dm^{-3})						
	200 μM	150 μM	100 μM	80 μM	60 μM	40 μM	20 μM
6	0.00514	0.00469	0.00445	0.00393	0.00377	0.00259	0.00197
7	0.00583	0.00547	0.00477	0.00454	0.00388	0.00253	0.00247
8	0.00708	0.00639	0.00568	0.00506	0.00452	0.00309	0.00253
9	0.00698	0.00703	0.00639	0.00591	0.00521	0.00325	0.00295
10	0.00818	0.00800	0.00709	0.00645	0.00574	0.00387	0.00302
11	0.00901	0.00884	0.00752	0.00702	0.00638	0.00445	0.00352
12	0.0103	0.00922	0.00849	0.00771	0.00707	0.00495	0.00386

10.5 Calculate the initial rate of reaction at each of the GTP concentrations.

10.6 Express the equation obtained in part **(d)** in the form *y* = *mx* + *c*.

10.7 Hence determine V_{max} and K_m for this enzyme (you may assume that the kinetic scheme outlined above is valid for this enzyme)

SOLUTION OF PREPARATORY PROBLEM 10

10.1 **i)** $$\frac{d[ES]}{dt} = k_1[E][S] - (k_{-1} + k_2)[ES]$$

ii) $$\frac{d[P]}{dt} = k_2\,[ES]$$

10.2 $$[ES] = \frac{[S][E]_0}{K_M + [S]}$$

10.3 $$\frac{d[P]}{dt} = \frac{k_2[E]_0[S]}{K_M + [S]}$$

10.4 $$\frac{d[P]}{dt} = \frac{V_{max}[S]}{K_M + [S]}$$

10.5 The extinction coefficient of the product is calculated to be 9000 mol dm^{3}cm^{-1} at 299 nm. The product concentrations at each time point and the initial rate of production at each concentration of GTP are given in the table below:

GTP concentration (M = mol dm^{-3})	200 μM	150 μM	100 μM	80 μM	60 μM	40 μM	20 μM
Time (s)	Product concencentration (μM)						
6	0.571	0.521	0.494	0.437	0.419	0.288	0.219
7	0.648	0.608	0.530	0.504	0.431	0.281	0.274
8	0.787	0.710	0.631	0.562	0.502	0.343	0.281
9	0.776	0.781	0.710	0.657	0.579	0.361	0.328
10	0.909	0.889	0.788	0.717	0.638	0.430	0.336
11	1.00	0.982	0.836	0.780	0.709	0.494	0.391
12	1.14	1.02	0.943	0.857	0.786	0.550	0.429

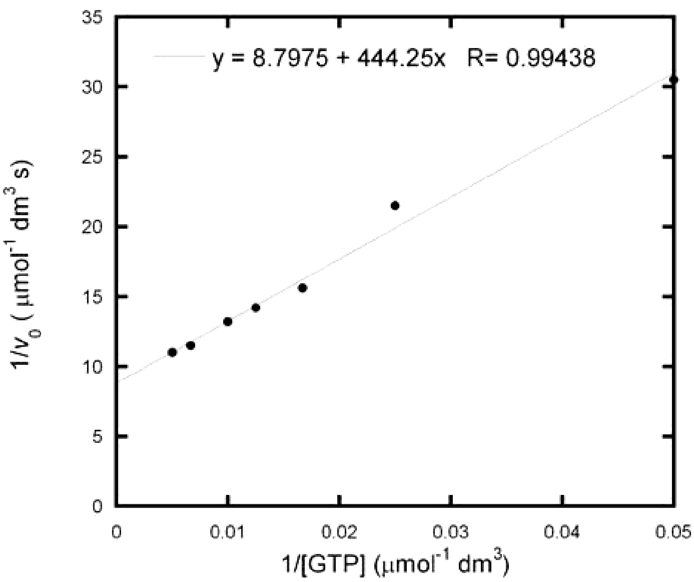
10.6 There are a number of different linear forms for the equation obtained in part 10.4. Writing d[P]/dt as V, the simplest form is:

$$\frac{1}{V} = \frac{K_M}{V_{max}\,[S]} + \frac{1}{V_{max}}$$

10.7

[GTP] (μmol dm^{-3})	V_0 (μmol dm^{-3} s^{-1})	1/ [GTP] (μmol^{-1} dm^3)	1/ V_0 (μmol^{-1} dm^3 s)
20	0.0328	0.0500	30.5
40	0.0464	0.0250	21.5
60	0.0640	0.0167	15.6
80	0.0702	0.0125	14.2
100	0.0755	0.0100	13.2
150	0.0871	0.00667	11.5
200	0.0910	0.00500	11.0

Plotting $1/V_0$ against 1/[GTP] gives:



Therefore the value for V_{max} is 0.114 μmol dm^{-3} s^{-1} whilst that for K_M is 50.5 μmol dm^{-3}.

THEORETICAL PROBLEM 11

Hydrocyanic acid

Hydrocyanic acid is a weak acid with dissociation constant $K_a = 4.93\times10^{-10}$

11.1 Find the pH of a 1.00 M solution of HCN.

11.2 10 dm^3 of pure water is accidentally contaminated by NaCN. The pH is found to be 7.40. Deduce the concentrations of each of the species, Na^+, H^+, OH^-, CN^-, HCN, and hence calculate the mass of NaCN added.

SOLUTION OF PREPARATORY PROBLEM 11

11.1

$$\mathrm{HCN} \rightleftarrows \mathrm{H^+} + \mathrm{CN^-}$$
$$c(1-x) \quad cx \quad cx$$

$$K_a = \frac{c\,x^2}{1-x} \;\Rightarrow\; c\,x^2 + K_a\,x - K_a = 0$$

$$\Rightarrow \quad x = \frac{-K_a + \sqrt{K_a^2 + 4\,K_a\,c}}{2\,c}$$

$[H^+] = c\,x = 2.22\times10^{-5} \Rightarrow$ pH = 4.65. Acceptable to ignore $[OH^-]$

11.2 (1) $[H^+][CN^-] = K_a[HCN]$

(2) $[H^+][OH^-] = K_w$

(3) $[H^+] + [Na^+] = [CN^-] + [OH^-]$

(4) $[Na^+] = [CN^-] + [HCN]$

(5) $[H^+] = 3.98\times10^{-8}$

From (2): $[OH^-] = 2.51\times10^{-7}$

From (1): $[HCN] = \dfrac{[H^+]\,[CN^-]}{K_a} = 80.8\,[CN^-]$

From (3): $[Na^+] = [CN^-] + 2.11\times10^{-7}$

From (4) $[HCN] = 2.11\times10^{-7}$

Hence $c(CN^{-}) = 2.62\times10^{-9}$ mol dm^{-3}, $c(Na^{+}) = 2.14\times10^{-7}$ mol dm^{-3}

Hence 10 dm^3 contains 2.14×10^{-6} mol NaCN, i. e. = 0.105 mg NaCN

THEORETICAL PROBLEM 12

Chlorine electrochemistry

12.1 State the Nernst equation.

12.2 You are given the following set of standard electrode potentials and half cell reactions for chlorine.

Alkaline	**E°/ V**	**Acidic**	**E°/ V**
$ClO_4^- + H_2O$ / $ClO_3^- + 2\ OH^-$	0.37	$ClO_4^- + 2\ H^+$ / $ClO_3^- + H_2O$	1.20
$ClO_3^- + H_2O$ / $ClO_2^- + 2\ OH^-$	0.30	$ClO_3^- + 3\ H^+$ / $HClO_2 + H_2O$	1.19
$ClO_2^- + H_2O$ / $ClO^- + 2\ OH^-$	0.68	$HClO_2 + 2\ H^+$ / $HOCl + H_2O$	1.67
$ClO^- + H_2O$ / ½ $Cl_2 + 2\ OH^-$	0.42	$HOCl + H^+$ / ½ $Cl_2 + H_2O$	1.63
½ Cl_2 / Cl^-	1.36	½ Cl_2 / Cl^-	1.36

Calculate the following quantities

i) The ionic product of water, K_w.

ii) The equilibrium constants for the disproportionation reaction of chlorine to oxidation states +1 and –1 under both acidic and alkaline conditions.

iii) The pK_a value for HOCl.

iv) The concentrations at pH 7.5 of HOCl and ClO^- in a solution where the total concentration of hypochlorite (chlorate (I)) is 0.20 mmol dm^{-3}, and the electrode potential for the reduction of this system to chlorine at this pH with unit activity of chlorine. These conditions are typical of a swimming pool.

SOLUTION OF PREPARATORY PROBLEM 12

12.2 i) The difference between the alkaline and acidic perchlorate half cells is:

	$E°$ / V	$G°$ / kJ mol^{-1}
$ClO_4^- + H_2O + 2\ e^- \rightarrow ClO_3^- + 2\ OH^-$	0.37	–71.4
$ClO_4^- + 2\ H^+ + 2\ e^- \rightarrow ClO_3^- + H_2O$	1.20	–231.6
$2\ H_2O \rightarrow 2\ H^+ + 2\ OH^-$		–80.1

Hence $K_w = 9.2\times10^{-15}$

ii) Alkaline conditions

	$E°$ / V	$G°$ / kJ mol^{-1}
$½\ Cl_2 + e^- \rightarrow Cl^-$	1.36	–131.2
$ClO^- + H_2O + e^- \rightarrow ½\ Cl_2 + 2\ OH^-$	0.42	–40.5
$Cl_2 + 2\ OH^- \rightarrow ClO^- + Cl^- + H_2O$		–90.7

Hence $K_c = 7.9\times10^{15}$.

Acidic conditions

	$E°$ / V	$G°$ / kJ mol^{-1}
$½\ Cl_2 + e^- \rightarrow Cl^-$	1.36	–131.2
$HOCl + H^+ + e^- \rightarrow ½\ Cl_2 + H_2O$	1.63	–157.3
$Cl_2 + H_2O \rightarrow HOCl + Cl^- + H^+$		+26.1

Hence $K_c = 2.7\times10^{-5}$

iii) The pK_a value for HOCl.

	$G°$ / kJ mol^{-1}
$HOCl + H^+ + e^- \rightarrow ½ Cl_2 + H_2O$	–157.3
$ClO^- + H_2O + e^- \rightarrow ½ Cl_2 + 2 OH^-$	–40.5
$HOCl + H^+ + 2 OH^- \rightarrow ClO^- + 2 H_2O$	–116.8
$2 H_2O \rightarrow 2 H^+ + 2 OH^-$	+160.2
$HOCl \rightarrow H^+ + ClO^-$	+43.4

$K_a = 2.4\times10^{-8}$ and pK_a = 7.61

iv) With this value of K_a, at pH 7.5 we have the ratio [HOCl] / [OCl$^-$] = 1.29, thus [HOCl] = 0.113×10^{-3} and [OCl$^-$] = 0.087×10^{-3}

$$E = E^o - \frac{RT}{F}\ln\left(\frac{a_{Cl_2}^{1/2}}{[HOCl][H^+]}\right) \quad \text{or} \quad E = E^o - \frac{RT}{F}\ln\left(\frac{a_{Cl_2}^{1/2}\,[OH^-]^2}{[OCl]^-}\right)$$

In either case, taking the activity of chlorine as 1, the result is 1.13 V.

THEORETICAL PROBLEM 13

The solubility of CuBr

The EMF of the cell

$$Pt|H_2(g)\ (p = 1.0\ bar)\ |\ HBr(aq)\ (1.0\times10^{-4}\ mol\ dm^{-3})\ |\ CuBr\ |\ Cu$$

is 0.559 V at 298 K. (Assume that all species in the cell behave ideally).

13.1 Write down half cell reactions for the right and left hand electrodes, the Nernst equation for the cell and the standard electrode potential for the CuBr electrode.

13.2 The standard electrode potential for the $Cu/Cu^+(aq)$ couple is 0.522 V. Calculate $\Delta G°$ for the dissolution of CuBr at 298 K and hence th e solubility product of CuBr.

13.3 Calculate the concentration of $Cu^+(aq)$ ions in the cell shown above.

13.4 By how much would the EMF of the cell change if the pressure of hydrogen were doubled?

SOLUTION OF PREPARATORY PROBLEM 13

13.1 RH: $CuBr(s) + e^- \rightarrow Cu(s) + Br^-(aq)$

LH: $H^+(aq) + e^- \rightarrow ½\ H_2(g)$

$$E = E^o - \frac{RT}{F}\ln\left(\frac{[H+][Br^-]}{p_{H_2}^{1/2}}\right) \qquad E^o = +0.086\ V$$

13.2 Using $\Delta G° = -n\,E^o F$,

$$\Delta G^o\left(CuBr(s) + e^- \rightarrow\ Cu(s) + Br^-(aq)\right)\left(CuBr(s) + e^- \rightarrow\ Cu(s) + Br^-(aq)\right). =$$

$$= -8.3\ kJ\ mol^{-1}$$

$$\Delta G°\left(Cu^+(aq) + e^- \rightarrow\ Cu(s)\right) = -50.4\ kJ\ mol^{-1}$$

Taking the difference

$$\Delta G°(CuBr(s) + e^- \rightarrow\ Cu^+(aq) + Br^-(aq)) = +42.1\ kJ\ mol^{-1}$$

Using $\Delta G° = -\ RT \ln K_s$, $K_s = 4.2\times10^{-8}$

13.3 Since [Br$^-$(aq)] = 1.0×10^{-4} , [Cu$^+$] = 4.2×10^{-4}

13.4 Using the Nernst equation

$$E_2 - E_1 = \frac{RT}{F}\ln\left(\frac{p_2^{1/2}}{p_1^{1/2}}\right) = \frac{RT}{2F}\ln 2 = 0.0089 \text{ V}$$

THEORETICAL PROBLEM 14

Electrochemical equilibria

14.1 Calculate the standard electrode potential for the aqueous couple $[Fe(CN)_6]^{3-}$ / $[Fe(CN)_6]^{4-}$ from the following data:

$E°(Fe^{3+}(aq) \mid Fe^{2+}(aq)) = + 0.770$ V

$Fe^{3+}(aq) + 6\ CN^-(aq) \rightleftharpoons [Fe(CN)_6]^{3-}(aq)$ $\log_{10}K_c = 43.9$

$Fe^{2+}(aq) + 6\ CN^-(aq) \rightleftharpoons [Fe(CN)_6]^{4-}(aq)$ $\log_{10}K_c = 36.9$

The following standard electrode potentials have been reported:

$In^+(aq) + e^- \rightleftharpoons In(s)$ $E° = -0.13$ V

$In^{3+}(aq) + 3\ e^- \rightleftharpoons In(s)$ $E° = -0.34$ V

$Tl^+(aq) + e^- \rightleftharpoons Tl(s)$ $E° = -0.34$ V

$Tl^{3+}(aq) + 3\ e^- \rightleftharpoons Tl(s)$ $E° = +0.72$ V

14.2 Calculate the equilibrium constant for the disproportionation reaction $3\ M^+(aq) \rightarrow M^{3+}(aq) + 2\ M(s)$ for In and Tl. Comment on the result.

SOLUTION OF PREPARATORY PROBLEM 14

14.1 $Fe^{3+}(aq) + e^- \rightarrow Fe^{2+}(aq)$; $E° = +0.770$ V ; $\Delta G° = -74.3$ kJ mol^{-1}

$Fe^{3+}(aq) + 6\ CN^-(aq) \rightarrow Fe(CN)_3^{6-}(aq)$; $K_c = 7.9\times10^{43}$; $\Delta G° = -250.4$ kJ mol^{-1}

$Fe^{2+}(aq) + 6\ CN^-(aq) \rightarrow Fe(CN)_6^{4-}(aq)$; $K_c = 7.9\times10^{36}$; $\Delta G° = -210.5$ kJ mol^{-1}

Hence, from the cycle:

$Fe(CN)_6^{3-}(aq) + e^- \rightarrow Fe(CN)_6^{4-}(aq)$; $E° = +0.356$ V $\Delta G° = -34.4$ kJ mol^{-1} ;

b) (1) $In^+(aq) + e^- \rightarrow In(s)$ $E° = -0.13$ V, $\Delta G° = 12.5$ kJ mol^{-1}

(2) $In^{3+}(aq) + 3\ e^- \rightarrow In(s)$ $E° = -0.34$ V, $\Delta G° = 98.4$ kJ mol^{-1}

To balance 3×(1) – (2).

$3\ In^+(aq) + 3\ e^- \rightarrow 2\ In(s) + In^{3+}(aq)$ $K_c = 4.5\times10^{10}$ $\Delta G° = -60.8$ kJ mol^{-1}

(1) $Tl^{+}(aq) + e^{-} \rightarrow Tl(s)$ $E° = -0.34$ V, $\Delta G° = 32.8$ kJ mol^{-1}

(2) $Tl^{3+}(aq) + 3\ e^{-} \rightarrow Tl(s)$ $E° = +0.72$ V, $\Delta G° = -208.4$ kJ mol^{-1}

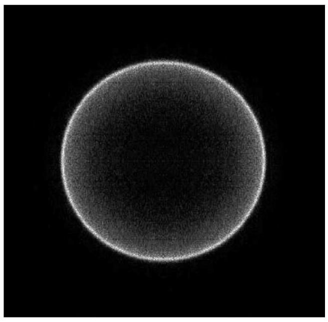
$3Tl^{+}(aq) + 3\ e^{-} \rightarrow 2\ Tl(s) + Tl^{3+}(aq)$ $\Delta G° = +306.8$ kJ mol^{-1}

THEORETICAL PROBLEM 15

Photodissociation of Cl_2

Photodissociation is the process in which a molecule fragments after absorbing a photon with sufficient energy to break a chemical bond. The rupture of a chemical bond is one of the most fundamental chemical processes, and has been studied in great detail.

In a modified time-of-flight mass spectroscopy technique for studying Cl–Cl bond cleavage, a laser beam is crossed with a molecular beam of Cl_2, and dissociation occurs at the crossing point. A second laser beam ionises the resulting Cl atoms (without affecting their velocities), so that a carefully tuned electric field may be used to guide them along a 40 cm flight path to a position sensitive detector.



The image of the Cl fragments recorded at the detector is shown on the right. Note that this represents a two-dimensional projection of the full three-dimensional velocity distribution.

15.1 A potential of 3000 V is used to direct the ionised Cl atoms to the detector. What is their flight time? Take the molar mass of Cl to be 35 g mol^{-1}.

15.2 The image appears as a single ring of Cl atoms as a result of conservation of energy and momentum. The outside diameter of the ring is 12.68 mm. What velocity did the Cl atoms acquire as a result of the photodissociation?

15.3 The bond dissociation energy of Cl_2 is 243 kJ mol^{-1}. Use conservation of energy to determine the laser wavelength.

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SOLUTION OF PREPARATORY PROBLEM 15

15.1 The kinetic energy of the ions is $eV = ½\, m\, v^2$, so $v = (2\, eV / m)^{1/2}$ = 128 600 m s^{-1}.

The distance the ions fly is d = 0.4 m, so the flight time is $t = d / v$ = 3.11 μs.

15.2 The atoms travel a radial distance of 6.34 mm in 3.11 μs, so their velocity is v_{Cl} = 2038 m s^{-1}.

15.3 Conservation of energy requires that $h\nu - D_0 = 2\, (½\, m_{\mathrm{Cl}}\, v_{\mathrm{Cl}}^2)$.

From the data given,

$D_0 = 4.035\times10^{-19}$ J (2.519 eV), $m_{Cl} = 5.812\times10^{-26}$ kg,

$v_{Cl} = 2038$ m s^{-1}.

The photon energy is therefore $h\nu = 6.449\times10^{-19}$ J (4.026 eV), corresponding to a wavelength $\lambda = hc / E$ of 308 nm.

THEORETICAL PROBLEM 16

Laser Cooling

This question is about laser cooling, which is a quick and efficient way of cooling ions down to very cold temperatures. The mean kinetic energy of a molecule is related to its temperature by $E = \frac{3}{2} k_B T$, where k_B is the Boltzmann constant.

16.1 Calcium atoms leak out of an oven at 600 °C. Calculate the mean kinetic energy of the calcium atoms and hence the rms momentum and rms speed of a ^{40}Ca atom, whose relative isotopic mass is 39.96.

16.2 The atoms drift into an ion trap where they are photoionised and trapped. While in this trap they are bombarded with laser light of wavelength 396.96 nm. Calculate the frequency, energy and momentum of a photon with this wavelength.

16.3 The ions go through an optical cycle repeatedly. Ions absorb a photon from the laser when they are moving in the opposite direction to the light (this is achieved using the Doppler Effect) and then re-emit a photon in a random direction. The net effect of this procedure is to slow the ion down slightly. Calculate the change in mean momentum and speed at each cycle and the number of photons that would need to be absorbed to bring the ion approximately to rest. (In practice this process was found to reduce the temperature to about 0.5 mK.)

16.4 Write down the ground electronic configuration of the Ca^+ ion, and calculate the orbital and spin angular momentum of the unpaired electron.

16.5 In the excited configuration involved in the laser cooling transition the unpaired electron has been excited into the lowest available *p* orbital. Calculate the orbital and spin angular momentum of the unpaired electron.

16.6 In this excited state the electron experiences a magnetic field because of its own orbital motion around the charged nucleus. The spin of the electron can line up either parallel or antiparallel to this field, and the two states have slightly different energies. The resultant quantum number, *j*, for the total electronic angular momentum takes values from $|l - s|$ to $|l + s|$ in integer steps. Calculate the possible values of *j*.

16.7 The laser cooling transition is to the lower of these two levels, the transition from the ground state to the higher level has a wavelength 393.48 nm. Calculate the energy difference between the two levels resulting from the excited configuration.

SOLUTION OF PREPARATORY PROBLEM 16

16.1 $E = 3/2\ kT = 1.81\times10^{-20}$ J

$p = \sqrt{2\,mE} = 4.90\times10^{-23}$ kg m s^{-1}

$v = p\ /\ m = 738$ m s^{-1}

16.2 $\nu = c\ /\ \lambda = 7.5522\times10^{14}$ Hz

$E = h\ \nu = 5.0042\times10^{-19}$ J

$p = h\ /\ \lambda = 1.6692\times10^{-27}$ kg m s^{-1}

16.3 At each cycle the mean momentum of the ion is reduced by the momentum of the photon it has absorbed. The re-emission is isotropic and has no effect on the mean momentum.

$\Delta p_{atom} = -1.6692\times10^{-27}$ kg m s^{-1}

$\Delta v_{atom} = p_{atom}\ /\ m = -2.5156\times10^{-2}$ m s^{-1}

To slow the ion to rest therefore takes approximately 2.93×10^{4} photons.

16.4 Ca^+: $1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 4s^1$.

$l = 0$, hence $\hbar\sqrt{l(l+1)} = 0$

$s = ½$, hence $\hbar\sqrt{s(s+1)} = h\,\dfrac{\sqrt{3}}{2}$

16.5 For an electron in a p orbital, $l = 1$, hence $\hbar\sqrt{l(l+1)} = \hbar\sqrt{2}$

$s = ½$, hence $\hbar\sqrt{s(s+1)} = h\,\dfrac{\sqrt{3}}{2}$

16.6 $j = 1/2$ (antiparallel)

$j = 3/2$ (parallel)

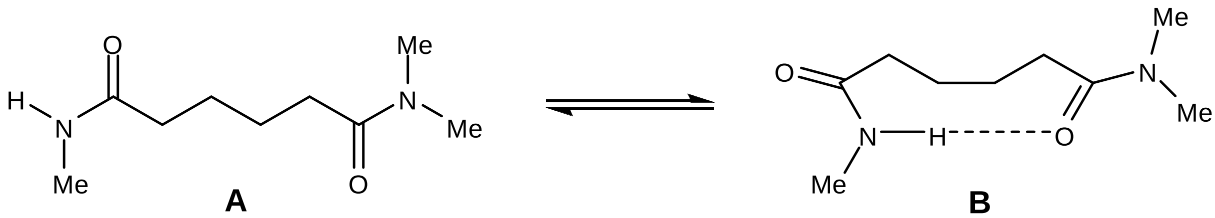
16.7 The first transition was calculated in 16.2: $E = h\nu = 5.0042\times10^{-19}$ J

The second transition is $E = hc\ /\ \lambda = 5.0484\times10^{-19}$ J

The energy difference is $\Delta E = 4.43\times10^{-21}$ J

THEORETICAL PROBLEM 17

Hydrogen bond strength determination



In an experiment to measure the strength of the intramolecular hydrogen-bond in **B**, the chemical shift of the amide proton δ_{obs}, was measured at various temperatures.

T / K	δ_{obs} / ppm
220	6.67
240	6.50
260	6.37
280	6.27
300	6.19

The observed chemical shift, δ_{obs}, is the weighted average of the shifts of the N–H proton when the amide is completely hydrogen bonded, δ_h, and when it is completely free, δ_f.

17.1 Derive an expression for the observed chemical shift of the N–H proton, δ_{obs}.

17.2 Derive an expression for the equilibrium constant *K* for **A** $\rightleftharpoons$ **B** in terms of δ_{obs}, δ_h, and δ_f.

17.3 Given that δ_h = 8.4 ppm and δ_f = 5.7 ppm, calculate the equilibrium constants for the cyclisation at the different temperatures.

17.4 By plotting a suitable graph, determine the standard enthalpy change for **A** → **B** and the standard change in entropy at 300 K.

17.5 Discuss the significance of your answers to part (17.2).

SOLUTION OF PREPARATORY PROBLEM 17

17.1 $\delta_{\text{obs}} = x_h\delta_h + x_f\,\delta_f$

where x_h and x_f are the mole fractions of the hydrogen bonded species and the free species, respectively, and so $x_h + x_f = 1$.

17.2 $K = \dfrac{x_h}{x_f}$

$\delta_{\text{obs}} = x_h\,\delta_h + x_f\,\delta_f = x_h\,\delta_h + (1 - x_h)\,\delta_f \Rightarrow x_h\,(\delta_h - \delta_f) = \delta_{\text{obs}} - \delta_f$

also

$\delta_{\text{obs}} = (1 - x_f)\delta_h + x_f\,\delta_f \quad \Rightarrow x_f\,(\delta_f - \delta_h) = \delta_{\text{obs}} - \delta_h$

$$K = \frac{x_h}{x_f} = \frac{\delta_{\text{obs}} - \delta_f}{\delta_h - \delta_f} \times \frac{\delta_f - \delta_h}{\delta_{\text{obs}} - \delta_h} = \frac{\delta_{\text{obs}} - \delta_f}{\delta_h - \delta_f} \times \frac{\delta_h - \delta_f}{\delta_h - \delta_{\text{obs}}} = \frac{\delta_{\text{obs}} - \delta_f}{\delta_h - \delta_{\text{obs}}}$$

17.3

T / K	δ_{obs}	K
220	6.67	0.5607
240	6.5	0.4211
260	6.37	0.3300
280	6.27	0.2676
300	6.19	0.2217

17.4 A plot of ln$K$ *vs* 1/T gives a straight line with slope (= – $\Delta_rH°/R$) = 764.1 K

[and intercept (= $\Delta_rS°/R$) = – 4.050].

$\Delta_rH° = -764.1 \times 8.3145\ \text{J mol}^{-1} = -6.4\ \text{kJ mol}^{-1}$

$\Delta_rS°_{(300)} = ((\Delta_rH° - \Delta_rG°_{(300)}) / 300)\ \text{J K}^{-1}\ \text{mol}^{-1} = -34\ \text{J K}^{-1}\ \text{mol}^{-1}$

17.5 The enthalpy change is exothermic, which is not surprising since a new bond is formed. However, the value is much smaller than that for forming a full covalent bond.

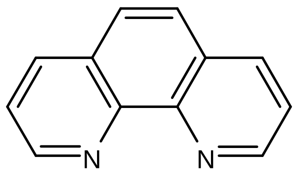
The entropy change is negative due to the loss of rotational freedom as the chain becomes a ring.

THEORETICAL PROBLEM 18

Magnetic Complexes

Reaction of $FeCl_2$ with phenanthroline (phen) and two equivalents of K[NCS] yields the octahedral iron (II) complex $Fe(phen)_2(NCS)_2$ (**A**). At liquid nitrogen temperature **A** has a magnetic moment of 0.0 B.M. but a magnetic moment near 4.9 B.M. at room temperature. [The effective magnetic moment, μ_{eff}, for a complex containing n unpaired electrons is given by:

$$\mu_{eff} = \sqrt{n(n+2)} \text{ Bohr magnetons, [B.M.]}$$



Phenanthroline

18.1 Draw structures of the possible isomers of **A**

18.2 Determine the number of valence electrons which occupy the *d*-orbitals of **A**

18.3 Draw electronic configurations for the *d*-orbital occupancy consistent with the high temperature and low temperature magnetic behaviour of **A** [You should determine the expected effective magnetic moment in each case]

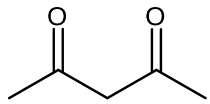
18.4 Which of the following statements is/are consistent with the low temperature magnetic data:

	YES	NO	INSUFFICIENT DATA
Hund's Rules are obeyed	☐	☐	☐
The Pauli Exclusion Principle is obeyed	☐	☐	☐

18.5 Which of the following statements is/are consistent with the low temperature magnetic data:

	YES	NO	INSUFFICIENT DATA
Hund's Rules are obeyed	☐	☐	☐
The Pauli Exclusion Principle is obeyed	☐	☐	☐

The ligand Hacac (**B**, $C_5H_8O_2$) is shown below. Treatment with NH_3 yields the anion $acac^-$ (**C**) whose C–O bond lengths are longer than those in **B** and whose ^1H NMR exhibits just two peaks. Addition of three equivalents of acac$^-$ to an aqueous solution of $FeCl_3$ yields a bright red octahedral complex (**D**) of composition $C_{15}H_{21}O_6Fe$ with an effective magnetic moment of 5.9 B.M.



Hacac

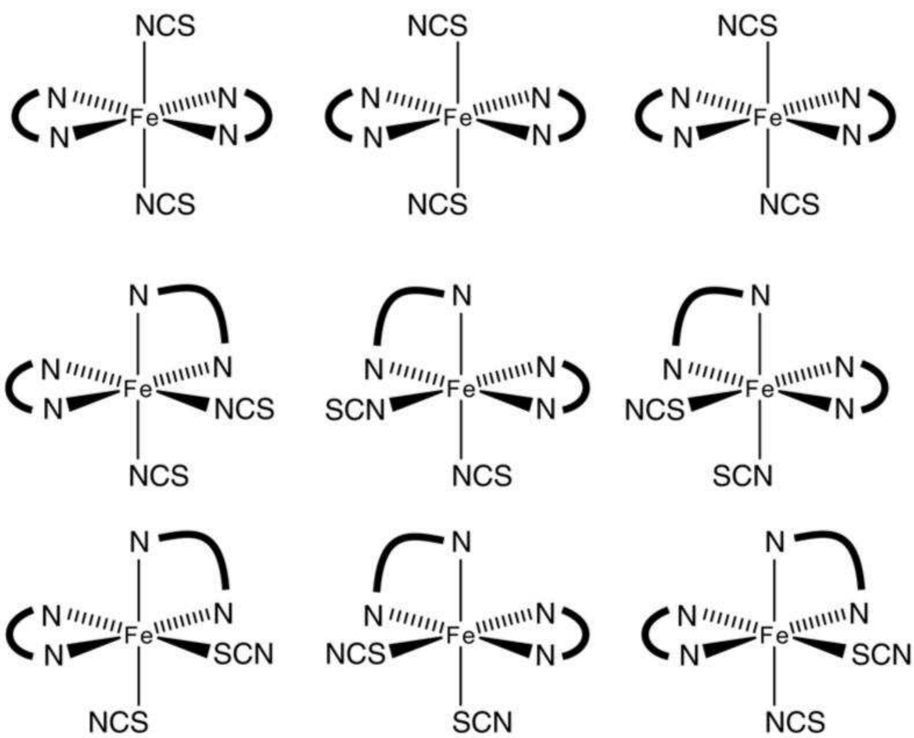
18.6 Draw the anion acac$^-$ (**C**) and determine a resonance structure to explain the difference in C–O bond lengths between **B** and **C**.

18.7 Draw the structures of **B** and **C** and clearly label the hybridisation state at each carbon in each case.

18.8 Draw possible isomers of **D** and predict the *d*-orbital occupancy in light of the observed magnetic data.

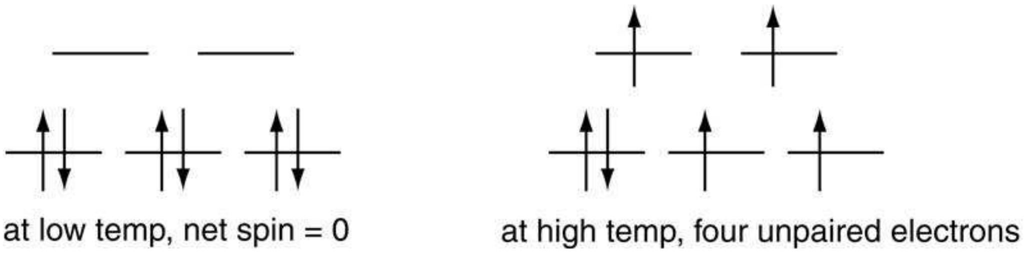
SOLUTION OF PREPARATORY PROBLEM 18

18.1 The NCS ligand could bond either through the sulfur, or through the nitrogen atom. Representing the bidentate phenanthroline ligand as a line between two adjacent sites on the octahedral complex gives the following isomers.



18.2 Since the iron is in the +2 state, the number of d electrons the Fe contributes is 6.

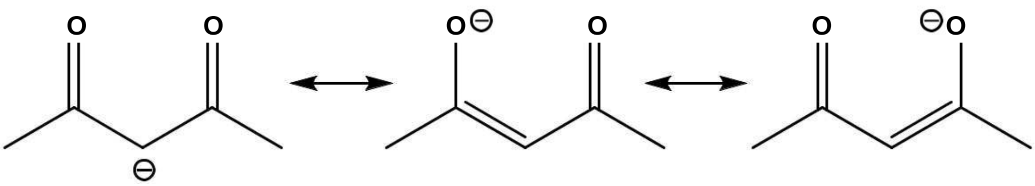
18.3 μ_{eff} = 4.9 B.M. = $\sqrt{n(n+2)}$. Solving gives n = 4.



18.4 & 18.5

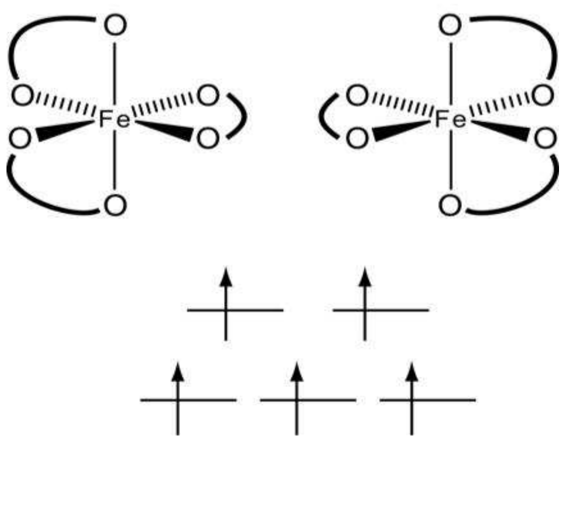
Unfortunately, this question is rather vague. Hund's Rules of maximum multiplicity apply only to degenerate ortbitals; the Pauli exclusion principle is always obeyed.

18.6



18.7

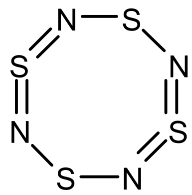
18.8 μ_{eff} = 5.9 B.M. = $\sqrt{n(n+2)}$. Solving gives n = 5.



THEORETICAL PROBLEM 19

Explosive S_4N_4

Bubbling gaseous NH_3 through a solution of SCl_2 generates a red explosive solid, S_4N_4. Its structure can be represented in a number of ways; one way is as shown below.



19.1 Write a balanced equation for the formation of S_4N_4 from NH_3 and SCl_2

19.2 Construct a Born-Haber cycle for the formation of S_4N_4 and use the data below to detine the enthalpy of formation of S_4N_4

19.3 Use the additional data and your answer to part 19.1 to determine the enthalpy change for the reaction of NH_3 with SCl_2

The S_4N_4 molecule has a rich reaction chemistry including both oxidation and reduction reactions. Treatment of S_4N_4 with an excess of AsF_5 in sulfur dioxide generates the salt $[S_4N_4][AsF_6]_2$ whereas treatment with excess $SnCl_2 \times 2\ H_2O$ in methanol yields $S_4N_4H_4$

19.4 Write balanced equations for these two reactions

Additional data:

E(S–S) = 226 kJ mol^{-1}	E(N≡N) = 946 kJ mol^{-1}
E(S–N) = 273 kJ mol^{-1}	E(S=N) = 328 kJ mol^{-1}
$\Delta H_{vap}(S_8)$ = 77 kJ mol^{-1}	$\Delta H_{vap}(S_4N_4)$ = 88 kJ mol^{-1}
$\Delta_f H(NH_3)$ = – 45.9 kJ mol^{-1}	$\Delta_f H(SCl_2)$ = – 50.0 kJ mol^{-1}
$\Delta_f H$(HCl) = – 92.3 kJ mol^{-1}	

SOLUTION OF PREPARATORY PROBLEM 19

19.1 $4\ NH_3 + 6\ SCl_2 \rightarrow S_4N_4 + 12\ HCl + 1/4\ S_8$

could also be written with the extra ammonia molecules needed to react with the product HCl. i.e.:

$12\ NH_3 + 6\ SCl_2 \rightarrow S_4N_4 + 12\ NH_4Cl + 1/4\ S_8$

19.2 To form one mole of S_4N_4 from the elements requires breaking four S–S bonds, two N≡N bonds and forming four S=N bonds and four S–N bonds:

$\Delta_f H° = (4 \times 226) + (2 \times 946) - (4 \times 328) - (4 \times 273) = 392\ \text{kJ mol}^{-1}$

(This value is somewhat out due to the imprecise nature of the bond strengths.)

19.3 For the reaction as first written in 19.1

$\Delta_r H° = \Delta_f H°(S_4N_4) + 12\ \Delta_f H°(HCl) + 1/4\ \Delta_f H°(S_8) - 4\ \Delta_f H°(NH_3) - 6\ \Delta_f H°(SCl_2)$

$392 + 12\times(-92.3) + 0 - 4\times(-45.9) - 6\times(-50.0) = -232\ \text{kJ mol}^{-1}$

19.4 i) $S_4N_4 + 3\ AsF_5 \rightarrow (S_4N_4)^{2+}\ 2\ AsF_6^- + AsF_3$

Further complexation occurs with the AsF_3 with AsF_5 and AsF_6^- so the reaction may also be written:

$S_4N_4 + 4\ AsF_5 \rightarrow (S_4N_4)^{2+}\ AsF_6^- + [As_3F_{14}]^-$

ii) During this reaction, the Sn(II) becomes oxidised to Sn(IV):

$S_4N_4 + 2\ SnCl_2 + 4\ MeOH \rightarrow S_4N_4H_4 + 2\ SnCl_2(MeO)_2$

THEORETICAL PROBLEM 20

Sulfur compounds

20.1 Identify the compounds **A** to **D** in the scheme shown below and describe their structures with the aid of suitable sketches.

You may wish to refer to the following additional information:

Compound **A** is a yellow liquid containing 52.5 % Cl and 47.5 % S.

Compound **B** is a moisture-sensitive, red liquid.

Compound **C** is a colourless liquid containing 59.6 % Cl, 26.95 % S and 13.45 % O.

Compound **D** has a molar mass of 134.96 g mol^{-1}. Compound **D** can also be obtained by direct reaction of **C** with O_2.

$$\text{Elemental sulfur} \xrightarrow[130\ ^\circ\text{C}]{Cl_2} \mathbf{A} \xrightarrow[\text{Fe(III) catalyst}]{Cl_2} \mathbf{B} \xrightarrow{Cl_2} \mathbf{C} + \mathbf{D}$$

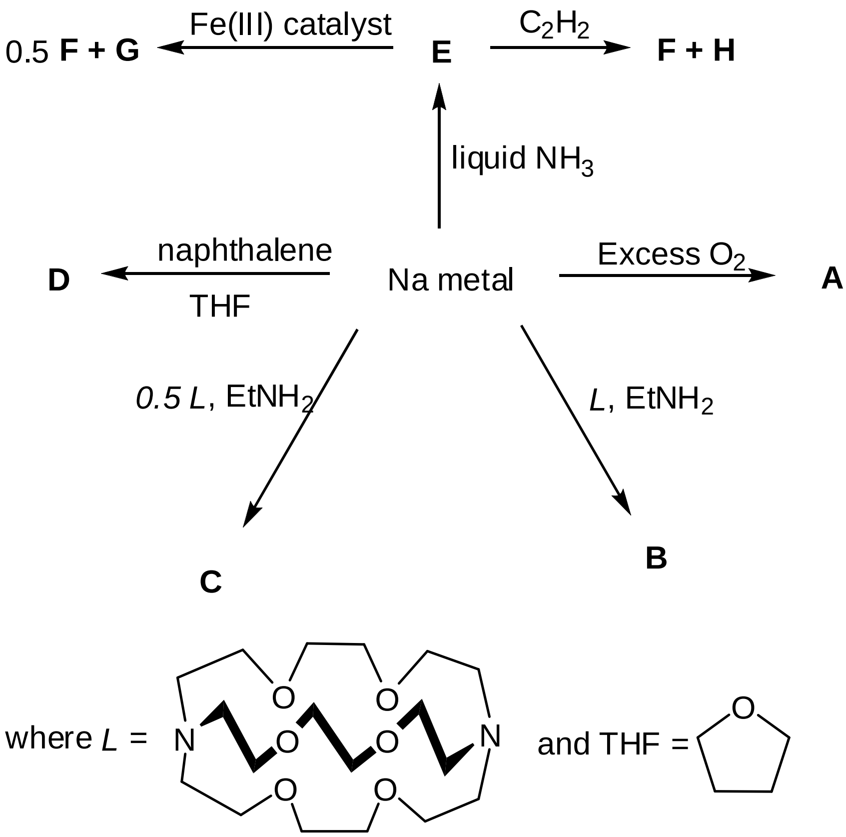
SOLUTION OF PREPARATORY PROBLEM 20

20.1 **A** – S_2Cl_2 **B** – SCl_2 **C** – $SOCl_2$ **D** – SO_2Cl_2

THEORETICAL PROBLEM 21

Reactions of sodium

The scheme below summarises some reactions of sodium metal.



21.1 Compound **A** is white, crystalline solids. Identify it and discuss the bonding in the anion. How do the metals Li and K react with excess O_2?

21.2 Compounds **B** and **C** are both deeply coloured solids. Identify each of them and briefly discuss the driving force for their formation. Note that the $EtNH_2$ acts only as a solvent for these reactions.

21.3 Solutions of **D** and **E** are deep green and blue, respectively. What are the species present in these solutions?

21.4 Compound **G** is a white crystalline ionic solid, while **F** is a colourless, highly flammable gas that does not condense in liquid NH_3. Identify **F** and **G**.

21.5 Compound **H** is a white, ionic solid. One mole of the gas **F** is formed for each mole of **H** that is formed. Identify compound **H**.

SOLUTION OF PREPARATORY PROBLEM 21

21.1 **A** = Na_2O_2

$2\ Li + O_2 \rightarrow 2\ Li_2O$

$K + O_2 \rightarrow KO_2$

21.2 **B** = $NaL^+\ e^-$

C = $NaL^+\ Na^-$

21.3 **D** = naphthalene anion radical

E = $Na^+\ e^-(NH_3)$

21.4 **F** = H_2

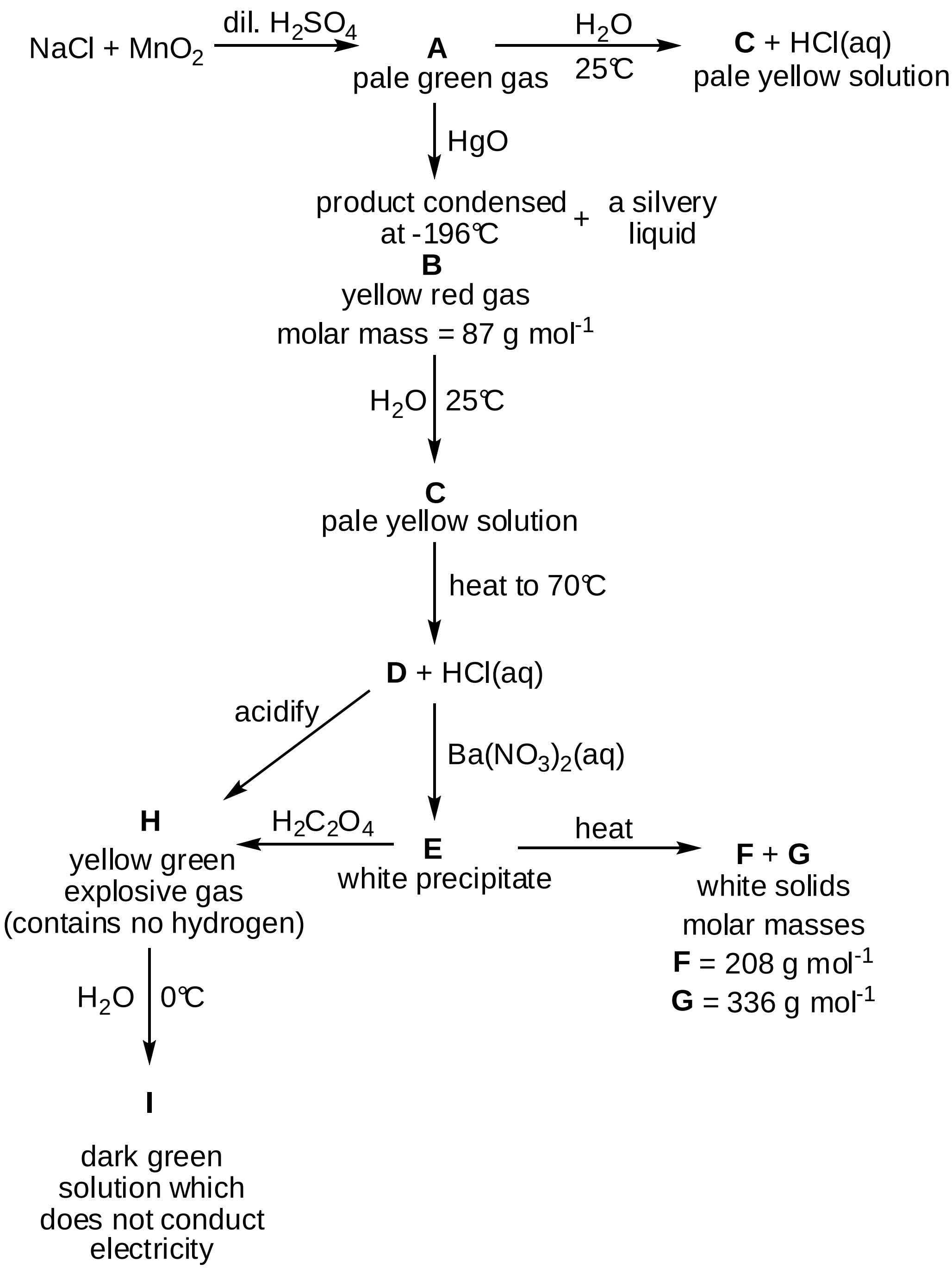
G = $NaNH_2$

21.5 **H** = C_2HNa

THEORETICAL PROBLEM 22

Chlorine compounds

Compounds **A** to **I** all contain chlorine.



22.1 Identify **A** to **I** and write balanced equations for the following reactions:

$$\mathbf{A} + H_2O \rightarrow \mathbf{C} + HCl$$

$$\mathbf{B} + H_2O \rightarrow \mathbf{C}$$

$$\mathbf{B} \rightarrow \mathbf{D} + HCl$$

$$\mathbf{E} \rightarrow \mathbf{F} + \mathbf{G}$$

22.2 Predict the structures of **B**, **D**, **F** and **H**, and comment on points of interest in the structure of **H**.

22.3 Comment on the conditions used in the sequence of reactions:

$$\mathbf{B} + H_2O \longrightarrow \mathbf{C} + HCl$$
$$\mathbf{C} \longrightarrow \mathbf{D} + HCl$$
$$\mathbf{C} \longrightarrow \mathbf{F} + \mathbf{G}$$

SOLUTION OF PREPARATORY PROBLEM 22

22.1

A	Cl_2	**B**	Cl_2O	**C**	HClO	**D**	$HClO_3$
E	$Ba(ClO_3)_2$	**F**	$BaCl_2$	**G**	$Ba(ClO_4)_2$	**H**	ClO_2

Chemical equations:

Cl_2 (**A**) + H_2O $\longrightarrow$ HClO (**C**) + HCl

Cl_2O (**B**) + H_2O $\longrightarrow$ 2 HClO (**C**)

3 HClO (**C**) $\longrightarrow$ $HClO_3$ (**D**) + 2 HCl

4 $Ba(ClO_3)_2$ (**E**) $\longrightarrow$ $BaCl_2$ (**F**) + 3 $Ba(ClO_4)_2$ (**G**)

22.2 **B:** bent molecule Cl-O-Cl

D: trigonal pyramidal Cl(O)3 with hydrogen atom bounded to one oxygen atom

F: $BaCl_2$ is an ionic compound. It consists of cations Ba^{2+} and anions Cl^-. It crystallizes in two forms (polymorphs): cubic and orthorhombic.

H: bent molecule O-Cl-O

22.3

$$\mathbf{A} + H_2O \xrightarrow{25℃} \mathbf{C} + HCl$$
$$\mathbf{C} \xrightarrow{70℃} \mathbf{D} + HCl$$
$$\mathbf{E} \xrightarrow{\text{heat}} \mathbf{F} + \mathbf{G}$$

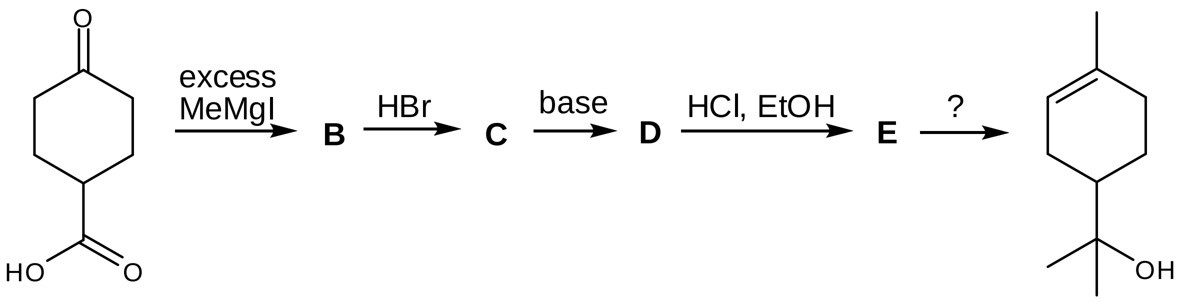
THEORETICAL PROBLEM 23

Perkin Junior

Sir William Henry Perkin accidentally discovered "mauveine", the first commercial synthetic dyestuff, in 1856 while working in his home laboratory. His love of chemistry was passed on to his eldest son William Henry Perkin, Jr. (1860-1929). William Henry Perkin Jr is best known for his work on the synthesis and structure elucidation of natural products including α-terpineol. Perkin's synthesis of this monoterpene forms the basis of this question.

As Perkin stated, the synthesis of α-terpineol (**F**) *"was undertaken with the object of synthesising…terpineol…, not only on account of the interest which always attaches to syntheses of this kind, but also in the hope that a method of synthesis might be devised of such a simple kind that there would no longer be room for doubt as to the constitution of these important substances"*.

We begin Perkin's synthesis of α-terpineol with the ketone **A**.



A **F**

23.1 Identify the intermediates **B**, **C**, **D** and **E**.

23.2 What reagent would you use to convert **E** into α-terpineol **F**.

23.3 Suggest reagents for the preparation of **A** from 4-hydroxybenzoic acid. α-Terpineol **F** has been used to prepare other monoterpenes.

23.4 Treatment of α-terpineol **F** with potassium hydrogen sulfate gave compound **G** which reacts with two equivalents of bromine. Identify **G** given that it is chiral.

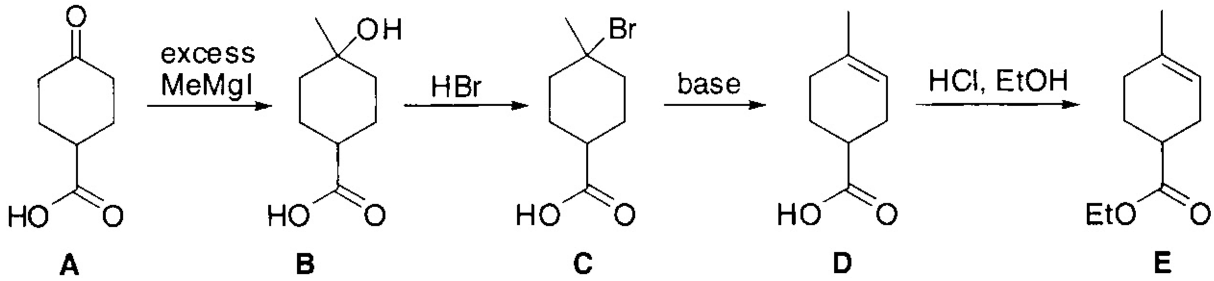
23.5 Treatment of α-terpineol **F** with aqueous acid gives compound **H**. Exposure of **H** to stronger acid gives **I**. Identify **H** and **I**.

In the ^{1}H NMR spectrum of **H** addition of D_2O results in the disappearance of one signal corresponding to two hydrogens, whereas the ^{1}H NMR spectrum of compound **I** remains unchanged on addition of D_2O.

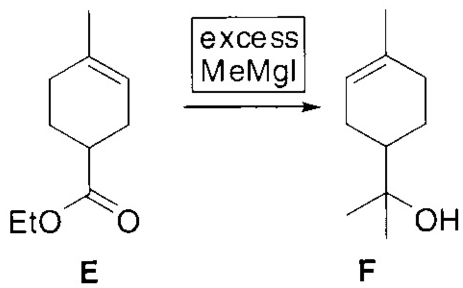
Neither compound **H** nor **I** are chiral, and neither react with bromine.

SOLUTION OF PREPARATORY PROBLEM 23

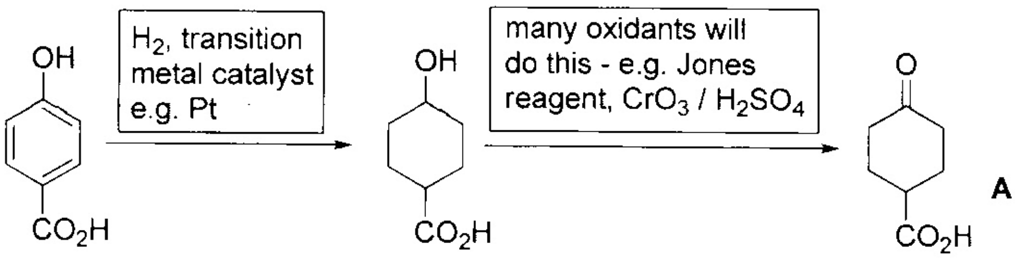
23.1



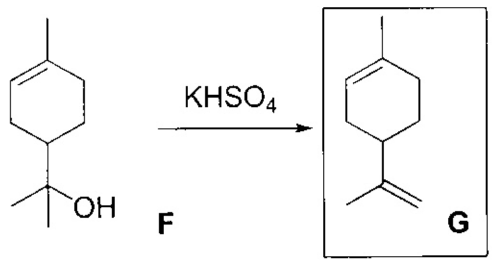
23.2



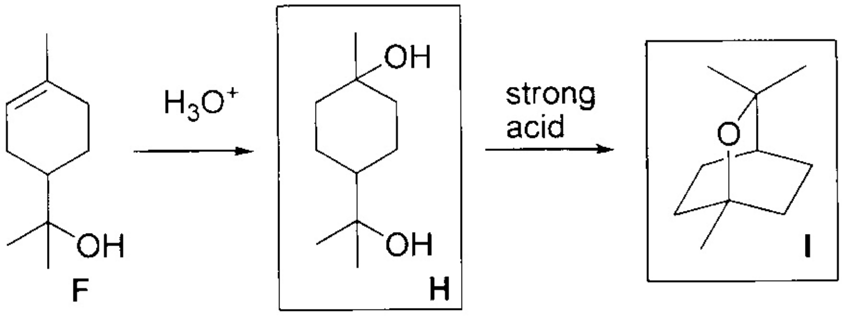
23.3



23.4



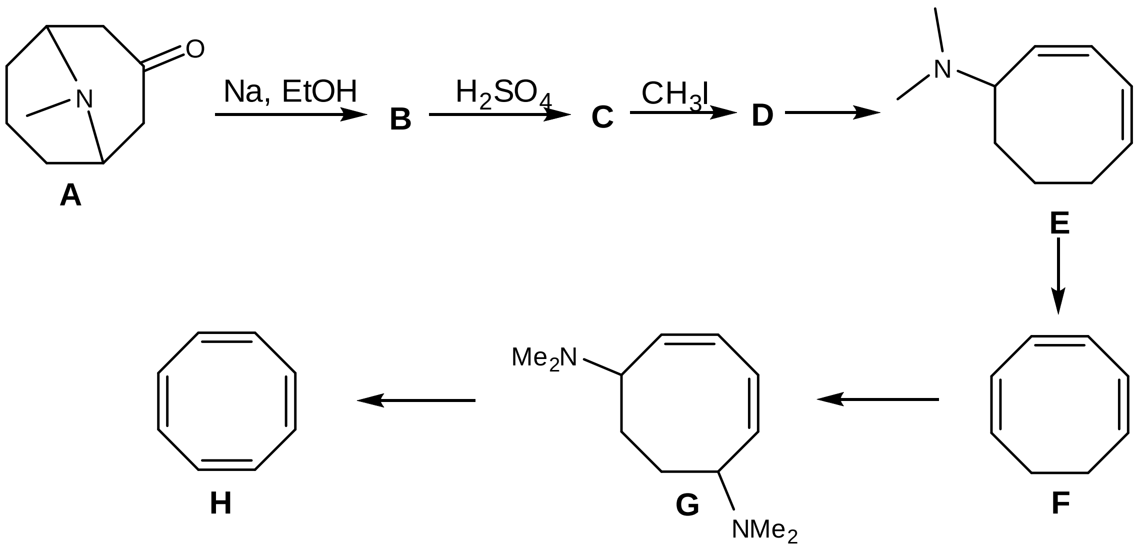
23.5



THEORETICAL PROBLEM 24

Cyclooctatetraene

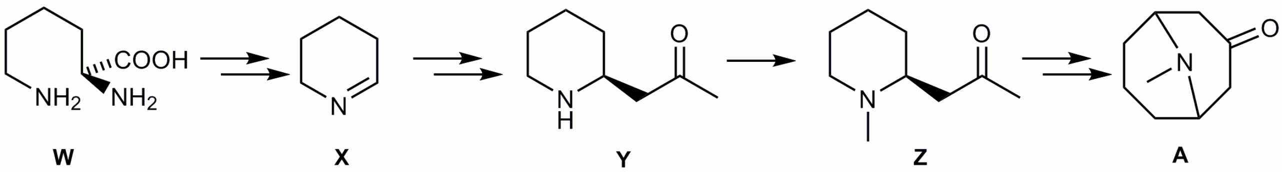
Cyclooctatetraene H was an exceedingly important molecule in the development of the theory of organic chemistry. It belongs to a class of compounds which, although they have alternating single and double bonds in a ring, do not benefit from the increase in stability that aromatic compounds such as benzene do. Cyclooctatetraene was first synthesised by Willstätter starting from the natural product pseudopelletierine **A**, according to the scheme below; in 1940 Reppe reported a one step synthesis of cyclooctatetraene from acetylene thus making this previously precious laboratory chemical into a commercially available material.



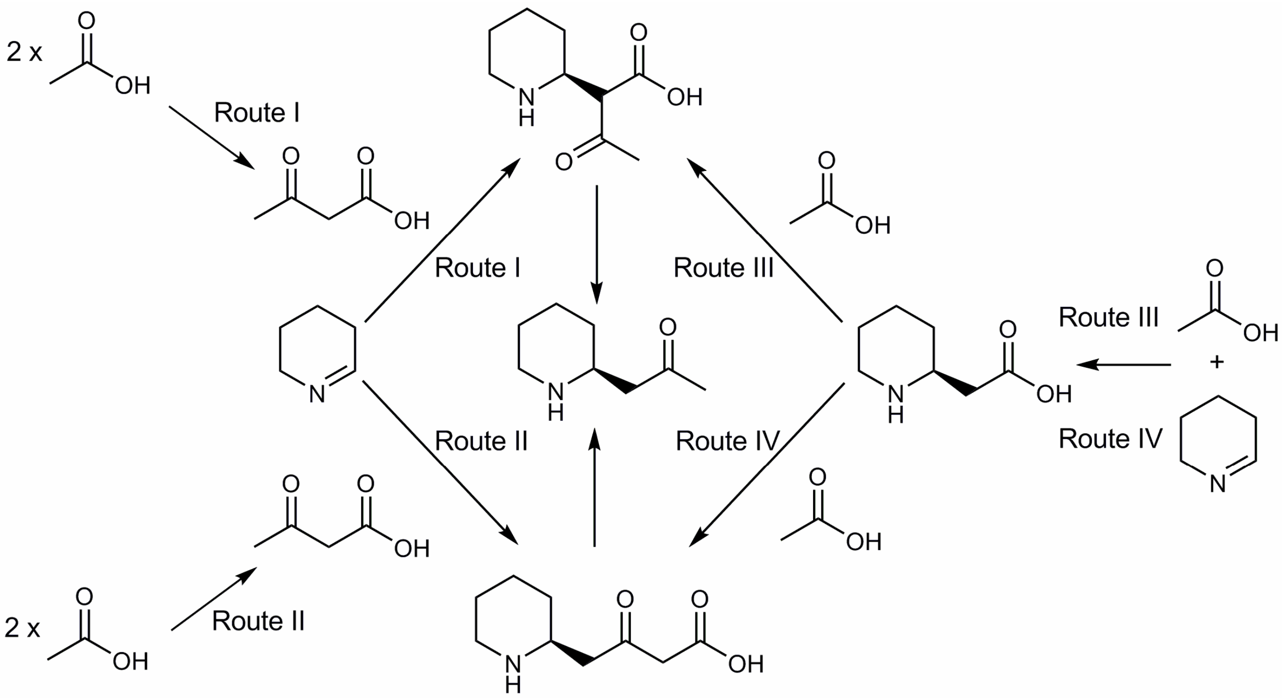
24.1 Identify intermediates **B**, **C**, and **D**.

24.2 Suggest reagents for the conversion of **D** into **E**, **E** into **F**, **F** into **G** and **G** into cyclooctatetraene.

Pseudopelletierine A is a natural product found in the bark of the pomegranate. Biochemical labelling studies have shown that it is biosynthesised from lysine W, and ethanoate via Δ^1–piperideine X, pelletierine Y and N-methylpelletierine Z.



The route by which pelletierine is formed from Δ^1–piperideine and ethanoate was determined using ^{13}C labelling studies. Four possible routes can be postulated:



To distinguish between the different biosynthetic routes two experiments were carried out. In the first experiment plants were fed a mixture of sodium ethanoate labelled with ^{13}C at both carbon positions (sodium [1,2-$^{13}C_2$]ethanoate) and the unlabelled compound (a mixture was used to increase the probability that only a single labelled ethanoate molecule would be incorporated into each molecule of pelletierene).

24.3 Draw structures of pelletierine indicating the position at which ^{13}C labels would appear in each of the biosynthetic routes. You may assume that in each case only one of the incorporated ethanoate molecules was ^{13}C labelled.

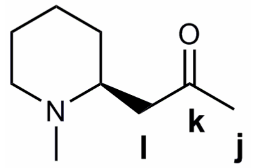
24.4 Which biosynthetic routes can be distinguished in this experiment?

In a second experiment plants were fed a mixture of sodium 3-oxobutanoate labelled with ^{13}C at all carbon positions (sodium [1,2,3,4-$^{13}C_4$]3-oxobutanoate) and the unlabelled compound.

24.5 Which biosynthetic routes can be distinguished in this experiment?

N-methylpelletierene was isolated from plants grown in each of the experiments and also from plants grown in presence of compounds with a natural abundance of ^{13}C (the control experiment). The ^{13}C NMR spectrum of each of the samples was recorded.

In *N*-methylpelletierene isolated from the control experiment atoms labelled **j**, **k** and **l** in the structure shown have ^{13}C NMR chemical shifts of 31.0, 207.8 and 47.1 respectively. Each of these peaks is a singlet. These peaks also appear in the spectra of *N*-methylpelletierene isolated in experiments 1 and 2, however there are also the following additional peaks:



N-methylpelletierene

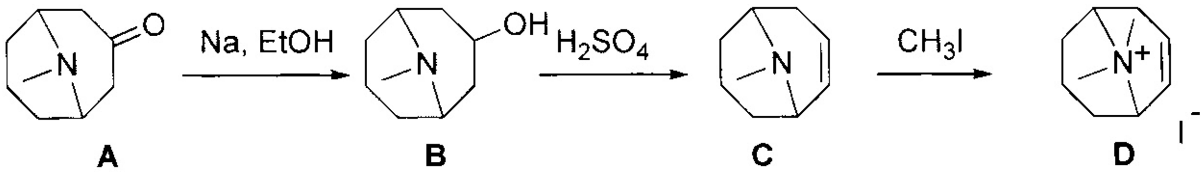
These peaks also appear in the spectra of *N*-methylpelletierene isolated in experiments 1 and 2, however there are also the following additional peaks:

Experiment 1			Experiment 2		
^{13}C shift (ppm)	Multiplicity	Coupling constant (Hz)	^{13}C shift (ppm)	Multiplicity	Coupling constant (Hz)
31.0	doublet	40.4 ± 1.8	31.0	doublet of doublets	39.8 ± 1.8 14.4 ± 1.8
207.8	doublet	39.5 ± 1.8	47.1	doublet of doublets	39.4 ± 1.8 13.7 ± 1.8
			208.7	doublet of doublets	39.4 ± 1.8 39.5 ± 1.8

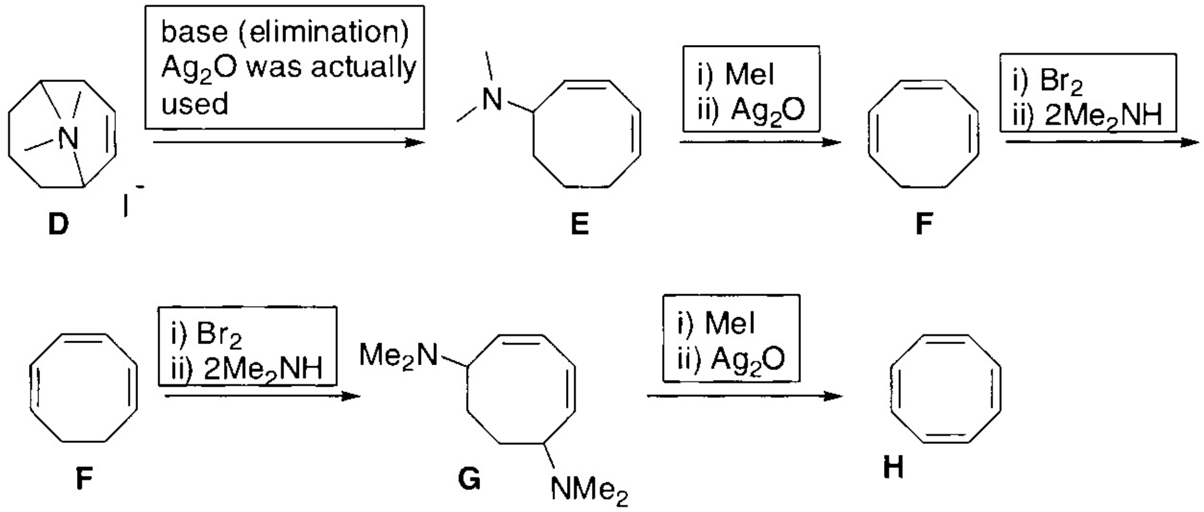
24.6 Which route does the biosynthesis of pelletierene follow?

SOLUTION OF PREPARATORY PROBLEM 24

24.1

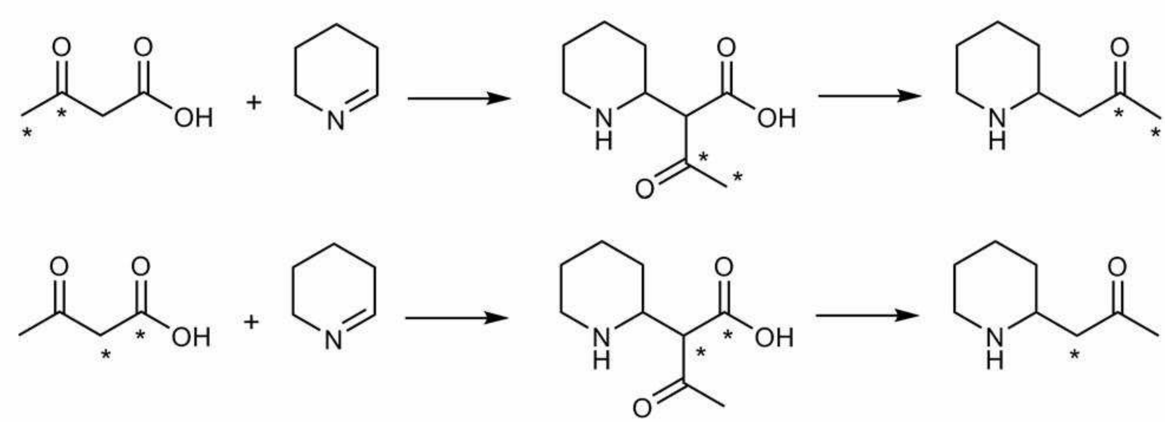


24.2

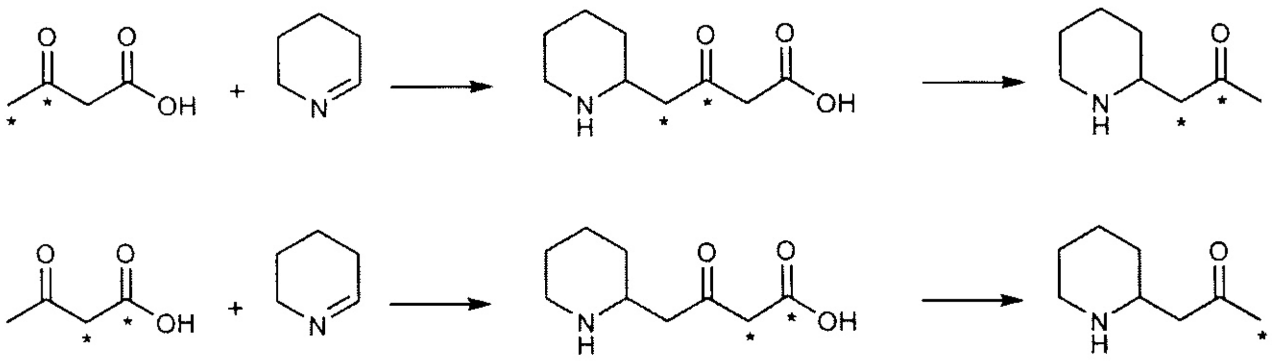


24.3 The positions at which 13C labels would appear if each of the biosynthetic routes were followed are indicated with an asterisk:

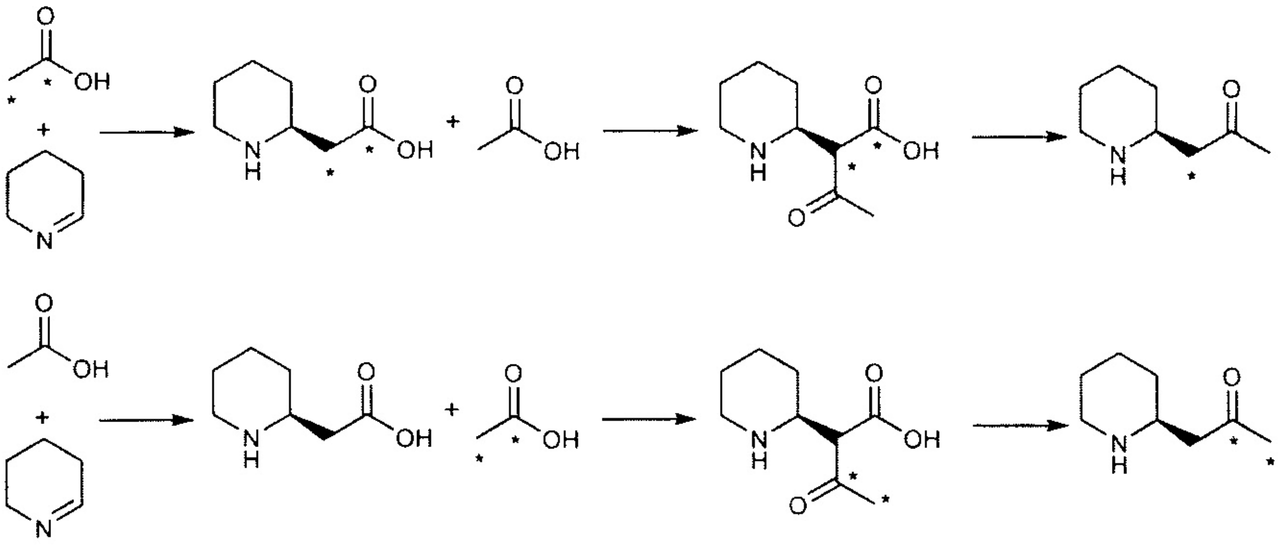
Route I



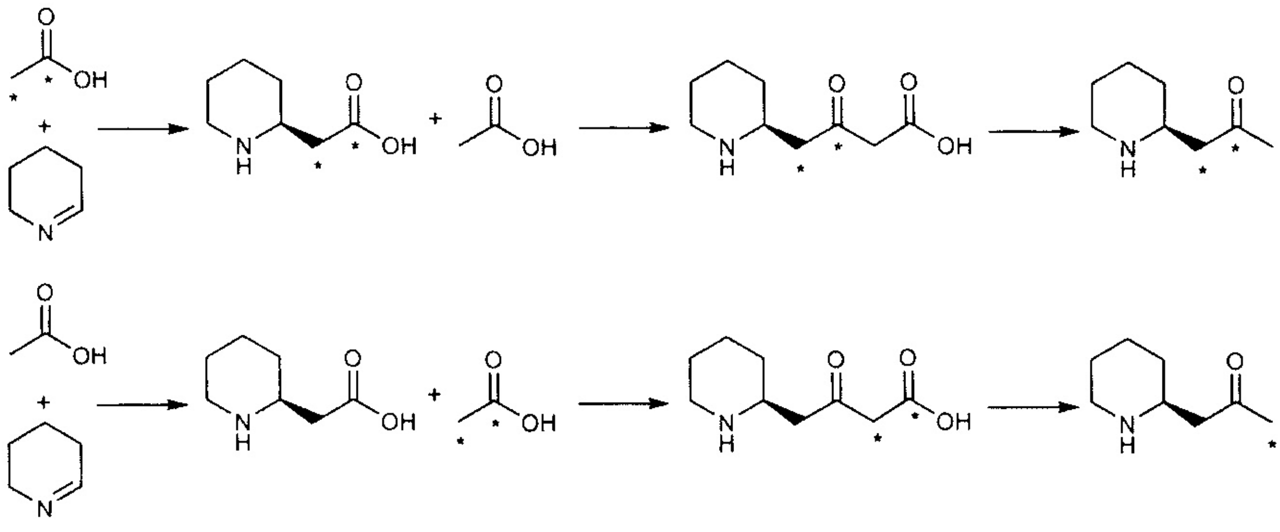
Route II



Route III



Route IV



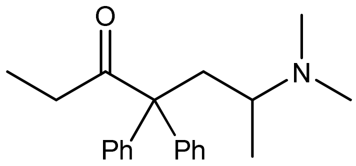
24.4 Routes I & III can be distinguished from II & IV in this experiment.

24.5 Routes I & II can be distinguished from III & IV in this experiment.

24.6 The additional peaks in the NMR spectra from experiments 1 and 2 arise from coupling between 13C nuclei. Experiment 1 shows that carbons k and j are 13C labelled thus pelletierene must be synthesised via route I or route III. In experiment 2 a 13C label is seen at carbon j, k and l showing that the biosynthesis proceeds via route I.

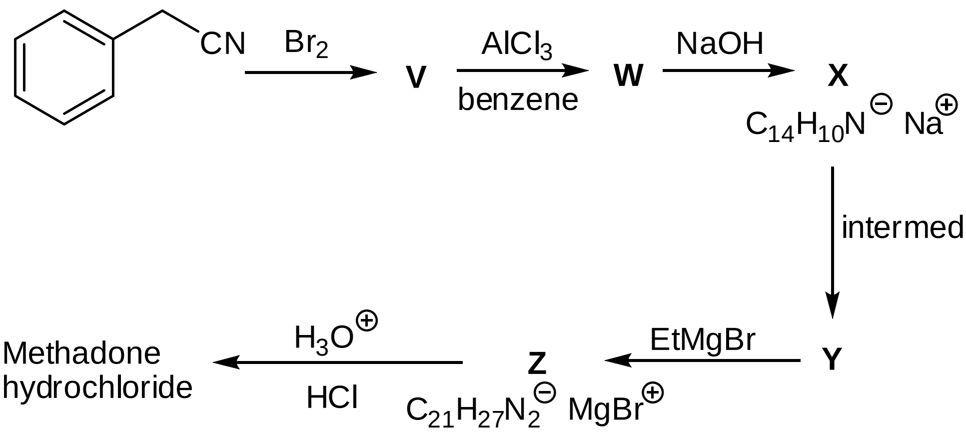
THEORETICAL PROBLEM 25

The synthesis of methadone



Methadone

Methadone is an analgesic drug with a similar activity to morphine and is used in treating heroin addicts. It may be prepared as its hydrochloride salt by the following multi-stage synthesis:



Intermediate **C** is a chloride salt and may be prepared by treating two isomeric compounds with $SOCl_2$ and then heating up the reaction mixture:

1-(dimethylamino)-propan-2-ol $\xrightarrow{SOCl_2}$ **A**

2-(dimethylamino)-propan-1-ol $\xrightarrow{SOCl_2}$ **B**

A $\xrightarrow{\text{warm}}$ intermediate **C** $\xleftarrow{\text{warm}}$ **B**

25.1 Deduce the structures for the compounds **V**, **W** and **X**.

25.2 Deduce the structures for the compounds **A**, **B** and hence for the intermediate **C**.

25.3 Deduce the structures for the compounds **Y**, **Z** and methadone hydrochloride.

25.4 Assign, as fully as possible, the ^{1}H NMR spectrum of methadone.

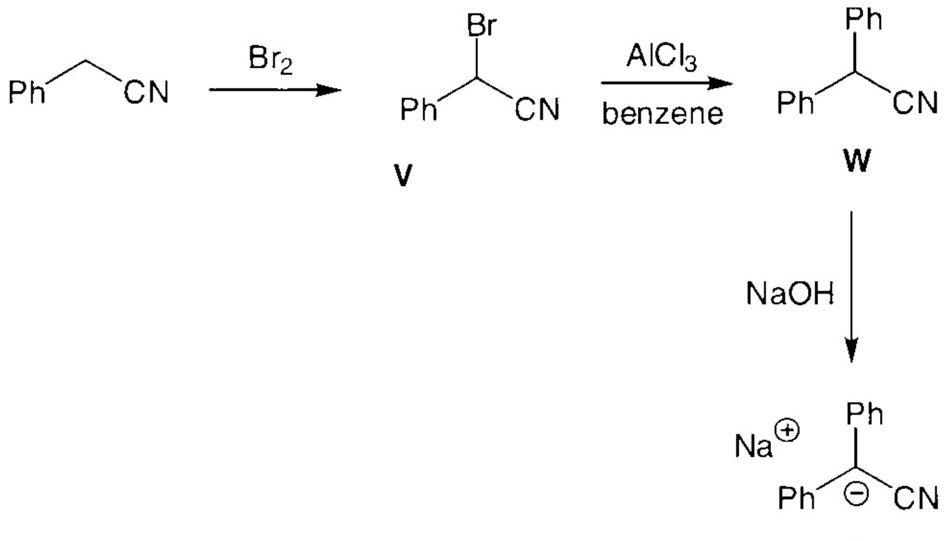
^{1}H NMR δ 7.40–7.30 (10H, m), 2.78 (1H, dqd, 10.6 Hz, 6.2 Hz, 2.3 Hz), 2.49 (2H, q, 6.8 Hz), 2.26 (6H, s), 2.22 (1H, dd, 11.5 Hz, 10.6 Hz), 2.00 (1H, dd, 11.5 Hz, 2.3 Hz), 1.10 (3H, d, 6.2 Hz), 1.05 (3H, t, 6.8 Hz).

The synthesis above yields a racemic mixture. In order to obtain the pure, biologically active (*R*)-enantiomer resolution may be achieved by crystallisation with (+)–tartaric acid.

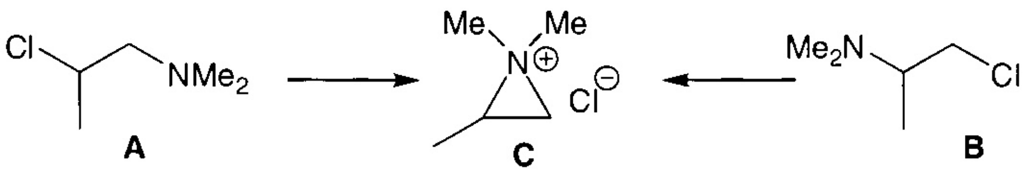
25.5 Draw the structure of the biologically active enantiomer of methadone.

SOLUTION OF PREPARATORY PROBLEM 25

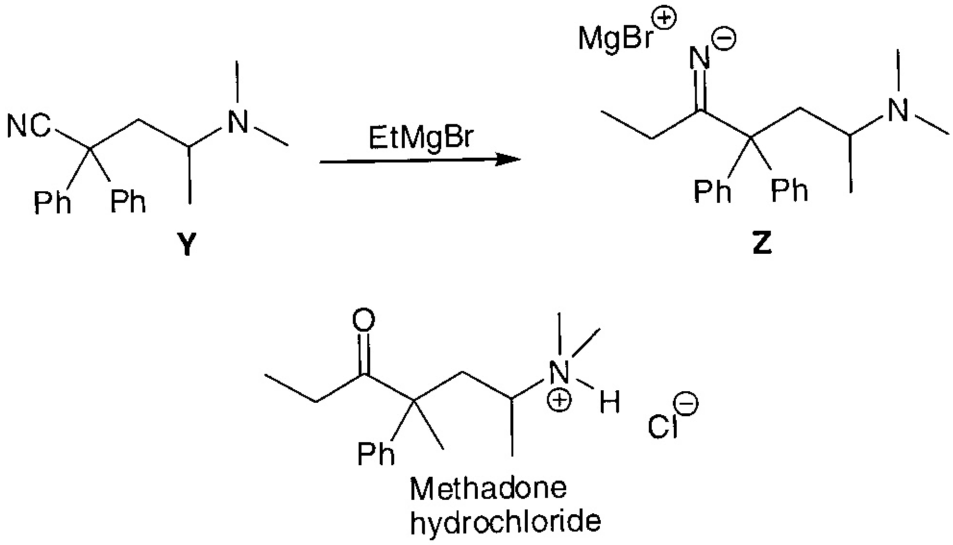
25.1



25.2

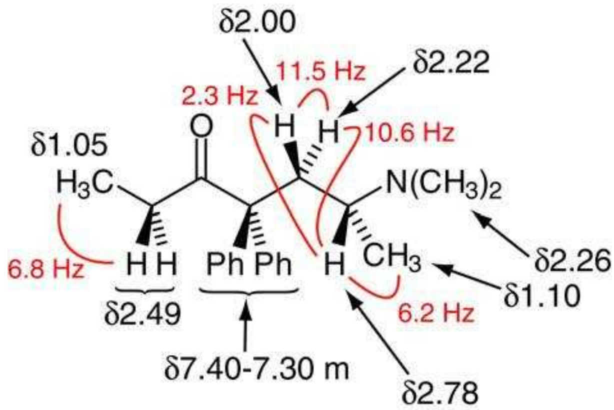


25.3



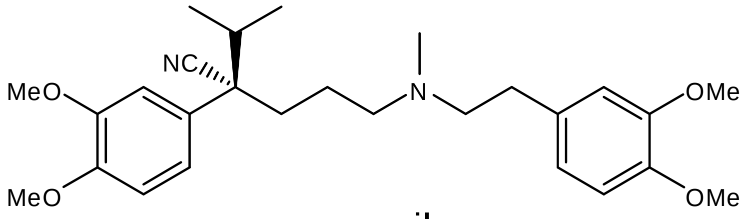
25.4 and 25.5

The structure and spectral assignment of *R*-methadone is shown below.



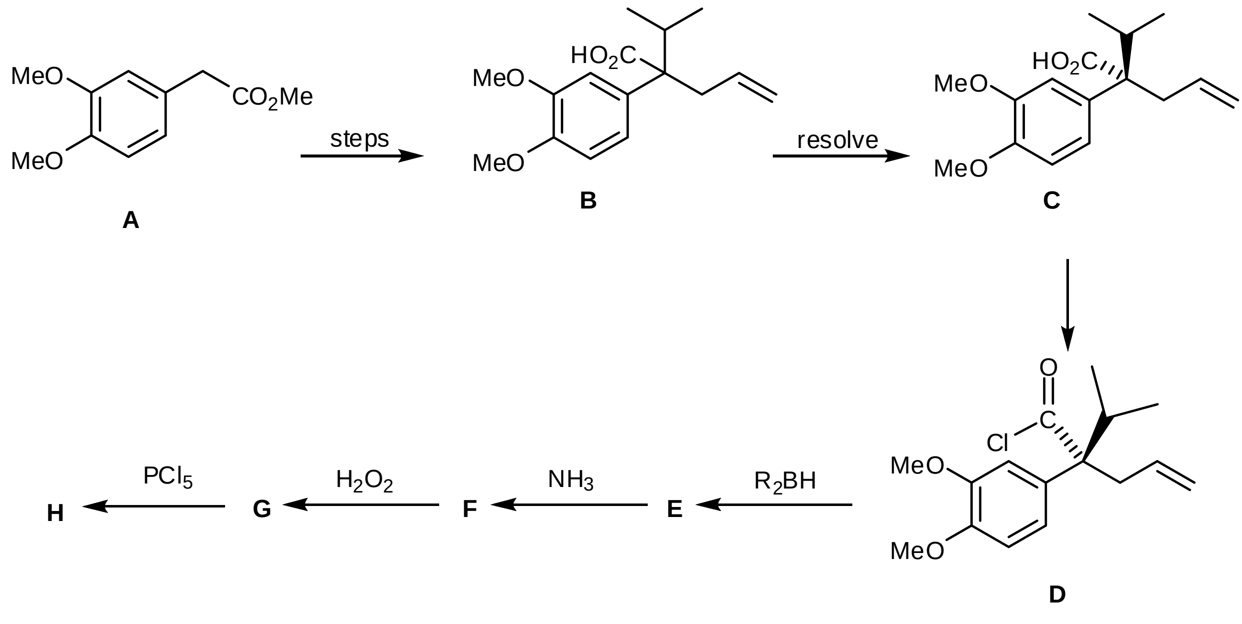
THEORETICAL PROBLEM 26

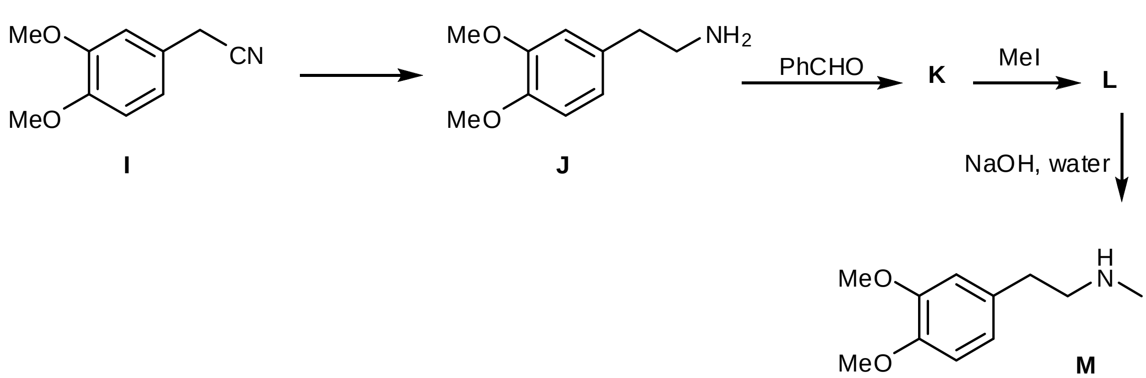
Verapamil



verapamil

Verapamil is a calcium channel blocker used for, among other things, the treatment of hypertension and cardiac arrhythmia. It can be prepared from the reaction between **H** and **M** which can be synthesised according to the schemes below.





26.1 Suggest reagents for the multi-step conversion of **A** into the racemic acid **B**.

The acid **B** can be resolved to give the enantiopure acid **C** on treatment with cinchonidine.

26.2 Suggest a reagent for the conversion of **C** in **D**.

26.3 Suggest structures for intermediates **E**, **F**, **G** and **H**.

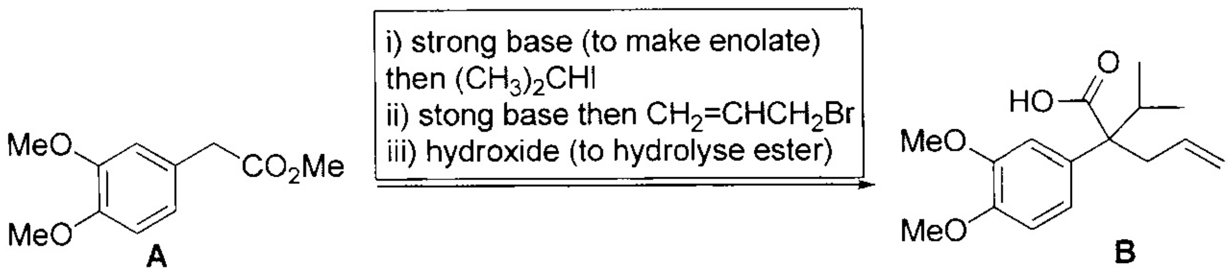
26.4 Suggest a reagent for the conversion of **I** into **J**.

26.5 Direct monomethylation of amines with MeI is generally not possible and hence amine **J** was converted into amine **M** by way of intermediates **K** and **L**. Suggest structures for **K** and **L**.

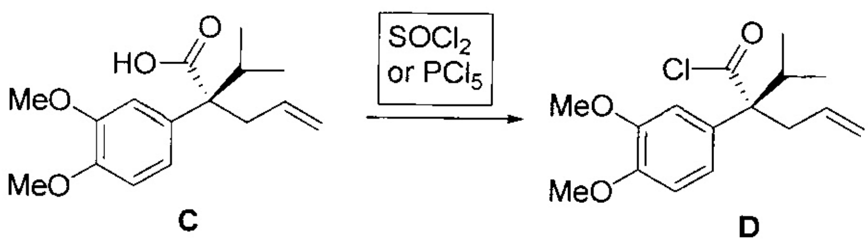
26.6 How would you prepare the ester **A** from the nitrile **I**.

SOLUTION OF PREPARATORY PROBLEM 26

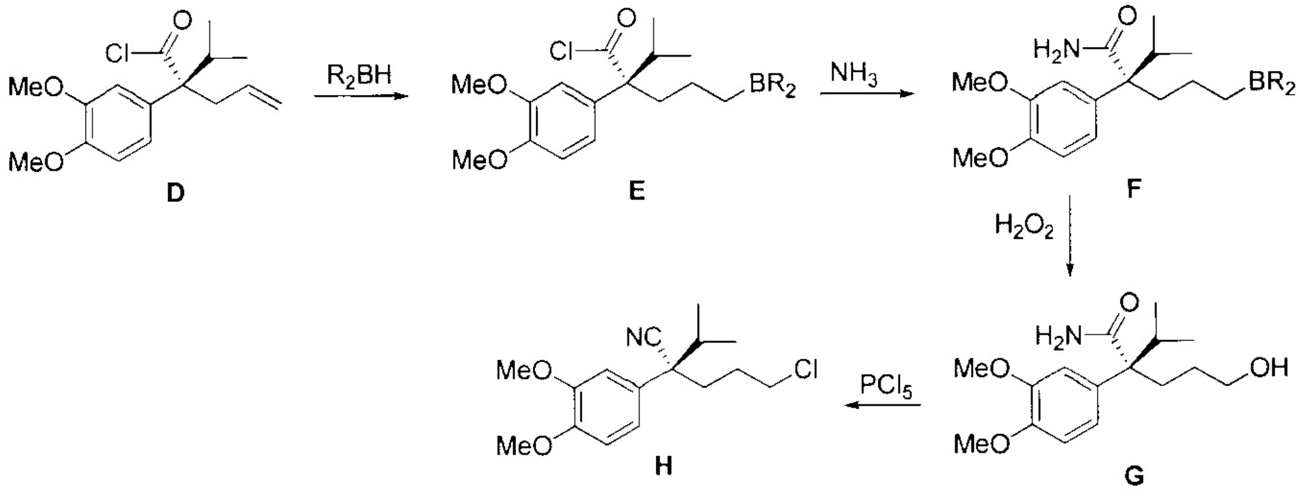
26.1



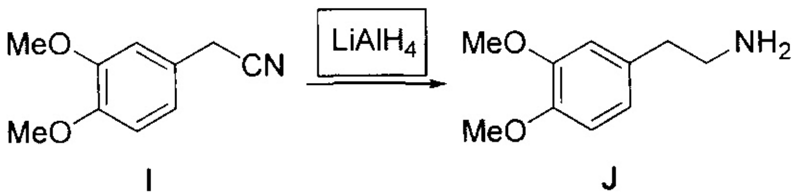
26.2



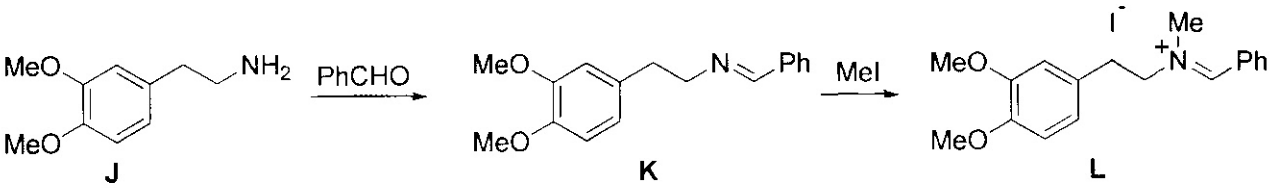
26.3



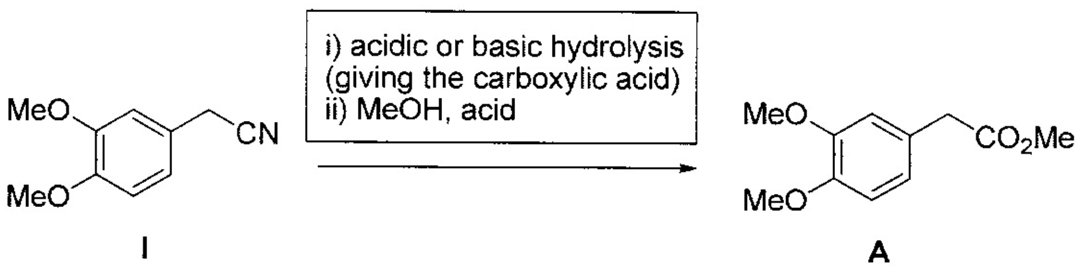
26.4



26.5



26.6



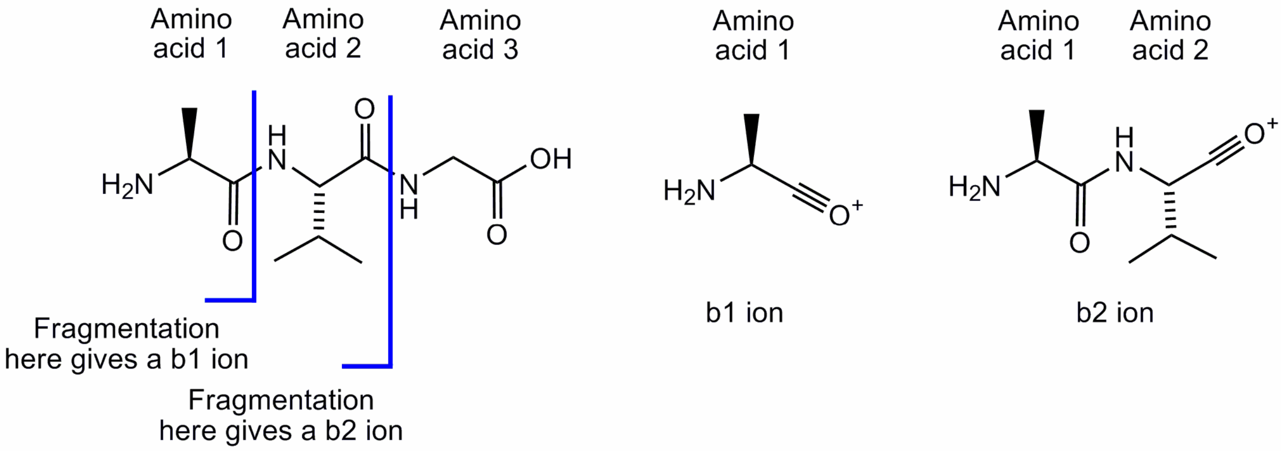
THEORETICAL PROBLEM 27

Mass spectrometry of a peptide

Note: the structures, names, and codes of the amino acids are given in the Appendix.

Snake venom is composed of a variety of polypeptides and other small molecules. Venom polypeptides have a range of biological effects including muscle necrosis and the disruption of neurotransmission. Characterisation of the components of snake venom is important in the development of lead-compounds for the pharmaceutical industry and also in the creation of antivenins.

Tandem mass spectrometery (MS-MS) provides a rapid approach for determining the sequence of polypeptides. This involves formation of a parent ion, which is then fragmented to form other smaller ions. In peptides fragmentation often occurs at the amide bond, giving rise to so-called 'b ions'. The b ions formed from an alanine-valine-glycine polypeptide are shown below. Remember that by convention the first amino acid is that with the free $-NH_2$ group.



Polypeptide **X** was isolated from the venom of the pit viper, *B. insularis*. The amino acid composition of polypeptide **X** may be found by acid hydrolysis of the peptide. Under the conditions used for the hydrolysis, Asp and Asn are indistinguishable and are termed Asx; similarly Glu and Gln are indistinguishable and termed Glx. The composition of polypeptide **X** was found to be: 1 × Asx, 2 × Glx, 1 × His, 1 × Ile, 4 × Pro and 1 × Trp.

27.1 How many unique decapeptide sequences can be formed from these aminoacids:

i) assuming Glx are both the same amino acid?

ii) assuming that one of the Glx amino acids is Glu, the other Gln?

27.2 What are the possible masses for Polypeptide **X**?

In the mass spectrum of Polypeptide **X** the parent ion showed at peak at an *m*/*z* of 1196.8. It is known that although snake toxins are synthesised from the 20 common amino acids shown in the table some of these amino acids can be chemically modified after polypeptide synthesis. The mass spectrum of the parent ion suggests that one of the amino acids in Polypeptide X has been modified in a way that is not evident after acid hydrolysis.

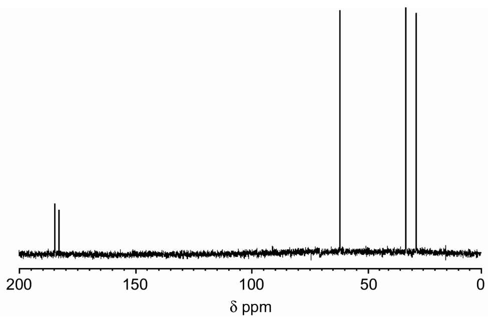
Polypeptide **X** was sequenced using MS-MS. The masses of the b ions are shown in the table below:

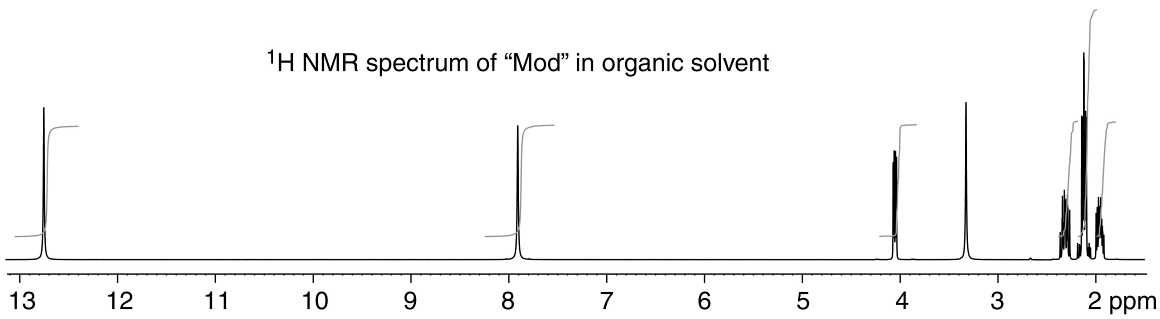
ion	*m/z*	ion	*m/z*	ion	*m/z*
b_1	112.2	b_4	509.7	b_7	872.0
b_2	226.4	b_5	646.7	b_8	985.0
B_3	412.5	b_6	743.8	b_9	1082.2

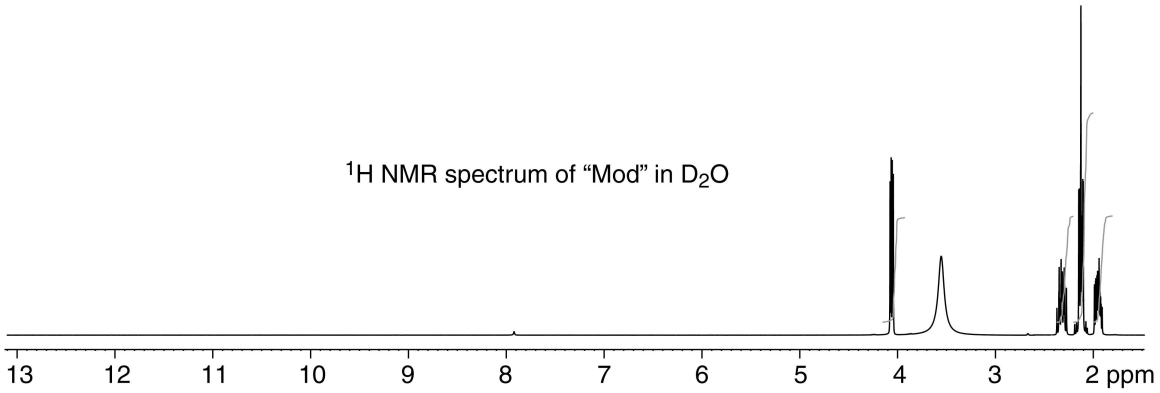
27.3 What is the sequence of Polypeptide **X**? You may use "**Mod**" for the modified aminoacid.

27.4 What is the mass of the modified amino acid?

The ^{13}C NMR spectra of "**Mod**" in D_2O is shown on the right. The ^{1}H NMR spectra, taken in an organic solvent, and in D_2O are shown below.







27.5 Draw the structure of **Mod** and suggest which protons give rise to which signals in the ^{1}H NMR spectrum. You need not explain the multiplicity of the signals.

SOLUTION OF PREPARATORY PROBLEM 27

27.1 i) If Glx are both the same amino acid then the number of unique sequences is given by 10!/(4! x 2!). This gives 75600 sequences.

ii) If Glx are two different amino acids then the number of unique sequences is given by 10!/4!. This gives 151200 sequences.

27.2 There are six possible peptides that could be formed depending upon the identity of Asx and Glx:

Amino Acids	Peptide mass	Amino Acids	Peptide Mass
Asn, Gln, Gln	1213	Asp, Gln, Gln	1214
Asn, Gln, Glu	1214	Asp, Gln, Glu	1215
Asn, Glu, Glu	1215	Asp, Glu, Glu	1216

27.3 The mass of ion b1 can be used to determine the identity of the first amino acid in the polypeptide:

$$M_r(\text{amino acid 1}) = \text{mass(b1)} + M_r(\text{O}) + M_r(\text{H}) = 129.2.$$

This does not correspond to the mass of any of the 20 amino acids typically found in proteins, therefore amino acid 1 must be Mod.

The identity of amino acids 2 to 9 can be determined using consecutive b-ions:

ion	m/z	Mass difference between b(n) and b(n-1)	Number of corresponding amino acid in sequence	Mass of amino acid
b9	1082.2	97.2	9	115.2
b8	985	113	8	131.0
b7	872	128.2	7	146.2
b6	743.8	97.1	6	115.1
b5	646.7	137	5	155.0
b4	509.7	97.2	4	115.2
b3	412.5	186.1	3	204.1
b2	226.4	114.2	2	132.2
b1	112.0			

Finally the identity of amino acid 10 can be verified using the masses of the polypeptide X and ion b9:

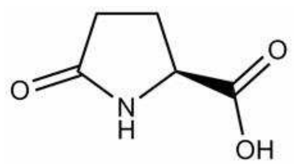
$$M_r(\text{amino acid 1}) = M_r(\mathbf{X}) - \text{mass(b9)} + M_r(\text{H}) = 115.6.$$

The sequence is therefore:

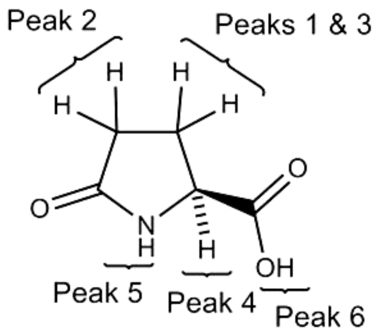
Mod – Asn –Trp – Pro – His – Pro – Gln – Ile – Pro – Pro

27.4 The mass of the modified amino acid is 129.2.

27.5 It is known from the amino acid composition that Mod must be based on Gln or Glu. The mass and NMR spectra are consistent with the cyclic amino acid usually referred to as pyroglutamatic acid:



27.6 If the peaks in the ^{1}H NMR spectrum of mod in organic solvent are numbered 1 to 6 from low to high chemical shift then the assignment is as follows:



Note:

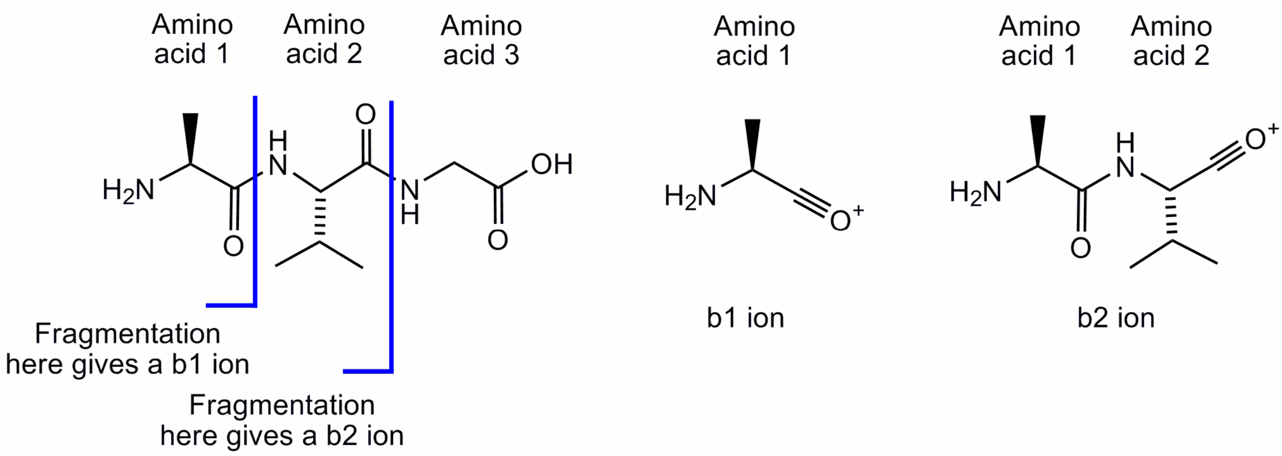
Students are not expected to be able to completely assign peaks 1 and 3.

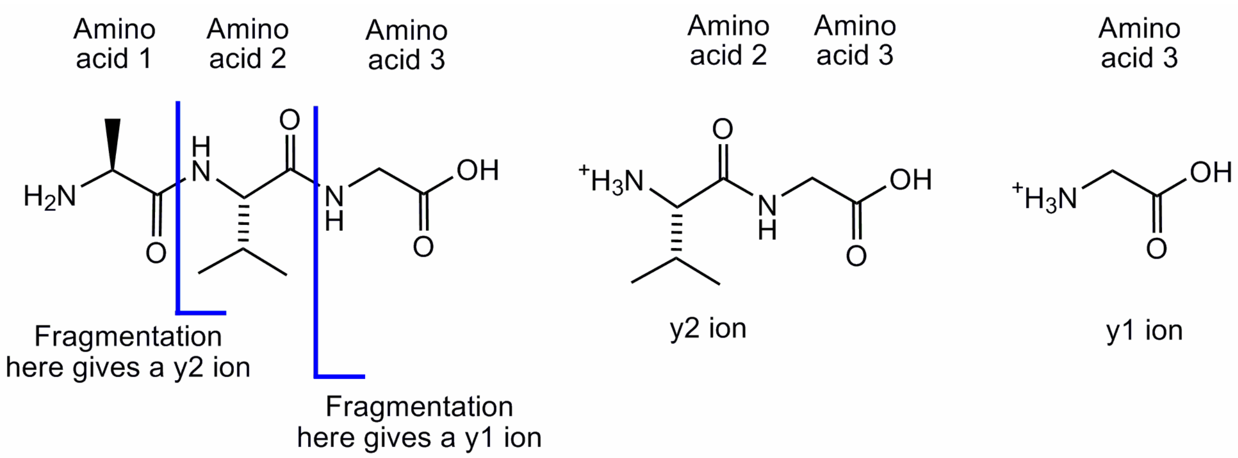
THEORETICAL PROBLEM 28

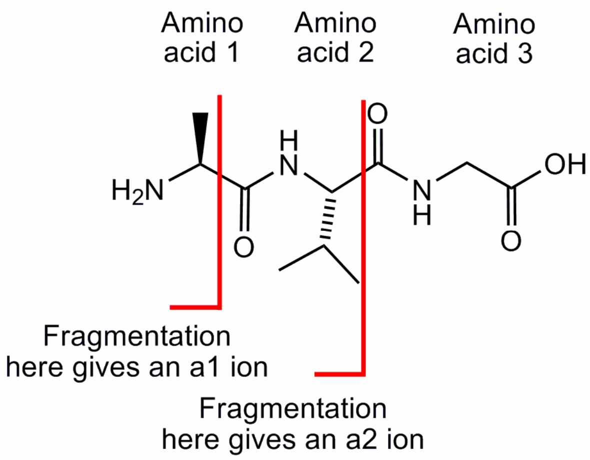
A fossilized peptide

Note: the structures, names, and codes of the amino acids are given in the Appendix.

Tandem mass spectrometery (MS-MS) provides a rapid approach for determining the sequence of polypeptides. This involves formation of a parent ion, which is then fragmented to form other smaller ions. In peptides fragmentation often occurs along the polypeptide backbone; the fragment ions are named depending on where fragmentation occurs and which atom retains the positive charge. Some of the ions formed in the fragmentation of an alanine-leucine-glycine peptide are shown below:

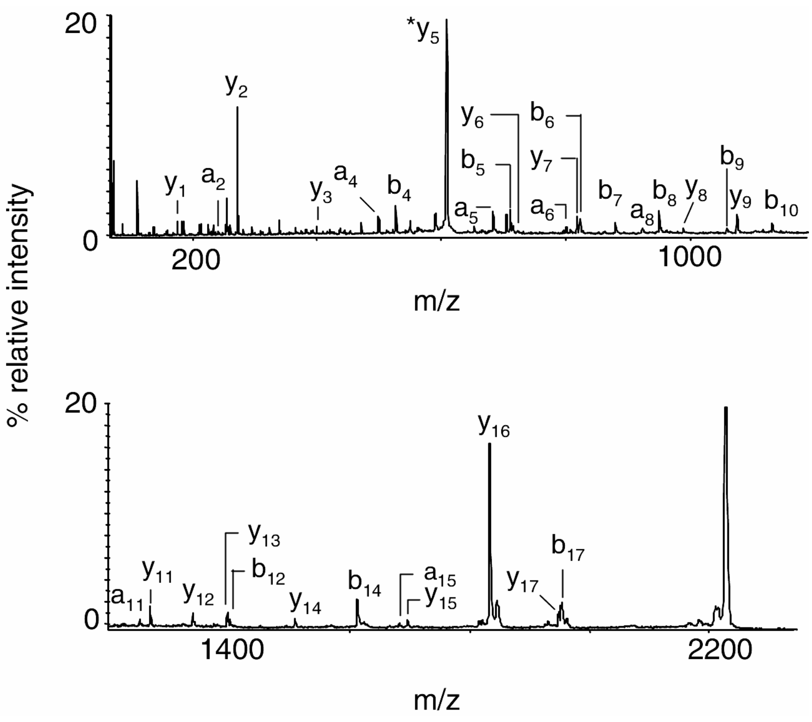






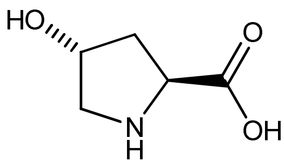
Fossilised bones potentially contain DNA and protein sequences that can be used to infer evolutionary links to modern species. Advances in mass spectrometry have made it possible to get sequence information from subpicomolar quantities of polypeptide, allowing analysis of material obtained from fossils. In reality, fossil polypeptide sequences typically have to be determined from mass-spectra using a combination of database searching and synthetic polypeptide standards. However for some younger fossils, where more material can be extracted, it is possible to determine the polypeptide sequence from the mass spectra once the ions have been identified.

The protein osteocalcin was extracted from a 42000 year old fossil bone found in Juniper Cave, Wyoming, USA. The MS-MS spectrum of a 19 amino acid polypeptide fragment of this protein is shown below:



ion	*m*/*z*	ion	*m*/*z*	ion	*m*/*z*	ion	*m*/*z*
y_1	175.1	b_5	715.3	y_8	986.5	b_{12}	1400.7
a_2	249.1	y_6	726.4	b_9	1069.5	y_{14}	1508.8
y_2	272.2	a_6	800.4	y_9	1083.5	b_{14}	1612.7
y_3	401.2	y_7	823.4	b_{10}	1140.5	a_{15}	1681.8
a_4	501.2	b_6	828.4	a_{11}	1209.6	y_{15}	1694.9
b_4	529.2	b_7	885.4	y_{11}	1267.6	y_{16}	1831.9
y_5	611.4	a_8	928.4	y_{12}	1338.7	y_{17}	1946.9
a_5	687.3	b_8	956.5	y_{13}	1395.7	b_{17}	1951.9

28.1 Using the mass spectrum and the table of ion masses determine as far possible the sequence of this polypeptide. Where there is more than one possible amino acid at a position all possibilities should be listed. The first two amino acids in the polypeptide sequence are Tyr-Leu. The polypeptide sequence also contains the amino acid hydroxyproline, Hyp, which has a mass of 131.1:



Part of the polypeptide sequence of osteocalcin from a number of different modern species are shown below:

Carp DLTVAQLESLKEVCEANLACEHMMDVSGIIAAYTAYYGPIPY
Chicken HYAQDSGVAGAPPNPLEAQREVCELSPDCDELADQIGFQEAYRRFYGPV
Cow YLDHWLGAPAPYPDPLEPKREVCELNPDCDELADHIGFQEAYRRFYGPV
Horse YLDHWLGAPAPYPDPLEPRREVCELNPDCDELADHIGFQEAYRRFYGPV
Human YLYQWLGAPVPYPDPLEPRREVCELNPDCDELADHIGFQEAYRRFYGPV
Rabbit QLINGQGAPAPYPDPLEPKREVCELNPDCDELADQVGLQDAYQRFYGPV
Sheep YLDPGLGAPAPYPDPLEPRREVCELNPDCDELADHIGFQEAYRRFYGPV
Toad SYGNNVGQGAAVGSPLESQREVCELNPDCDELADHIGFQEAYRRFYGPV

Both hydroxyproline and proline are represented by P in the polypeptide sequences shown above.

28.2 To which modern species does the protein from the fossil appear to be most closely related?

____

SOLUTION OF PREPARATORY PROBLEM 28

28.1 The mass of ion y1 can be used to determine the identity of the last amino acid in the polypeptide. The y1 ion is one mass unit larger in size than the corresponding amino acid; therefore the last amino acid must be Arg.

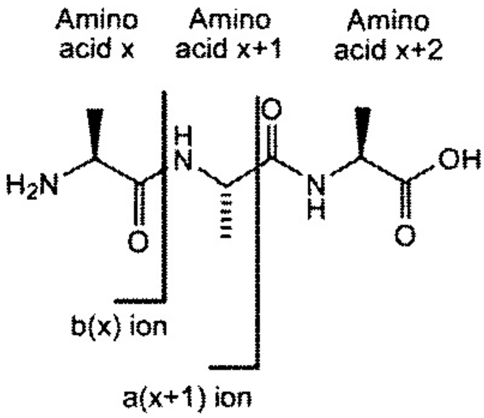
The y-series of ions is the most complete, comparison of the masses of consecutive y-ions can be used to determine the sequence:

ion	m/z	Mass difference between b(n) and b(n-1)	Corresponding amino acid	Mass of amino acid
y1	175.1			
y2	272.2	97.1	18	115.1
y3	401.2	129.0	17	147.0
y4				
y5	611.4			
y6	726.4	115.0	14	133.0
y7	823.4	97.1	13	115.1
y8	986.5	163.1	12	181.1
y9	1083.5	97.1	11	115.1
y10				
y11	1267.6			
y12	1338.7	71.0	8	89.0
y13	1395.7	57.0	7	75.0
y14	1508.8	113.1	6	131.1
y15	1694.9	186.1	5	204.1
y16	1831.9	137.1	4	155.1
y17	1946.9	115.0	3	133.0

From the y-series the sequence is:

Tyr-Leu-Asp-His-Trp-Leu/Ile/Hyp-Gly-Ala-xxx-xxx-Pro-Tyr-Pro-Asp-xxx-xxx-Glu-Pro-Arg

The identity of the 15th amino acid in the sequence can be determined from the difference in mass between b14 and a15:



M_r(amino acid 15) = mass(a15) – mass(a14) + M_r(C) + 2 M_r(O) + 2 M_r(H) = 115.0

Therefore amino acid 15 must be Pro.

The difference in mass between ions y3 and y5 gives the mass of the fragment corresponding to amino acids 15 and 16.

M_r(15-16 dipeptide) = mass(y5) – mass(y3) + $M_r(H_2O)$

M_r(amino acid 16) = M_r(15-16 dipeptide) – M_r(amino acid 15) + $M_r(H_2O)$ = 131.1

Amino acid 16 must therefore be Ile, Leu or Hyp.

The mass of amino acid 10 can be determined from the difference in mass between b9 and b10:

M_r(amino acid 10) = mass(b10) – mass(b9) + $M_r(H_2O)$

Amino acid 10 is Ala.

The difference in mass between ions y11 and y9 gives the mass of the fragment corresponding to amino acids 9 and 10.

M_r(9-10 dipeptide) = mass(y11) – $mass_r$(y9) + $M_r(H_2O)$

M_r(amino acid 9) = M_r(9-10 dipeptide) – M_r(amino acid 10) + $M_r(H_2O)$

Amino acid 9 has a mass of 131.1, so must be Ile, Leu or Hyp.

The sequence of the polypeptide is therefore:

Tyr-Leu-Asp-His-Trp-Leu/Ile/Hyp-Gly-Ala-Leu/Ile/Hyp-Ala-Pro-Tyr-Pro-Asp-Pro-Leu/Ile/Hyp-Glu-Pro-Arg

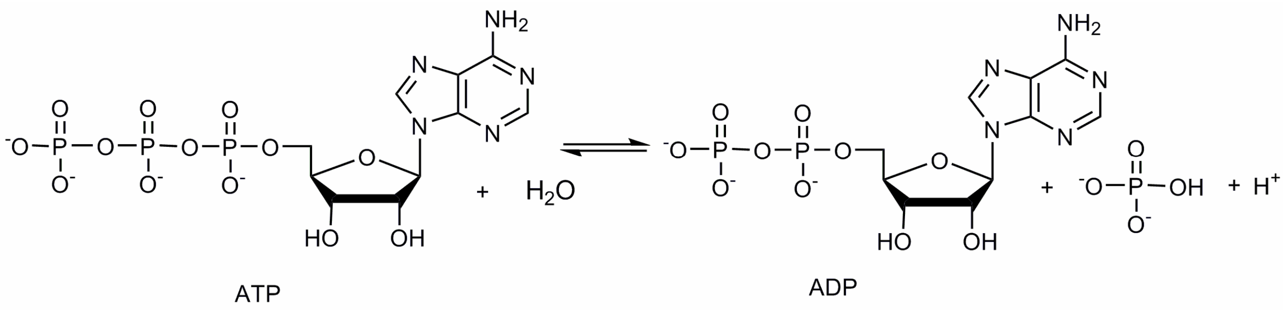
28.2 The sequence is most similar to that of the horse.

THEORETICAL PROBLEM 29

Creatine kinase

The factors governing energy production in muscle are important in understanding the response of the body to exercise and also in the determination of the physiological effect of cardiac and muscular diseases.

Cells use adenosine triphosphate (ATP) as the molecular energy currency; the hydrolysis of ATP to adenosine diphosphate (ADP) is often coupled with other chemical reactions.



Biochemistry textbooks often represent this reaction as:

$$\text{ATP} + H_2O \rightleftharpoons \text{ADP} + P_i + H^+$$

In order to simplify free-energy calculations for biochemical reactions the standard free-energy change at pH 7.0, typically denoted $\Delta_r G^{\circ\prime}$, is used. The equilibrium constant at pH 7.0 is denoted K'. For the ATP hydrolysis reaction the relation between $\Delta_r G'$ and the concentration of species present will therefore be:

$$\Delta_r G' = \Delta_r G^{o} + RT \ln \frac{[\text{ADP}]\,[\text{P}_\text{i}]}{[\text{ATP}]}$$

At 37 °C the value of K' for the hydrolysis of ATP to ADP is 138000.

29.1 A solution of ATP (c = 10 mmol dm^{-3}) is prepared in a solution buffered at pH 7.0 at 37 °C. What are the concentrations of ATP, ADP and P_i at equilibrium?

29.2 What is the value of $\Delta_r G^{\circ\prime}$ at 37 °C?

One hypothesis for exhaustion after exercise is that an increase in the concentration of ADP relative to ATP could occur, leading to an increase in the value of $\Delta_r G'$ for ATP hydrolysis below that required for normal cellular metabolism.

The *in vivo* concentration of ATP and P_i can be measured using ^{31}P NMR. Unfortunately the concentration of ADP is too low to be measured using ^{31}P NMR. Instead the concentration of ADP has to be determined indirectly from the ^{31}P NMR measured concentration of phosphocreatine and the value of K' for the enzyme creatine kinase. Creatine kinase catalyses the reaction:

$$\text{creatine + ATP} \rightleftharpoons \text{ADP + phosphocreatine + H}^+$$

To a good approximation this reaction is at equilibrium in the cell with a K' value of 0.006. It is also known that ([creatine] + [phosphocreatine]) is maintained at 42.5×10^{-3} mol dm^{-3} in the cell.

The ^{31}P NMR spectrum of a forearm muscle was measured in volunteers after a period of rest and after two different intensities of exercise (squeezing a rubber ball). These spectra were used to calculate the concentration of the following phosphorus species:

Condition	**[Phosphocreatine] (mol dm^{-3})**	**[ATP] (mol dm^{-3})**	**[P_i] (mol dm^{-3})**
At rest	38.2×10^{-3}	8.2×10^{-3}	4.0×10^{-3}
Light exercise	20.0×10^{-3}	8.5×10^{-3}	22×10^{-3}
Heavy exercise	10.0×10^{-3}	7.7×10^{-3}	35×10^{-3}

Assuming that the pH of the cell remains constant at pH 7.0 during exercise:

29.3 Calculate the concentration of ADP present under each of the three conditions.

29.4 Calculate the value of $\Delta_r G'$ for the hydrolysis of ATP under each of the three conditions.

29.5 Comment on whether these data support the hypothesis that exhaustion after exercise arises from an increase in the value of $\Delta_r G'$ for ATP hydrolysis.

SOLUTION OF PREPARATORY PROBLEM 29

29.1 Let n_0 be the initial number of moles of ATP and x the number of moles that of ATP that have formed ATP at equilibrium

	ATP	ADP	Pi	Total
Initial	n_0	0	0	n_0
Equilibrium	$n_0 - x$	x	x	$n_0 + x$

Therefore:

$$K = \left(\frac{\left(\dfrac{x^2}{(n_o + x)^2} \right)}{\left(\dfrac{n_o - x}{(n_o + x)} \right)} \right)$$

Which rearranges to give:

$$x = \sqrt{\frac{K\, n_0^2}{K + 1}}$$

Hence [ADP] = [P_i] = $9.99996377 \times 10^{-3}$ mol dm^{-3}

[ATP] = 3.62×10^{-8} mol dm^{-3}

29.2 –30.503 kJ mol^{-1}.

29.3 & 29.4

In order to calculate the [ADP], the [creatine] is first calculated from the [phosphocreatine] measured in the ^{31}P NMR spectrum and the total concentration of creatine and phosphocreatine in the cell.

The equilbrium constant for the creatine kinase reaction is then used in conjunction with [creatine], [ATP] and [phosphocreatine] to determine [ADP]. increase in $\Delta_r G'$(ATP). Finally these concentrations and the value for $\Delta_r G^{o\prime}$(ATP) calculated in part b) are used to determine $\Delta_r G'$(ATP):

Condition	[phospho-creatine] mol dm^{-3}	[ATP] mol dm^{-3}	[Pi] mol dm^{-3}	[crea-tine] mol dm^{-3}	[ADP] mol dm^{-3}	$\Delta_r G'$(ATP) kJ mol^{-1}
Rest	3.82×10^{-2}	8.20×10^{-3}	4.00×10^{-3}	4.30×10^{-3}	5.54×10^{-6}	-63.5
Light exercise	2.00×10^{-2}	8.50×10^{-3}	2.20×10^{-2}	2.25×10^{-2}	5.74×10^{-5}	-53.2
Heavy exercise	1.00×10^{-2}	7.70×10^{-3}	3.50×10^{-2}	3.25×10^{-2}	1.50×10^{-4}	-49.3

29.5 The data show an increase in the value of $\Delta_r G'$(ATP) when subjects undertake both light and heavy exercise, and the increase is greater after heavy exercise which would appear to support the hypothesis. However the increase in $\Delta_r G'$(ATP) is similar for both intensities of exercise, and in both cases the value of $\Delta_r G'$(ATP) is large and negative, so it is difficult to draw a firm conclusion from this limited data set. In fact, in the cell there is a large pH change after exercise and when this is taken into account the values of $\Delta_r G'$(ATP) are within error after both light and heavy exercise. Further experiments suggest that the rate of recovery of the concentration of metabolites such as creatine to resting levels plays an important role in exercise induced exhaustion.

PRACTICAL PREPARATORY PROBLEMS

PREPARATORY PROBLEM 30 (PRACTICAL)

The preparation and analysis of polyiodide salts

The propensity for iodine to catenate is well illustrated by the numerous polyiodides, which crystallise from solutions containing iodide ions and iodine. The stoichiometry of the crystals and the detailed geometry of the polyhalide depend very sensitively on the relative concentrations of the components and the nature of the cation.

In this experiment, you will generate and crystallise a quaternary ammonium polyiodide salt of the form $Me_4N^+I_n^-$ (n = 3, 5 or 7) and then titrate the amount of iodine in the anion using sodium thiosulphate. From the results of this analysis, you can determine which anion is present in your salt.

Experimental

Two salts, **A** and **B**, of different composition may be prepared by using different quantities of starting materials, as shown below. You can carry out the experiment for either one or both.

	Salt A	**Salt B**
mass of NMe_4I / g	1.00	0.50
mass of iodine / g	1.26	1.26

Chemicals and reagents

- tetramethylammonium iodide, solid
- iodine, solid
- sodium thiosulfate, aqueous solution, c = 0.1 mol dm^{-3}
- dichloromethane, liquid

Procedure

a) Add the iodine to a 100 cm^3 beaker containing 25 cm^3 ethanol and a magnetic bar. Heat and stir the solution until all the iodine has dissolved, then add the tetramethylammonium iodide. Continue to stir with moderate heating until no white solid remains. Do not allow the solution to boil at any time.

b) Allow the solution to cool slowly to room temperature and finally in an ice bath over about 15 – 20 minutes.

c) Collect the product under suction (Hirsch funnel) and wash on the filter with cold ethanol (10 cm^3) followed by ether (10 cm^3) using a disposable pipette.

d) Allow the product to dry on the filter for several minutes, and then transfer the crystals onto a filter paper. Place into a desiccator and leave under vacuum to dry.

Analysis

e) Weigh approximately 0.5 g of the product onto a weighing boat using a four decimal place balance. Record the weight accurately.

f) Using a distilled water wash-bottle, carefully transfer *all* the weighed product into a 250 cm^3 bottle.

g) Add approximately 25 cm^3 of dichloromethane, replace the stopper and shake to extract the iodine into the organic layer.

h) Fill a 50 cm^3 burette with sodium thiosulfate (c = 0.100 mol dm^{-3}) using a small glass funnel.

i) Remove the funnel and titrate the iodine by running small quantities of the sodium thiosulfate from the burette and then replacing the stopper and shaking the bottle.

j) The end-point is very sharp and is given by the removal of all iodine colour from the dichloromethane.

Questions

30.1 From the results of the titrations, calculate the formulae of the salts **A** and **B**.

30.2 What are the shapes of the anions?

PREPARATORY PROBLEM 31 (PRACTICAL)

The Williamson Synthesis of Ethers

Symmetrical aliphatic ethers may be prepared from the simpler primary and secondary alcohols by heating with sulphuric acid, but dehydration to the alkene is an important competing reaction. The sulphuric acid process is unsuited to the preparation of ethers from tertiary alcohols and of unsymmetrical ethers.

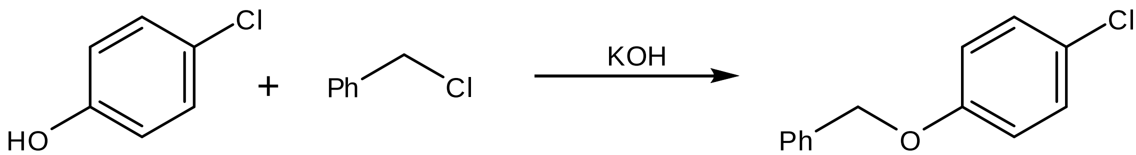
The Williamson synthesis, using an alkyl halide and a metal alkoxide, is of broader scope and can be used to obtain symmetrical or unsymmetrical ethers. For the latter type, either of two combinations of reactants is possible.

The proper choice depends mainly upon the structure of the alkyl halides involved. Competition arises between the substitution reaction (S_N2) to an ether (1° > 2° >> 3° halides) and the elimination of HX to form an alkene (3° >> 2° > 1° halides). Therefore 3° halides are not suitable for the reaction, but ethers having a 3° alkyl group can be prepared from a 3° alkoxide and a 1° halide.

The Williamson synthesis is an excellent method for the preparation of alkylaryl ethers – 1° and 2° alkyl halides react readily with sodium or potassium phenoxides.

In this experiment benzyl chloride is reacted with 4-chlorophenol under basic conditions to produce an ether.

The use of a fume cupboard protective clothing including gloves is essential for this experiment.



Chemicals

- benzyl chloride (*), liquid
- 4-chlorophenol, solid
- potassium hydroxide, solid
- lithium iodide, solid
- diethyl ether, liquid
- petroleum ether (*), liquid
- <u>absolute ethanol, liquid</u>

(*) This compound will not be used at the IChO competition

Experimental

a) Add absolute ethanol (50 cm^3) to potassium hydroxide pellets (0.87 g) in a 100 cm^3 round bottomed flask with a ground-glass joint.

b) Add 4-Chlorophenol (2 g) followed by benzyl chloride (1.8 cm^3) and lithium iodide (approx. 20 mg - the end of a micro-spatula).

c) Add a boiling stick, fit the flask with a condenser and heat under gentle reflux for 1 hour (an isomantle is recommended but keep careful control of the heating to maintain gentle reflux otherwise vigorous bumping can occur).

d) Allow the reaction mixture to cool and pour onto ice/water (150 cm^3) with swirling. Isolate the crude product by suction filtration and wash with ice-cold water (3×10 cm^3). Press dry on the filter.

f) The crude product should be recrystallised from *aqueous ethanol.* This entails dissolving your compound in the minimum volume of boiling ethanol and then adding water dropwise until the first crystals appear. Then set the hot solution aside to cool in the usual manner.

g) Record the yield of your product and run a thin layer chromatogram on a silica plate using ether/petroleum ether 2:8 as the eluent. Record the R_f value.

h) Measure and record the m.p.

Questions

31.1 What is the role of the lithium iodide added to the reaction mixture?

31.2 Substantial increases in the rate of reaction are often observed if S_N2 reactions are carried out in solvents such as dimethylformamide (DMF) or dimethylsulphoxide (DMSO). Suggest why this is so.

____

SOLUTION OF PREPARATORY PROBLEM 31

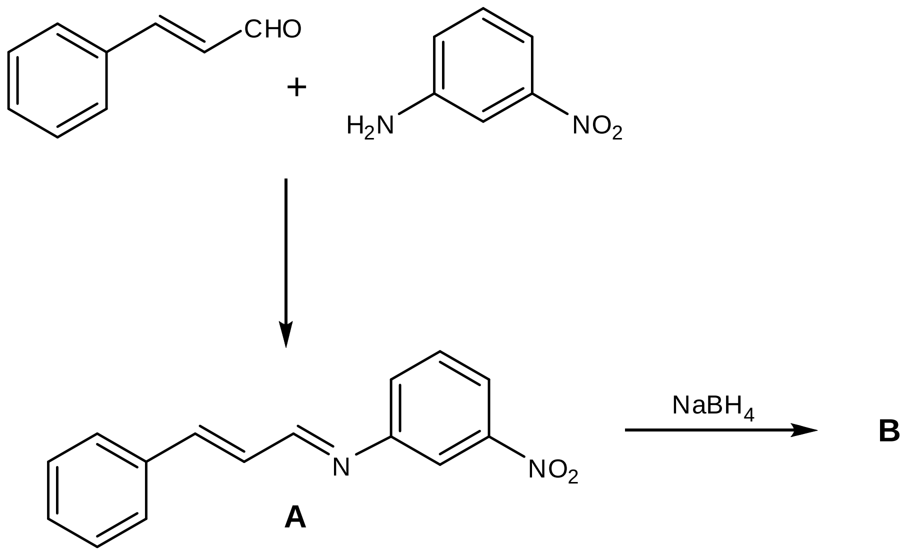
31.1 Lithium iodide transfers benzyl chloride to more reactive benzyl iodide.

31.2 This is true for those S_N2 reactions where transition state is more polar (better stabilised by polar solvent) than reactants. Williamson synthesis of ethers uses alkoxide as anionic nucleophile, it has less polar transition state than reactants and therefore will be retarded in more polar solvent.

PREPARATORY PROBLEM 32 (PRACTICAL)

Selective Reduction of a Highly Unsaturated Imine

Sodium borohydride is a selective reducing agent. In this experiment you will condense 3-nitroaniline with cinnamaldehyde to produce the highly unsaturated intermediate **A** (an imine). This is then selectively reduced with sodium borohydride to produce **B**. The structure of **B** can be deduced from the ^{1}H NMR spectrum.



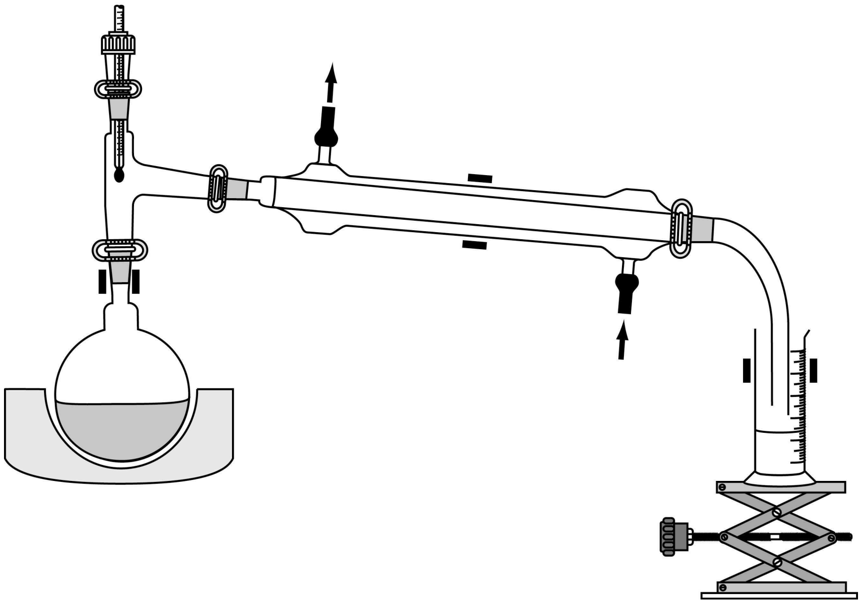
The experiment illustrates the classic method of imine formation (azeotropic removal of water).

Experimental

Chemicals

- 3-nitroaniline, solid,
- Cinnamaldehyde, liquid
- sodium borohydride, solid
- hexane liquid,
- ethyl acetate, liquid

Procedure



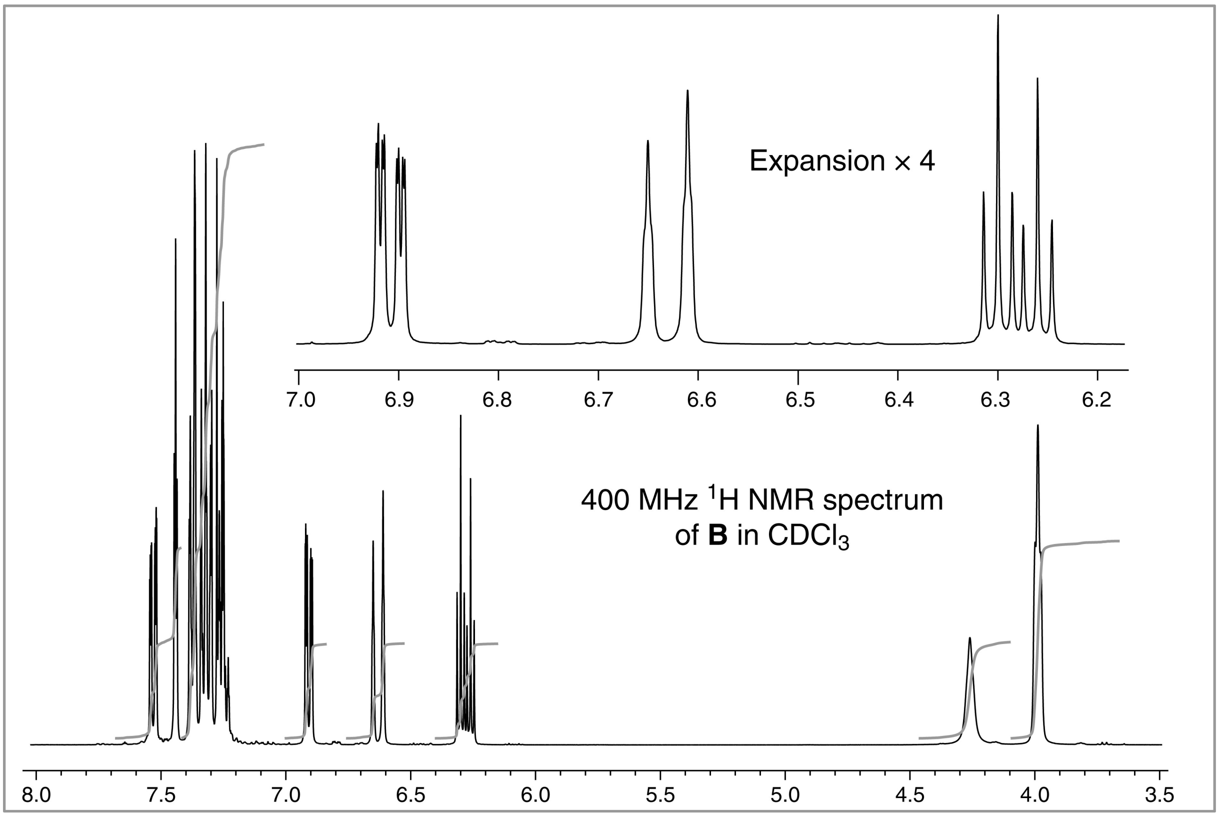
Place 3-Nitroaniline (2.76 g) and absolute ethanol (20 cm^3) in a 100 cm^3 round bottomed flask, together with a few anti-bumping granules. Set up the flask for distillation as shown above using an isomantle or steam bath as the heat source. Use a graduated measuring cylinder to collect the distillate.

Add dropwise a solution of cinnamaldehyde (2.9 g) in absolute ethanol (5 cm^3) through the thermometer inlet. Turn on the heat source and distil off approx. 22 cm^3 of solvent over a period of about 30 minutes. During the distillation dissolve with stirring sodium borohydride (0.76 g) in 95% ethanol (20 cm^3).

After the 22 cm^3 of solvent has distilled off, disconnect the apparatus. Set aside a small sample of the residue A which remains in the flask for thin layer chromatography. Then add 95 % ethanol (20 cm^3) to the flask to dissolve the remaining residue. To this solution of **A** add VERY CAREFULLY the sodium borohydride solution. This must be added slowly and with constant swirling of the reaction flask (vigorous effervescence occurs). After the addition, heat the mixture under reflux for 15 minutes, then cool the flask and pour the contents into water (50 cm^3). The product **B**, should crystallise out slowly on standing in an ice bath. Recrystallise your product from 95% ethanol.

Record the yield of your product. Run a thin layer chromatogram of your product **B** and the sample of **A** on a silica plate using hexane/ethyl acetate 1 : 1 as the eluent.

Record the R_f value of each. Measure and record the m.p. of **B**. Predict the structure of **B** using the ^{1}H NMR spectrum given below.



Questions

32.1 In the preparation of **A** why is *absolute* ethanol and not 95% used?

32.2 Why is the solvent removed during the reaction?

SOLUTION OF PREPARATORY PROBLEM 32

32.1 Water is product of the reaction of imine **A** formation. The use of aqueous ethanol as a solvent will negatively influence equilibrium.

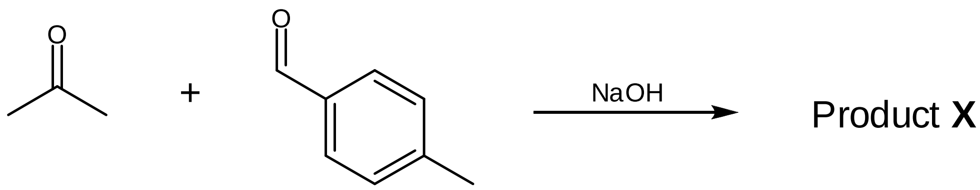
32.2 Ethanol forms azeotropic mixture with water. Produced water is thus removed from the reaction mixture what shifts the equilibrium towards intermediate **A**.

PREPARATORY PROBLEM 33 (PRACTICAL)

A Simple Aldol Codensation

The Claisen-Schmidt reaction involves the synthesis of an α,β-unsaturated ketone by the condensation of an aromatic aldehyde with a ketone. The aromatic aldehyde possesses no hydrogens α-to the carbonyl group, it cannot therefore undergo self condensation but reacts rapidly with the ketone present.

The initial aldol adduct cannot be isolated as it dehydrates readily under the reaction conditions to give an α,β-unsaturated ketone. This unsaturated ketone also possesses activated hydrogens α-to a carbonyl group and may condense with another molecule of the aldehyde.



In this experiment you will carry out the base catalysed aldol condensation of *p*-tolualdehyde with acetone. The product will be purified by recrystallisation and its structure determined using the spectra provided.

Experimental

Substances

- *p*-tolualdehyde, solid
- acetone, liquid
- sodium hydroxide,10% aqeous solution
- diethyl ether, liquid
- petroleum ether (*), liquid

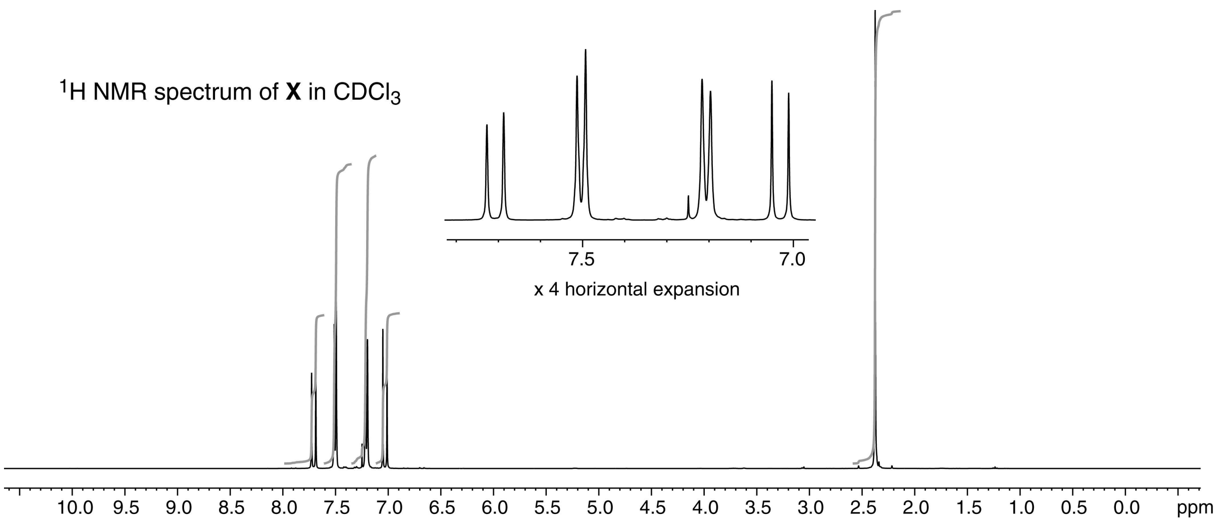
(*) This compound will not be used at the Olympiad

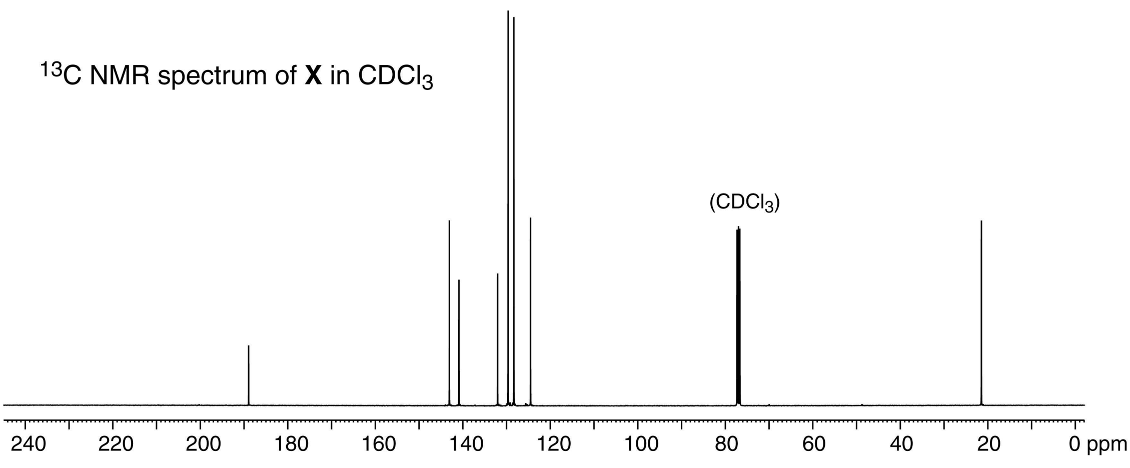
Procedure

Dissolve *p*-tolualdehyde (2.5 cm^3) and acetone (1 cm^3) in ethanol (25 cm^3) contained in a stoppered flask. Add bench sodium hydroxide solution (5 cm^3 of aqueous 10%) and water (20 cm^3). Stopper the flask and shake it for 10 minutes, releasing the pressure from time to time. Allow the reaction mixture to stand for 5 -10 minutes with occasional shaking and then cool in an ice bath. Collect the product by suction filtration, wash it well on the filter with cold water and recrystallise from ethanol.

Record the yield of your product. Run a thin layer chromatogram on a silica plate using ether/petroleum ether 2 : 8 as the eluent and record the R_f value of the product. Measure and record the m.p. of **X**.

Elemental analysis of **X** reveals it to have 88.99 % carbon and 6.92 % hydrogen. Use this information together with the NMR spectra to suggest a structure for **X**.

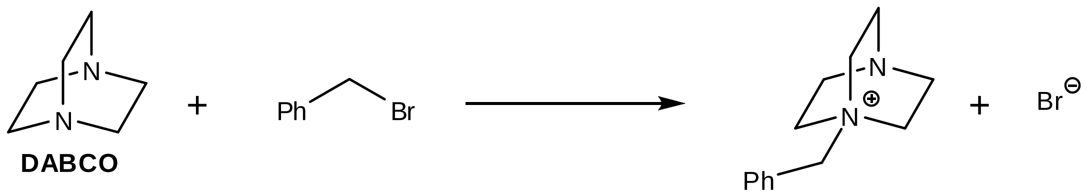




PREPARATORY PROBLEM 34 (PRACTICAL)

The Menshutkin Reaction

The nucleophilic substitution reaction between a tertiary amine and an alkyl halide is known as the Menshutkin reaction. This experiment investigates the rate law for the reaction between the amine known as DABCO (1,4-diazabicylo[2.2.2]octane) and benzyl bromide:



It is possible for the second nitrogen in the DABCO molecule to react with a second benzyl bromide. However, in this experiment the DABCO will always be in excess so further reaction is unlikely. The reaction could proceed by either the S_N1 or the S_N2 mechanism. In this experiment, you will confirm that the order with respect to benzyl bromide is 1 and determine the order with respect to DABCO. This should enable you to distinguish between the two possible mechanisms.

As the reaction proceeds neutral species, DABCO and benzyl bromide, are replaced by charged species, the quaternary ammonium ion and Br^-. Therefore the electrical conductivity of the reaction mixture increases as the reaction proceeds and so the progress of the reaction can be followed by measuring the electrical conductivity as a function of time.

Benzyl bromide is a lacrymator. This experiment should be performed in a fume cupboard.

The Method in Principle

The rate law for the reaction can be written as

$$\frac{\mathrm{d}[\mathrm{Br}^-]}{\mathrm{d}t} = k\,[\mathrm{RBr}]\,[\mathrm{DABCO}]^{\alpha} \qquad [1]$$

where we have assumed that the order with respect to the benzyl bromide, RBr, is 1 and the order with respect to DABCO is α.

In the experiment, the concentration of DABCO is in excess and so does not change significantly during the course of the reaction. The term $k[\text{DABCO}]^{\alpha}$ on the right-hand side of Eqn. [1] is thus effectively a constant and so the rate law can be written

$$\frac{d[\text{Br}^-]}{dt} = k_{\text{app}}[\text{RBr}] \quad \text{where} \quad k_{\text{app}} = k\,[\text{DABCO}]^{\alpha} \qquad [2]$$

k_{app} is the apparent first order rate constant under these conditions; it is not really a rate "constant", as it depends on the concentration of DABCO.

To find the order with respect to DABCO we measure k_{app} for reaction mixtures with different excess concentrations of DABCO. From Eqn. [2], and taking logs, we find

$$\ln k_{\text{app}} = \ln k + \alpha \ln[\text{DABCO}] \qquad [3]$$

So a plot of $\ln k_{app}$ against ln [DABCO] should give a straight line of slope α.

The constant k_{app} may be found by measuring the conductance at time t, $G(t)$, and at time infinity, G_∞. In the supplementary material it is shown that a graph of $\ln[G_\infty - G(t)]$ against t should be a straight line with slope k_{app}.

In practice it is rather inconvenient to measure conductance at time infinity but this can be avoided by analysing the data using the *Guggenheim method.* In this method each reading of the conductance at time t, is paired up with another at time $t + \Delta$, $G(t+\Delta)$, where Δ is a fixed time interval that needs to be at least a half-life. As shown in the supplementary material, a plot of $\ln[G(t+\Delta) - G(t)]$ against time should be a straight line of slope – k_{app}. For example, suppose we take measurements at fixed regular intervals, say each 30 s and choose an appropriate value of Δ, say 3 minutes (180 s). The plot made is of the points $\{x,y\}$ = {0, ln[G(180)- G (0)]}, {30, ln[G(210)- G(30)]}, {60, ln[G(240)- G(60)]}, ...

The Apparatus

Cheap conductivity meters are commercially available, for example the Primo5 conductivity stick meter from Hanna instruments works well with this practical. These simply dip into the solution and the conductance of the solution can be read off the digital display.

www.hannainst.co.uk/product/PRIMO5-Conductivity-stick-meter/PRIMO5/

Chemicals

- DABCO (1,4-diazabicylo[2.2.2]octane), three solutions in ethanol with a concentration of 0.15, 0.20 and 0.25 mol dm^{-3}, respectively
- benzyl bromide, solution in ethanol, c = 0.6 mol dm^{-3}

Procedure

You are provided with the following solutions, all in ethanol: 0.15, 0.20 and 0.25 mol dm^{-3} DABCO, and approx. 0.6 mol dm^{-3} benzyl bromide (this must be freshly made up). You should measure k_{app} for each of these solutions by measuring the conductance as a function of time and then analysing the data using the Guggenheim method. From the three values of k_{app}, the order with respect to DABCO can be found by plotting ln k_{app} against ln [DABCO], as shown by Eqn. [3].

Ideally we ought to keep the reagents and the reaction mixture in a thermostat. However, as the heat evolved is rather small, the temperature will remain sufficiently constant for our purposes.

Kinetic Runs

1. Rinse the conductivity dipping electrode with ethanol from a wash bottle, catching the waste in a beaker. Allow the excess ethanol to drain off and gently dry the electrode with tissue.
2. Transfer 10 cm^3 of the DABCO solution to a clean dry boiling tube.
3. Add 100 μl of the benzyl bromide solution.
4. Insert and withdraw the dipping electrode of the conductance meter a few times in order to mix the solution and then, with the electrode in place, start the stop-watch.
5. Record the conductance at 30 second intervals (it is essential to make the measurements at regular intervals), starting with the first reading at 30 seconds and continuing until there is no further significant change in the conductance, or for 10 minutes, whichever is the shorter time.
6. *From time to time*, *gently* lift the electrode in and out so as to stir the solution.
7. Once the measurements have been made, remove the electrode, discard the solution and clean the electrode as in step 1.
8. Make the measurements for the 0.15 mol dm^{-3} solution of DABCO, and then for the 0.20 and 0.25 mol dm^{-3} solutions.

Data Analysis

For each run determine k_{app} using the Guggenheim method – three minutes is about right for the fixed interval Δ. Then plot ln k_{app} against ln [DABCO] and hence determine the order with respect to DABCO.

Supplementary information

The key to this experiment is how to use the measured conductance of the reaction mixture to determine the first order rate constant, k_{app}. The first stage is simply to integrate the rate law; to do this we note that for each benzyl bromide molecule that reacts one bromide ion is generated so that at any time $[\text{Br}^-] = [\text{RBr}]_{\text{init}} - [\text{RBr}]$, where $[\text{RBr}]_{\text{init}}$ is the initial concentration of benzyl bromide. Thus the rate equation can be written in terms of $[\text{Br}^-]$ by putting $[\text{RBr}] = [\text{RBr}]_{\text{init}} - [\text{Br}^-]$; integration is then straightforward:

$$\frac{\text{d}[\text{Br}^-]}{\text{d}t} = k_{\text{app}}\left([\text{RBr}]_{\text{init}} - [\text{Br}^-]\right)$$

$$\int \frac{\text{d}[\text{Br}^-]}{\left([\text{RBr}]_{\text{init}} - [\text{Br}^-]\right)} = \int k_{\text{app}}\text{d}t$$

$$\text{i. e.} \qquad -\ln([\text{RBr}]_{\text{init}} - [\text{Br}^-]) = k_{\text{app}}t + \text{const.}$$

The constant can be found by saying that at time zero, $[\text{Br}^-] = 0$, hence

$$-\ln\left([\text{RBr}]_{\text{init}}\right) = \text{const.}$$

$$\text{hence} \quad -\ln\left([\text{RBr}]_{\text{init}} - [\text{Br}^-]\right) = k_{\text{app}}t - \ln\left([\text{RBr}]_{\text{init}}\right)$$

which can be written

$$[\text{Br}^-] = [\text{RBr}]_{\text{init}}\left(1 - \exp[-k_{\text{app}}t]\right) \qquad [4]$$

When the reaction has gone to completion, at time infinity, the concentration of bromide is equal to the initial concentration of RBr so Eqn. [4] can be written

$$[\mathrm{Br}^-] = [\mathrm{Br}^-]_\infty \left(1 - \exp[-k_{\mathrm{app}}t]\right) \qquad [5]$$

where $[\mathrm{Br}^-]_\infty$ is the concentration of Br^- at time infinity. Equation [5] says that the concentration of Br^- approaches a limiting value of $[\mathrm{Br}^-]_\infty$ with an exponential law. A similar relationship can be written for the other product, the quaternary ammonium ion, whose concentration will be written $[\mathrm{R_4Br^+}]$.

$$[\mathrm{R_4Br^+}] = [\mathrm{R_4Br^+}]_\infty \left(1 - \exp[-k_{\mathrm{app}}t]\right) \qquad [6]$$

We will assume that the conductance of the reaction mixture, G, is proportional to the concentration of the charged species present:

$$G = \lambda_{\mathrm{Br^-}}[\mathrm{Br}^-] + \lambda_{\mathrm{R_4N^+}}[\mathrm{R_4N^+}]$$

where λ are simply the constants of proportionality.

Using Eqns. [5] and [6] to substitute for the concentration of Br^- and $\mathrm{R_4N^+}$ we find

$$\begin{aligned} G &= \lambda_{\mathrm{Br^-}}\left\{[\mathrm{Br}^-]_\infty\left(1 - exp[-k_{\mathrm{app}}t]\right)\right\} + \lambda_{\mathrm{R_4N^+}}\left\{[\mathrm{R_4Br^+}]_\infty\left(1 - exp[-k_{\mathrm{app}}t]\right)\right\} \\ &= \left(\lambda_{\mathrm{Br^-}}[\mathrm{Br}^-]_\infty + \lambda_{\mathrm{R_4N^+}}[\mathrm{R_4Br^+}]_\infty\right)\left(1 - exp[-k_{\mathrm{app}}t]\right) \qquad [7] \\ &= G_\infty\left(1 - exp[-k_{\mathrm{app}}t]\right) \end{aligned}$$

where we have recognised that $\left(\lambda_{\mathrm{Br^-}}[\mathrm{Br}^-]_\infty + \lambda_{\mathrm{R_4N^+}}[\mathrm{R_4Br^+}]_\infty\right)$ is the conductance at time infinity, G_∞.

Equation [7] can be rearranged to give a straight line plot:

$$1 - \frac{G}{G_\infty} = \exp[-k_{\mathrm{app}}t]$$

$$\ln\left(1-\frac{G}{G_\infty}\right) = -k_{\text{app}}t \quad \text{or} \quad \ln\left(\frac{G_\infty - G}{G_\infty}\right) = -k_{\text{app}}t$$

$$\text{or} \quad \ln(G_\infty - G) = -k_{\text{app}}t + \ln G_\infty$$

Hence a plot of $\ln(G_\infty - G)$ against t should be a straight line with slope k_{app}.

The Guggenheim Method

From Eqn. [9] the conductance at time t, $G(t)$, can be written

$$G(t) = G_\infty\left(1 - \exp[-k_{app}t]\right)$$

At some time ($t + \Delta$) later the conductance is $G(t + \Delta)$

$$G(t+\Delta) = G_\infty\left(1 - \exp[-k_{app}(t+\Delta)]\right)$$

The difference $G(t + \Delta) - G(t)$ is

$$G(t+\Delta) - G(t) = G_\infty\left(1 - \exp[-k_{app}(t+\Delta)] - 1 + \exp[-k_{app}t]\right)$$

$$= G_\infty\left(\exp[-k_{app}t] - \exp[-k_{app}(t+\Delta)]\right)$$

$$= G_\infty \exp[-k_{app}t]\left(1 - \exp[-k_{app}\Delta]\right)$$

Taking logarithms of both sides gives, from the last line,

$$\ln\left(G(t+\Delta) - G(t)\right) = \ln G_\infty - k_{app}t + \ln\left(1 - \exp[-k_{app}\Delta]\right)$$

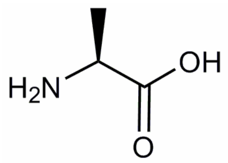
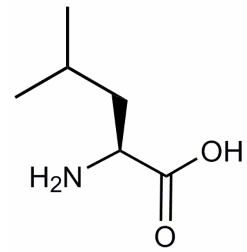
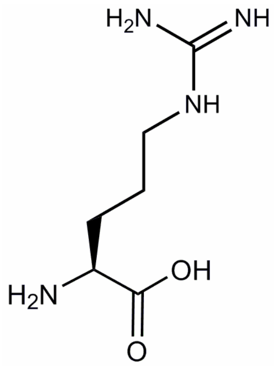
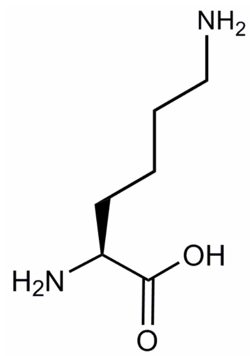
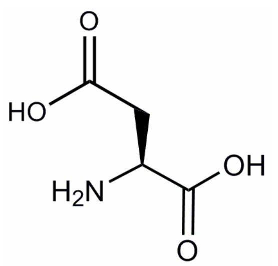
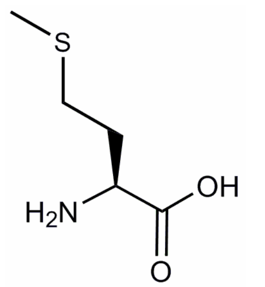
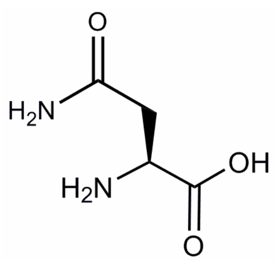
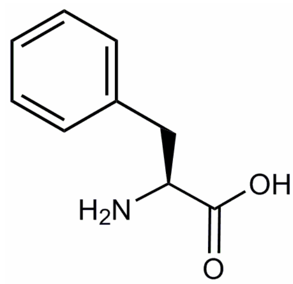
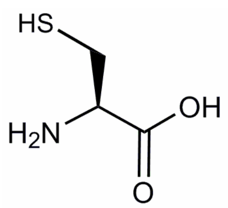
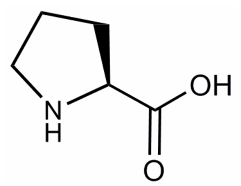
This implies that a plot of $\ln\left(G(t+\Delta) - G(t)\right)$ against time should be a straight line of slope –k_{app}; to make this plot there is no need to know the value of the conductance at infinite time, G_∞, and this is the main advantage of the Guggenheim method.

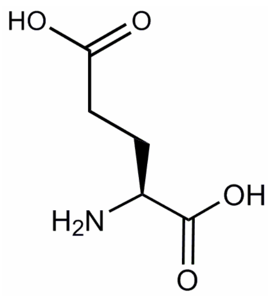
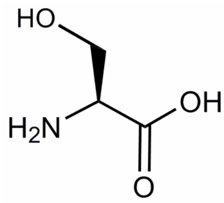
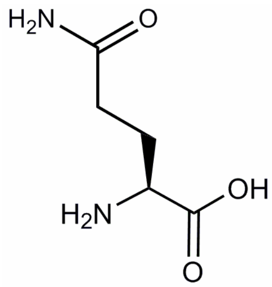
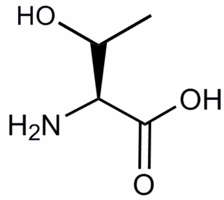
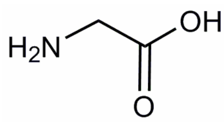
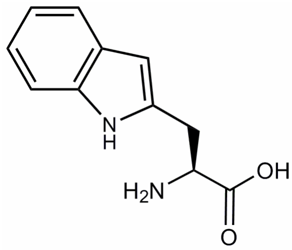
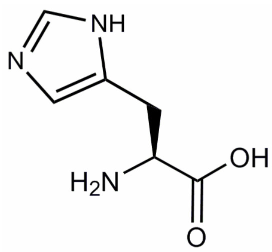
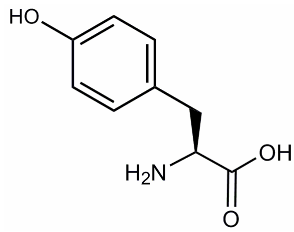
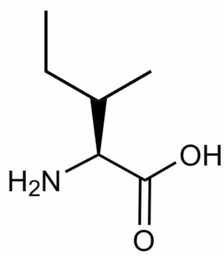
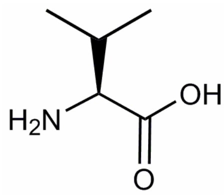
Appendix

Physical constants

Name	Symbol	Value
Avogadro's constant	N_A	6.0221×10^{23} mol^{-1}
Boltzmann constant	k_B	1.3807×10^{-23} J K^{-1}
Gas constant	R	8.3145 J K^{-1} mol^{-1}
Faraday constant	F	96485 C mol^{-1}
Speed of light	c	2.9979×10^{8} m s^{-1}
Planck's constant	h	6.6261×10^{-34} J s
Standard pressure	$p°$	10^5 Pa
Atmospheric pressure	p_{atm}	1.01325×10^5 Pa
Zero of the Celsius scale		273.15 K

Amino acids

Name	Mass	Structure	Name	Mass	Structure
Alanine Ala A	89.0		Leucine Leu L	131.1	
Arginine Arg R	174.1		Lysine Lys K	146.1	
Aspartic Acid Asp D	133.0		Methionine Met M	149.1	
Asparagine Asn N	132.1		Phenyalanine Phe F	165.1	
Cysteine Cys C	121.0		Proline Pro P	115.1	

Name	**Mass**	**Structure**	**Name**	**Mass**	**Structure**
Glutamic Acid Glu E	147.1		Serine Ser S	105.0	
Glutamine Gln Q	146.1		Theronine Thr T	119.1	
Glycine Gly G	75.0		Tryptophan Trp W	204.1	
Histidine His H	155.1		Tyrosine Tyr Y	181.1	
Isoleucine Ile I	131.1		Valine Val V	117.1	

Masses given are all monoisotopic.