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THEORETICAL PROBLEMS

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50th IChO 2018

International Chemistry Olympiad
SLOVAKIA & CZECH REPUBLIC

BACK TOWHERE IT ALL BEGAN



Table of Contents

Instructions.....	2
Physical constants and equations.....	3
Problem 1. DNA	5
Problem 2. Repatriation of remains in the middle ages.....	10
Problem 3. Emerging electro-mobility	17
Problem 4. Column chromatography of radioactive copper.....	23
Problem 5. Bohemian garnet	28
Problem 6. Let's go mushrooming	34
Problem 7. Cidofovir	39
Problem 8. Caryophyllene	46



Instructions

- This theoretical exam booklet contains 53 pages.
- You may begin writing as soon as the **Start** command is given.
- You have **5 hours** to complete the exam.
- All results and answers must be clearly written **in pen in their respective designed areas** on the exam papers. Answers written outside the answer boxes will not be graded.
- You were provided with 3 sheets of scratch paper. If you need more, use the backside of the exam sheets. Remember that **nothing outside the designed areas will be graded**.
- The periodic table and visible light spectrum are not part of this booklet; they are provided separately.
- Use only the pen and calculator provided.
- **The official English version** of the exam booklet is available upon request and serves for clarification only.
- If you need to leave the exam room (to use the toilet or have a snack), wave the blue IChO card. The exam supervisor will come to accompany you.
- The supervisor will announce a 30-minute warning before the **Stop** command.
- You must stop your work immediately when the **Stop** command is announced. Failure to stop writing by $\frac{1}{2}$ minute or longer will lead to nullification of your theoretical exam.
- After the **Stop** command has been given, place your exam booklet back in your exam envelope and wait at your seat. The exam supervisor will come to collect the envelope.



Physical constants and equations

Avogadro's constant:	$N_A = 6.022 \times 10^{23} \text{ mol}^{-1}$
Universal gas constant:	$R = 8.314 \text{ J K}^{-1} \text{ mol}^{-1}$
Speed of light:	$c = 2.998 \times 10^8 \text{ m s}^{-1}$
Planck's constant:	$h = 6.626 \times 10^{-34} \text{ J s}$
Faraday constant:	$F = 9.6485 \times 10^4 \text{ C mol}^{-1}$
Standard pressure:	$p = 1 \text{ bar} = 10^5 \text{ Pa}$
Normal (atmospheric) pressure:	$p_{\text{atm}} = 1.01325 \times 10^5 \text{ Pa}$
Zero of the Celsius scale:	273.15 K
Mass of electron:	$m_e = 9.109 \times 10^{-31} \text{ kg}$
Unified atomic mass unit:	$u = 1.6605 \times 10^{-27} \text{ kg}$
Ångström:	$1 \text{ Å} = 10^{-10} \text{ m}$
Electronvolt:	$1 \text{ eV} = 1.602 \times 10^{-19} \text{ J}$
Watt:	$1 \text{ W} = 1 \text{ J s}^{-1}$
Ideal gas equation:	$pV = nRT$
The first law of thermodynamics:	$\Delta U = q + W$
Power input for electrical device:	$P = UI$ where U is voltage and I electric current
Enthalpy:	$H = U + pV$
Gibbs free energy:	$G = H - TS$ $\Delta G^\circ = -RT \ln K = -zFE_{\text{cell}}^\circ$ $\Delta G = \Delta G^\circ + RT \ln Q$
Reaction quotient Q for a reaction $a A + b B \rightleftharpoons c C + d D$:	$Q = \frac{[C]^c [D]^d}{[A]^a [B]^b}$
Entropy change:	$\Delta S = \frac{q_{\text{rev}}}{T}$ where q_{rev} is heat for the reversible process
Heat change for temperature-independent c_m :	$\Delta q = n c_m \Delta T$ where c_m is molar heat capacity
Van 't Hoff equation:	$\frac{d \ln K}{dT} = \frac{\Delta_r H_m}{RT^2} \Rightarrow \ln \left(\frac{K_2}{K_1} \right) = -\frac{\Delta_r H_m}{R} \left(\frac{1}{T_2} - \frac{1}{T_1} \right)$



Henderson–Hasselbalch equation:
$$\text{pH} = \text{p}K_a + \log \frac{[\text{A}^-]}{[\text{HA}]}$$

Nernst–Peterson equation:
$$E = E^\circ - \frac{RT}{zF} \ln Q$$

Energy of a photon:
$$E = \frac{hc}{\lambda}$$

Relation between E in eV and in J:
$$E/\text{eV} = \frac{E/\text{J}}{q_e/\text{C}}$$

Lambert–Beer law:
$$A = \log \frac{I_0}{I} = \epsilon lc$$

Wavenumber:
$$\tilde{\nu} = \frac{\nu}{c} = \frac{1}{2\pi c} \sqrt{\frac{k}{\mu}}$$

Reduced mass μ for a molecule AX:
$$\mu = \frac{m_A m_X}{m_A + m_X}$$

Energy of harmonic oscillator:
$$E_n = h\nu \left(n + \frac{1}{2} \right)$$

Arrhenius equation:
$$k = A e^{-\frac{E_a}{RT}}$$

Rate laws in integrated form:

Zero order:
$$[\text{A}] = [\text{A}]_0 - kt$$

First order:
$$\ln[\text{A}] = \ln[\text{A}]_0 - kt$$

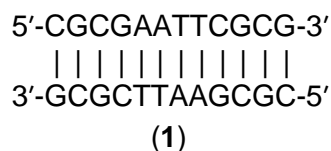
Second order:
$$\frac{1}{[\text{A}]} = \frac{1}{[\text{A}]_0} + kt$$



Theoretical Problem 1 7% of the total	Question	1.1	1.2	1.3	1.4	1.5	1.6	Total
	Points	5	5	4	12	12	24	62
	Score							

Problem 1. DNA

Palindromic sequences are an interesting class of DNA. In a palindromic double-stranded DNA (dsDNA) species, the sequence of one strand read in the 5'→3' direction matches the 5'→3' reading on the complementary strand. Hence, a palindromic dsDNA consists of two identical strands that are complementary to each other. An example is the so-called Drew–Dickerson dodecanucleotide (1):



- 1.1 How many different palindromic double-stranded DNA dodecanucleotides (i.e., dsDNA species with twelve base pairs) exist?

- 1.2 How many different palindromic double-stranded DNA undecanucleotides (i.e., dsDNA species with eleven base pairs) exist?

The melting temperature of dsDNA, T_m is defined as the temperature at which 50% of the original amount of DNA double strands are dissociated into separate strands.

- 1.3 Consider the Drew–Dickerson dodecanucleotide(1). Assume that a G–C nucleobase pair contributes to the DNA duplex stability more than an A–T pair does. What is the probability that its T_m increases when a single randomly selected base pair is replaced by a G–C pair?



Probability

Let us analyze the thermodynamics of formation of double-helical DNA from single strands, and its dependence on the length of the DNA and on the temperature. The equilibrium constant of association of single strands to form dsDNA differs for palindromic and non-palindromic dsDNA. A solution of dsDNA with the initial concentration of $c_{\text{init}} = 1.00 \times 10^{-6} \text{ mol dm}^{-3}$ was heated to T_m and equilibrium was reached.

- 1.4 Calculate the equilibrium constant of **association** of single strands at T_m for both non-palindromic and palindromic DNA.

Non-palindromic dsDNA

Calculation:

$K =$

Palindromic dsDNA

Calculation:



$K =$

The mean contributions to the Gibbs energy of association of two single strands to form dsDNA were estimated over a certain range of experimental conditions, and they amount to $-6.07 \text{ kJ mol}^{-1}$ per one G–C pair, and $-1.30 \text{ kJ mol}^{-1}$ per one A–T pair present in a dsDNA.

- 1.5 How many base pairs are there in the **shortest** dsDNA oligonucleotide that has T_m above 330 K? At this T_m , consider the following values of the equilibrium constant of association of single strands to form a dsDNA: $K_{np} = 1.00 \times 10^6$ for a non-palindromic dsDNA, $K_p = 1.00 \times 10^5$ for a palindromic dsDNA. Is the shortest oligonucleotide palindromic or non-palindromic?

Calculation of the number of base pairs:

The needed length of a non-palindromic dsDNA:

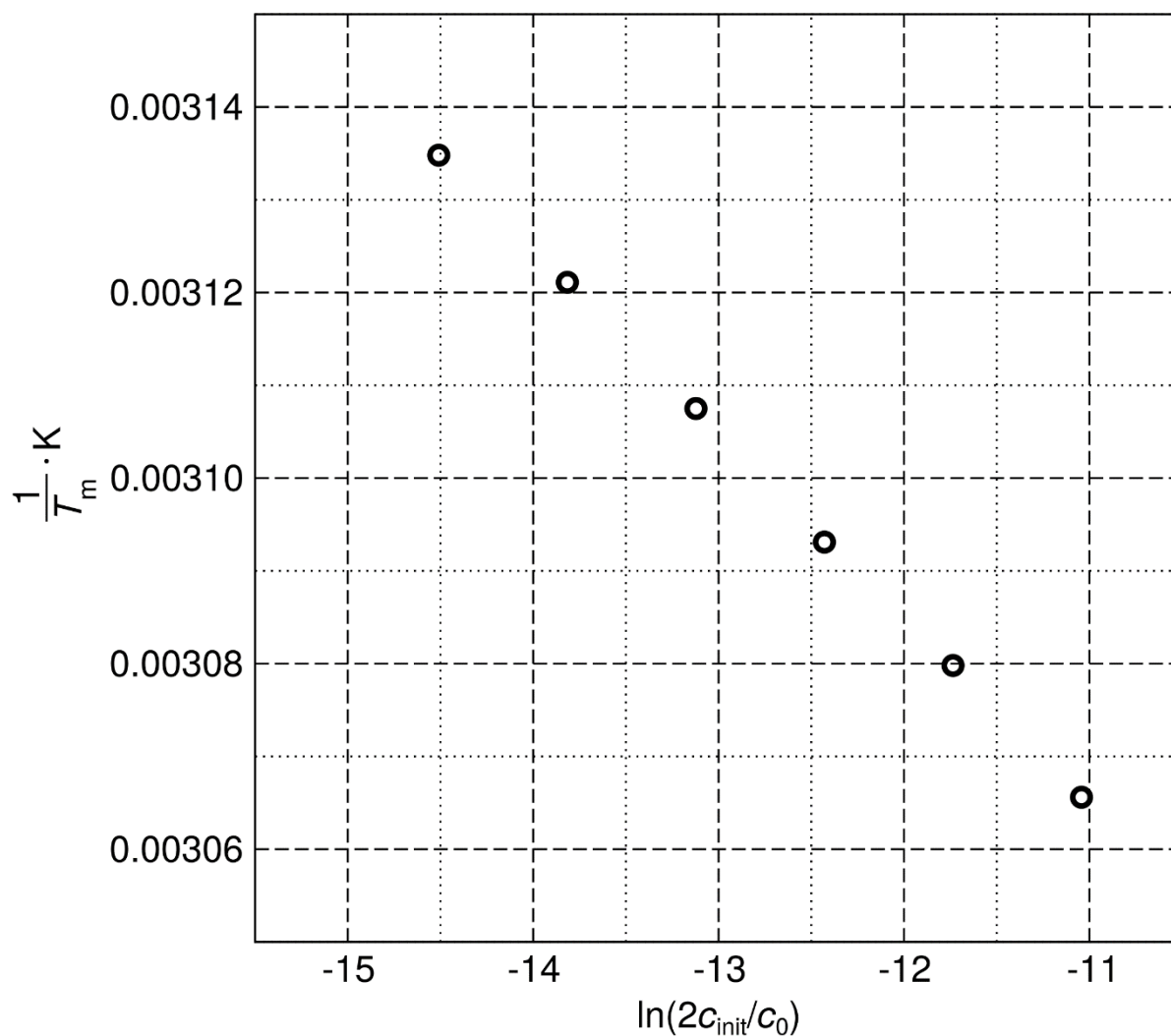
The needed length of a palindromic dsDNA:

The shortest oligonucleotide is

- palindromic (P)
 non-palindromic (NP).



Finally, let us leave the simplified idea of base pairs contributing individually to the **association** of DNA strands. The Gibbs energy of this process may be considered explicitly dependent on temperature. The dependence of the inverse T_m of the Drew–Dickerson dodecanucleotide (1) on the logarithm of the initial duplex concentration c_{init} is shown below. (Note: a standard concentration $c_0 = 1 \text{ mol dm}^{-3}$ is introduced.)



$c_{\text{init}} / 10^{-6} \text{ mol dm}^{-3}$	0.25	0.50	1.00	2.0	4.0	8.0
T_m / K	319.0	320.4	321.8	323.3	324.7	326.2



- 1.6 Calculate the standard enthalpy ΔH° and the standard entropy ΔS° of the association of DNA single strands to form the palindromic double-stranded Drew–Dickerson dodecanucleotide (1). Assume that ΔH° and ΔS° do not vary with temperature.

Calculation:



Theoretical Problem 2 8% of the total	Question	2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.8	Total
	Points	1	4	4	2	6	10	17	14	58
	Score									

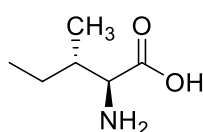
Problem 2. Repatriation of remains in the middle ages

At ambient temperatures, racemization is a slow reaction. As such, it can be used for dating biological objects and, moreover, for studying their thermal history. Let us take L-isoleucine (L-Ile) ((2*S*,3*S*)-2-amino-3-methylpentanoic acid) as an example. It isomerizes on the α -carbon and forms (2*R*,3*S*)-2-amino-3-methylpentanoic acid, also known as D-*allo*-isoleucine. As the configuration changes on only one of the two stereogenic centres, this process is called epimerization rather than racemization.

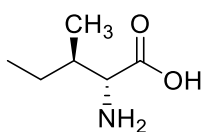
2.1 Choose all true statements.

- D-*allo*-isoleucine and L-isoleucine have the same values of specific optical rotation but they have different melting points.
- D-*allo*-isoleucine has an identical absolute value of specific optical rotation as L-isoleucine but the sign is opposite. The melting point is the same for both isomers.
- D-*allo*-isoleucine and L-isoleucine have different values of specific optical rotation but they have the same melting points.
- D-*allo*-isoleucine and L-isoleucine have different values of specific optical rotation and different melting points.
- D-*allo*-isoleucine is not optically active.

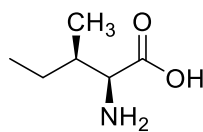
2.2 Assign the absolute configurations for each stereoisomer of isoleucine. (indicate the answers in the respective boxes by using appropriate alphabets)



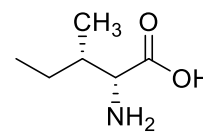
A



B



C



D

2*S*,3*R* (L-*allo*-isoleucine)

2*R*,3*S* (D-*allo*-isoleucine)

2*S*,3*S* (L-isoleucine)

2*R*,3*R* (D-isoleucine)



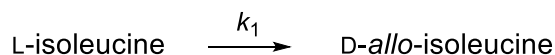
- 2.3 The equilibrium constant for L-isoleucine epimerization (K_{ep}) has the value of 1.38 (at 374 K). If we set molar Gibbs free energy of L-isoleucine $G_m^\circ = 0 \text{ kJ mol}^{-1}$, determine the Gibbs free energies for all structures **A–D** from question 2.2 at 374 K.

A	kJ mol^{-1}
B	kJ mol^{-1}
C	kJ mol^{-1}
D	kJ mol^{-1}

- 2.4 If we take into account stereoisomerism at all stereocentres, what is the maximum possible number of the stereoisomers of the tripeptide Ile-Ile-Ile?

The number of stereoisomers is

At the start of the epimerization, we **can neglect** the reverse reaction. The epimerization then follows the first-order kinetics:



The value of the rate constant for above reaction at 374 K is $k_1(374 \text{ K}) = 9.02 \times 10^{-5} \text{ h}^{-1}$ and at 421 K is $k_1(421 \text{ K}) = 1.18 \times 10^{-2} \text{ h}^{-1}$.

In the following calculation, shorten the concentration of L-isoleucine to [L] and of D-*allo*-isoleucine to [D].

We can define a quantity *de* (diastereomeric excess):

$$de = \frac{[L] - [D]}{[L] + [D]} \times 100(\%).$$

- 2.5 Let us boil L-isoleucine for 1943 hours at 374 K. What is the value of *de* (with three significant figures) for L-isoleucine a) before boiling and b) after boiling?



a) Before boiling

Calculation:

$de =$ % (with three significant figures)

b) After boiling

Calculation:

$de =$ % (with three significant figures)

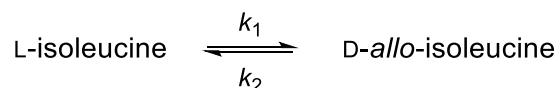
2.6 How long does it take to convert 10% of L-isoleucine to D-*allo*-isoleucine at 298 K?

Calculation:



$t =$ years

In fact, the reverse reaction cannot be neglected. The correct kinetic scheme is expressed as



Let us define the deviation of concentration from its equilibrium value $[L]_{eq}$

$$x = [L] - [L]_{eq}$$

It is possible to derive that x evolves with time according to the following equation:

$$x = x(0) \times e^{-(k_1 + k_2)t}$$

where $x(0)$ is the deviation from equilibrium at $t = 0$ h.

- 2.7 Let us boil 1.00 mol dm^{-3} L-isoleucine solution for 1943 hours at 374 K. The rate constant for the forward reaction is $k_1(374 \text{ K}) = 9.02 \times 10^{-5} \text{ h}^{-1}$, K_{ep} for L-isoleucine epimerization has the value of 1.38 (at 374 K). In the following calculation, shorten the concentration of L-isoleucine to $[L]$ and of D-*allo*-isoleucine to $[D]$. Evaluate (with three significant figures) - a) $[L]_{eq}$, b) diastereomeric excess (*de*) after boiling.

a) Calculation:



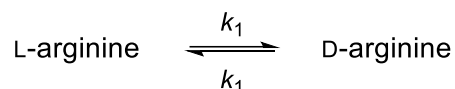
$[L]_{\text{eq}} =$ mol dm^{-3} (with three significant figures)

b) Calculation:



$de =$ % (with three significant figures)

Amino acids with a single chiral centre undergo racemization, e.g. L-arginine racemizes:



The time evolution of concentrations is governed by

$$\ln \frac{1 + \frac{[D]}{[L]}}{1 - \frac{[D]}{[L]}} = 2k_1 t + C$$

Here [D] and [L] are concentrations of D- and L-arginine at time t , k_1 is the rate constant, and the term C is set according to the initial concentrations.

Holy Roman Emperor Lothar III passed away during his journey to Sicily in 1137. To facilitate the repatriation of the remains, his body was boiled in water (373 K) immediately after his death for a certain time. Let us try to estimate the boiling time with the help of chemical kinetics. We know that the rate constant k_1 of arginine racemization within the protein at 373 K and pH = 7 has the value of $5.10 \times 10^{-3} \text{ h}^{-1}$.

In order to analyse the isomeric composition of arginine in Lothar's bones, we need to start with transferring arginine into solution. Lothar's bones were hydrolyzed in a highly acidic environment for 4 hours at 383 K. The ratio of the optical isomers was $\frac{[D]}{[L]} = 0.090$. Lothar's wife Richenza's body was not boiled after her death. Her bones were hydrolyzed using the same procedure and in this case the ratio was $\frac{[D]}{[L]} = 0.059$. (Note that the racemization also takes place during the hydrolysis, with the rate constant k'_1 , different from k_1).

2.8 How long was the Holy Roman Emperor Lothar III boiled in water in 1137?

Note: The racemization of arginine is an extremely slow process at temperatures typically encountered in graves. As both bodies are only some 880 years old, we can neglect the natural racemization during this time.



Calculation:

$t_{\text{boiling}} =$ h



Theoretical Problem 3 8% of the total	Question	3.1	3.2	3.3	3.4	3.5	3.6
	Points	2	6	7	3	7	8
	Score						
	Question	3.7	3.8	3.9	3.10	3.11	Total
	Points	6	10	5	2	6	62
	Score						

Problem 3. Emerging electro-mobility

Contemporary means of transportation rely on burning fossil fuels, although the efficiency of real combustion engines is inherently limited and typically ranges between 20 and 40%.

3.1 Mark the factors that can make the efficiency of a heat engine higher:

- Increasing the friction in the mechanical parts of the engine
- Increasing the burning temperature of the fuel in the engine
- Narrowing the working temperature interval of the engine
- Increasing the working pressure of the gas

Fuel cells represent a way to improve the engine efficiency for future vehicles. The engine efficiency can be improved by using hydrogen-based fuel cells.

3.2 The standard enthalpy of formation of liquid water is $\Delta_f H^\circ(\text{H}_2\text{O}, \text{l}) = -285.84 \text{ kJ mol}^{-1}$, and the standard combustion enthalpy of isooctane is $\Delta_c H^\circ(\text{C}_8\text{H}_{18}, \text{l}) = -5\,065.08 \text{ kJ mol}^{-1}$ (both at 323.15 K). Calculate the values of specific (per unit of mass) combustion enthalpy at 323.15 K of pure liquid isooctane and pure gaseous hydrogen.

$$\Delta_c H_s^\circ(\text{C}_8\text{H}_{18}) =$$

$$\Delta_c H_s^\circ(\text{H}_2) =$$



- 3.3 Calculate the standard electromotive force (EMF) of a fuel cell using gaseous oxygen and hydrogen, both ideal gases at 100 kPa and 323.15 K, to produce liquid water. Use the following entropy data for 323.15 K: $S^\circ(\text{H}_2\text{O},\text{l}) = 70 \text{ J K}^{-1} \text{ mol}^{-1}$, $S^\circ(\text{H}_2,\text{g}) = 131 \text{ J K}^{-1} \text{ mol}^{-1}$, $S^\circ(\text{O}_2,\text{g}) = 205 \text{ J K}^{-1} \text{ mol}^{-1}$.

Calculations:

EMF = V

- 3.4 Determine the ideal thermodynamic efficiency (η) of a fuel cell producing liquid water at 353.15 K. At this temperature, the enthalpy of formation of water is $\Delta_f H^\circ(\text{H}_2\text{O},\text{l}) = -281.64 \text{ kJ mol}^{-1}$ and the corresponding reaction Gibbs energy change is $\Delta_r G^\circ = -225.85 \text{ kJ mol}^{-1}$.

$\eta =$ %

- 3.5 A polymer membrane electrolyzer facility operates at the voltage of 2.00 V and is powered by a 10.0 MW wind turbine plant which was running at full power from 10 pm to 6 am. The electrolysis yielded 1090 kg of pure hydrogen. Calculate the electrolysis yield defined as the mass of produced hydrogen divided by its theoretical produced mass.

Calculations:



$$\eta_{\text{electrolysis}} = \quad \quad \quad \%$$

- 3.6 Calculate the mass of hydrogen required to drive the distance between Prague and Bratislava (330 km) at the average speed of 100 km h^{-1} with a car fitted with a 310 kW electric engine running on average at a 15% rate of its maximum power. Assume that the efficiency of the hydrogen cell producing electrical energy is 75%, the efficiency of the electric engine is 95%, and the Gibbs energy change for combustion of hydrogen fuel is $\Delta_r G = -226 \text{ kJ mol}^{-1}$.

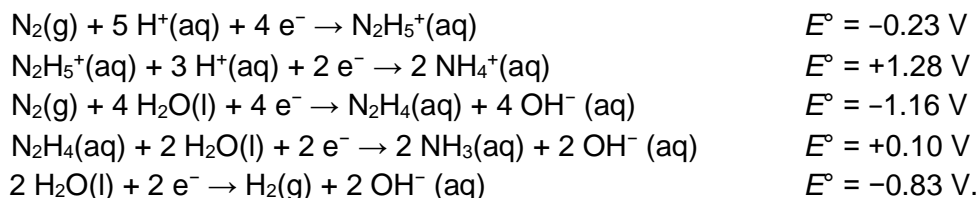
Calculations:

$$m = \quad \quad \quad \text{kg}$$

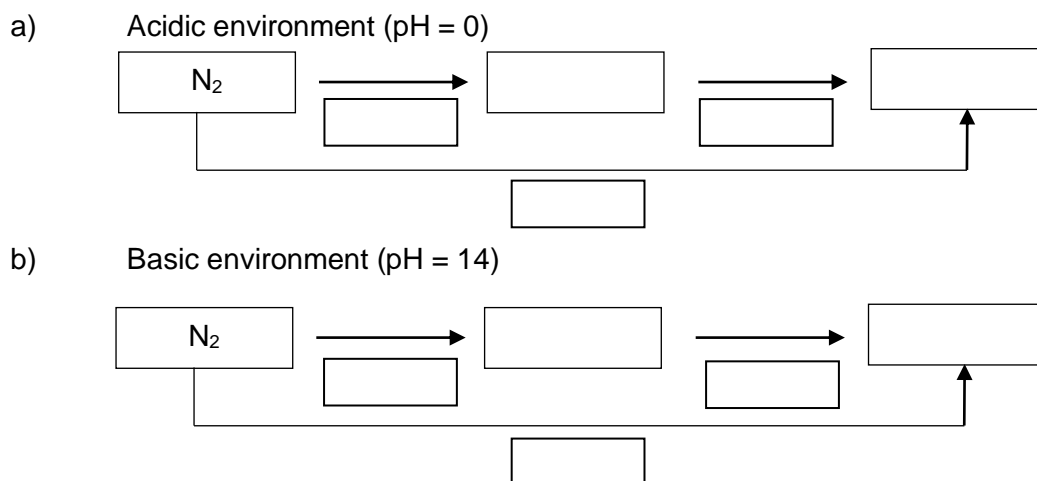


The low efficiency of hydrogen production and the safety issues connected with its storage, impede spreading the hydrogen-based transportation technology. Hydrazine (N_2H_4) fuel cells might be a suitable alternative.

The following standard reduction potentials for aqueous hydrazine systems are available:



3.7 Fill in the following Latimer diagrams with the forms of hydrazine and ammonia prevailing at the given conditions and write the redox potential value for each arrow representing the electrochemical half-reaction. Record all the necessary calculations.



Calculations:



Due to the toxicity, odour and its environmental impact, it is extremely unfavourable to produce ammonia in fuel cells.

- 3.8 Write down the net reaction for the decomposition of hydrazine under basic conditions to (i) ammonia and nitrogen and (ii) nitrogen and hydrogen and calculate the corresponding equilibrium constants at $T = 298.15 \text{ K}$.

Equations for hydrazine decomposition:

Calculations:

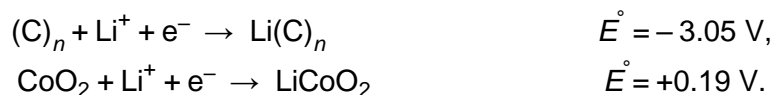
Hydrazine decomposition to NH_3 and N_2 in a basic environment:

$K =$

Hydrazine decomposition to H_2 and N_2 in a basic environment:

$K =$

Rechargeable lithium-based batteries are an alternative to fuel cells. Lithium-ion batteries commonly use graphite for one of the electrodes, in which lithium clusters intercalate in between the graphite sheets. The other electrode is made of lithium cobalt oxide, which can reversibly absorb lithium ions moving from one electrode to the other during the charge and discharge processes. The half-reactions relevant for the system can be formally written as:





- 3.9 Using the formalism given above, write down the overall chemical reaction occurring in the battery during the **discharge** process. Give the oxidation states of the cobalt atom.

- 3.10 Tick the boxes to get the correct statements which are valid for the **discharge** of the lithium-based battery described in 3.9:

Li(C) _n electrode is	<input type="checkbox"/>	cathode	<input type="checkbox"/>	because lithium ions are reduced here.
	<input type="checkbox"/>	anode	<input type="checkbox"/>	because lithium atoms are oxidized here.
LiCoO ₂ electrode is	<input type="checkbox"/>	cathode	<input type="checkbox"/>	because cobalt ions are reduced here.
	<input type="checkbox"/>	anode	<input type="checkbox"/>	because cobalt ions are oxidized here.

- 3.11 Assume that a C₆ unit, a CoO₂ unit and Li atom form the active battery mass required to transfer one electron between the electrodes. Using the corresponding standard EMF, calculate the theoretical specific reversible charge capacity (in mAh g⁻¹) and the energy density (in kWh kg⁻¹) of such a model lithium ion battery related to the whole active battery mass.

Calculations:

Charge capacity ($c_{q,s}$) = _____ mAh g⁻¹

Calculations:

Energy density (ρ_{el}) = _____ kWh kg⁻¹

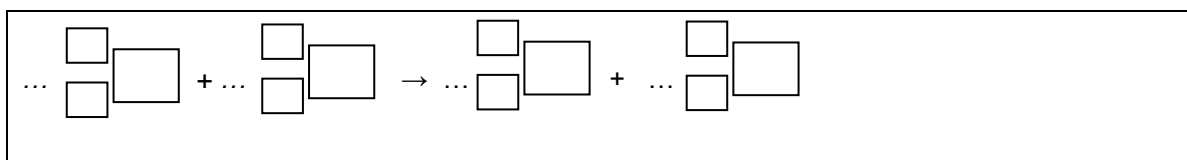


Theoretical Problem 4 6% of the total	Question	4.1	4.2	4.3	4.4	4.5	4.6	4.7	4.8	Total
	Points	2	5	1	2	7	2	3	2	24
	Score									

Problem 4. Column chromatography of radioactive copper

^{64}Cu for positron emission tomography is prepared by the bombardment of a zinc target with deuterium nuclei (further referred to as the activated target).

- 4.1 Write down the balanced equation for the ^{64}Zn nucleus bombardment with deuterium nuclei, giving ^{64}Cu . Specify the corresponding atomic and mass numbers of all species. Disregard the charges.



The activated target is dissolved in concentrated hydrochloric acid (HCl (aq)) to give a mixture containing Cu^{2+} and Zn^{2+} ions and their respective chloride complexes.

- 4.2 Calculate the mole fraction of negatively charged copper species with respect to the amount of copper prepared by zinc target activation. Assume $[\text{Cl}^-] = 4 \text{ mol dm}^{-3}$. For the overall complexation constants, β , see Table 1.

Before you start the calculation, write down the charges in the upper right boxes:

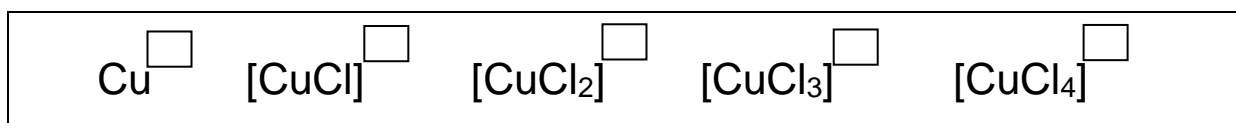


Table 1. **Overall complexation constants β** of Cu species (charges were omitted in the formulas). $\beta_i = \frac{[\text{CuCl}_i]}{[\text{Cu}] \cdot [\text{Cl}]^i}$

	<i>i</i> in $[\text{CuCl}_i]$			
	1	2	3	4
β_i	2.36	1.49	0.690	0.055



Calculation:

Mole fraction =

(answer with 2 digits after decimal point)

The mixture containing Cu^{2+} and Zn^{2+} ions and their respective chloride complexes was separated with an anion exchange resin. Dry resin in OH^- form was dispersed in water and the suspension was transferred into a column. To occupy all sites with Cl^- ions (i.e. to obtain resin in a Cl^- form), the resin was washed with hydrochloric acid and then with deionized water to wash out all the unbound Cl^- ions.

4.3 Everything was initially at laboratory temperature before washing with hydrochloric acid. Does the column temperature change during the washing with hydrochloric acid?

- No.
- Yes, the temperature decreases.
- Yes, the temperature increases.

The mixture containing Cu^{2+} and Zn^{2+} ions and their respective chloride complexes was transferred onto the resin-filled column. Hydrochloric acid solution was used as an eluent.

Using the simple experimental formula, you can calculate quantities that determine average elution properties of both copper species and zinc species on the column.

The retention volume V_R (the mobile phase volume at which 50% of the compound has been eluted from the column) can be calculated as follows:

$$V_R = D_g \times m_{\text{resin,dry,OH form}} + V_0$$



- 4.4 Using average mass distribution coefficients D_g ($D_g(\text{Cu species}) = 17.4 \text{ cm}^3 \text{ g}^{-1}$, $D_g(\text{Zn species}) = 78.5 \text{ cm}^3 \text{ g}^{-1}$), calculate the retention volumes V_R in cm^3 of both copper species and zinc species if the mass of dry resin in OH^- form $m_{\text{resin,dry,OH form}} = 3.72 \text{ g}$ and the void volume of a column $V_0 = 4.93 \text{ cm}^3$.

Calculation:

$$V_R(\text{Cu species}) = \quad \text{cm}^3 \text{ (answer with 1 digit after the decimal point)}$$

$$V_R(\text{Zn species}) = \quad \text{cm}^3 \text{ (answer with 0 digit after the decimal point)}$$

If you cannot find the answer, use $V_R(\text{Cu species}) = 49.9 \text{ cm}^3$ and $V_R(\text{Zn species}) = 324 \text{ cm}^3$ for further calculations.

Using the simple experimental formula, separation of two sets of species, **A** and **B**, can be considered complete if

$$V_{0.001}(\mathbf{A}) - V_{0.999}(\mathbf{B}) > 10V_c$$

where $V_{0.001}$ is the mobile phase volume at which 0.1% of **A** has been eluted from the column, and $V_{0.999}$ is the mobile phase volume at which 99.9% of **B** has been eluted from the column.

$$V_{0.001}(\mathbf{A}) = V_R(\mathbf{A}) \times \left(1 - 6.91 \sqrt{d_p/L_c}\right)$$

$$V_{0.001}(\mathbf{B}) = V_R(\mathbf{B}) \times \left(1 - 6.91 \sqrt{d_p/L_c}\right)$$

$$V_{0.999}(\mathbf{B}) = 2V_R(\mathbf{B}) - V_{0.001}(\mathbf{B})$$

- 4.5 Based on calculation, decide whether copper species were separated completely from zinc species. The volume of the column filled with the swollen resin $V_c = 10.21 \text{ cm}^3$, the resin particle diameter $d_p = 0.125 \text{ mm}$, and the height of the wet resin in a swollen state in the column $L_c = 13.0 \text{ cm}$.

$$V_{0.001}(\mathbf{A}) = \quad \text{cm}^3$$



$$V_{0.999}(\text{B}) = \quad \text{cm}^3$$

It is possible to separate copper species from zinc species.

True False

- 4.6 Calculate the theoretical value of the total ion exchange mass capacity of the dry resin used in this problem, $Q_{m,\text{theor}}$, in mmol g^{-1} . Consider tetraalkylammonium groups were the only ones responsible for ion exchange of the resin. No other nitrogen containing groups were present. The mass fraction of nitrogen in the dry resin was 4.83%.

$$Q_{m,\text{theor}} = \quad \text{mmol g}^{-1} \text{ (answer with 2 digits after decimal point)}$$

If you cannot find the answer, use $Q_{m,\text{theor}} = 4.83 \text{ mmol g}^{-1}$ for further calculations.

In reality, not all tetraalkylammonium groups are involved in the ion exchange. To determine the total ion exchange volume capacity, Q_v , the column filled with 3.72 g dry resin converted to the Cl^- form was washed with the excess of sodium sulfate solution. The effluent was collected in a 500 cm^3 volumetric flask, which was then filled with water to the mark. An aliquot of 100 cm^3 was potentiometrically titrated with $0.1027 \text{ mol dm}^{-3}$ silver nitrate. The silver nitrate solution volume at the equivalence point was 22.20 cm^3 . The volume of the column filled with the swollen resin, V_c , was 10.21 cm^3 .

- 4.7 Calculate the Q_v of the swollen resin in mmol of active tetraalkylammonium groups per cm^3 of the swollen resin.

$$Q_v = \quad \text{mmol cm}^{-3} \text{ (answer with 2 digits after decimal point)}$$



If you cannot find the answer, use $Q_v = 1.00 \text{ mmol cm}^{-3}$ for further calculations.

- 4.8 Calculate the mole fraction (x) of the tetraalkylammonium groups actively involved in the ion exchange.

$x =$ (answer with 3 digits after decimal point)



Theoretical Problem 5	Question	5.1	5.2	5.3	5.4	5.5	5.6	5.7	5.8	5.9
	Points	3	3	1	5	3	2	4	1	2
	Score									
8% of the total	Question	5.10	5.11	5.12	5.13	5.14	5.15	5.16	5.17	Total
	Points	5	7	3	2	6	1	1	1	50
	Score									

Problem 5. Bohemian garnet

Bohemian garnet (pyrope) is a famous Czech blood red coloured semi-precious stone. The chemical composition of natural garnets is expressed by the general stoichiometric formula of $A_3B_2(SiO_4)_3$, where A^{II} is a divalent cation and B^{III} is a trivalent cation. Garnets have a cubic unit cell that contains 8 formula units. The structure comprises 3 types of polyhedra: the A^{II} cation occupies a dodecahedral position (it is surrounded with eight O atoms), the B^{III} cation occupies an octahedral position (it is surrounded with six O atoms) and Si^{IV} is surrounded with four O atoms arranged into a tetrahedron.

The most common garnet mineral is almandine with the formula of $Fe_3Al_2(SiO_4)_3$. Its unit cell parameter is $a = 11.50 \text{ \AA}$.

5.1 Calculate the theoretical density of almandine.

$\rho =$ g cm^{-3}

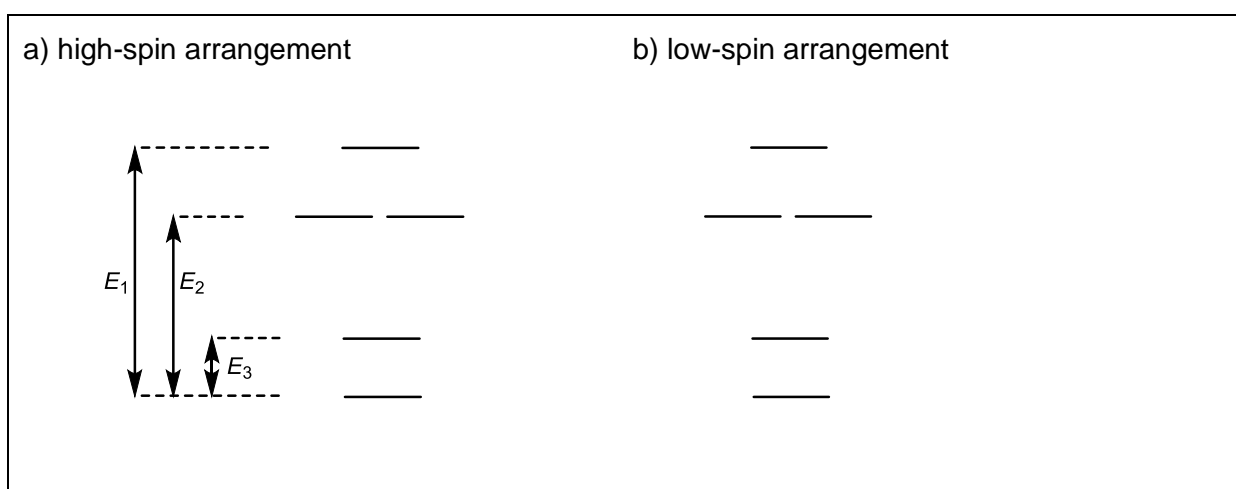
The Bohemian garnet has the composition of $Mg_3Al_2(SiO_4)_3$. Pure compound is colourless and the colour of natural garnets comes from chromophores– transition metal cations that substitute the host material cations. The blood red colour of the Bohemian garnet comes from trace amounts of Cr^{III} ions in the octahedral sites and Fe^{II} ions in the dodecahedral sites.

5.2 Draw the splitting diagram for the $[Cr^{III}O_6]^{oct}$ d-orbitals and fill it with electrons.



- 5.3 Identify the 1st row transition element(s) whose trivalent cation(s) M^{III} placed in an **octahedral** position is/are diamagnetic in the low-spin arrangement and paramagnetic in the high-spin arrangement.

- 5.4 The figure below shows d-orbitals splitting in the dodecahedral crystal field. Fill in the electrons for the $[Fe^{II}O_8]^{dod}$ chromophore for both existing arrangements.



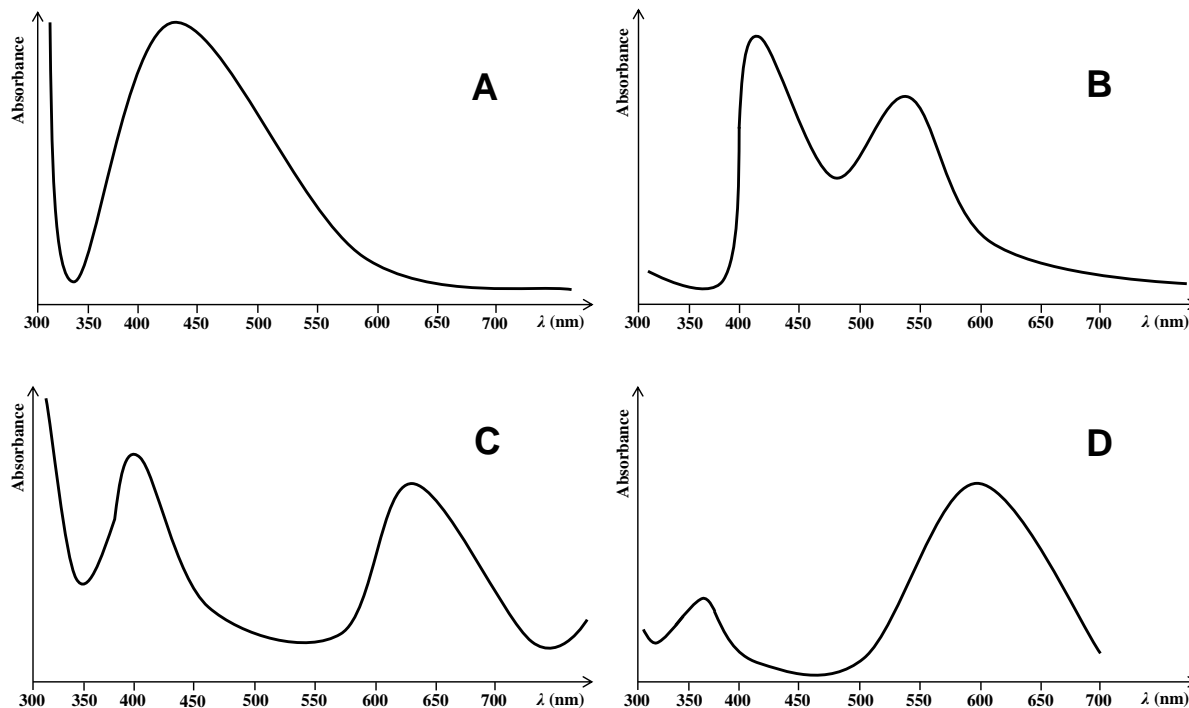
- 5.5 Derive the inequalities (e.g. $P < E_1 + E_2 + E_3$) for the pairing energy (P) magnitude in relation to energies E_1 , E_2 and E_3 for both the arrangements.

a) high-spin arrangement:	P
b) low-spin arrangement:	P

- 5.6 Assuming that $P > E_3$, identify the 1st row transition elements whose divalent cation M^{II} placed in dodecahedral position is diamagnetic in the low-spin arrangement and paramagnetic in the high-spin arrangement.



The figures below show simplified absorption spectra of four coloured minerals – blood red-coloured Bohemian garnet, green uvarovite, blue sapphire and yellow-orange citrine.



5.7 Match the spectra with the minerals. (indicate your answer using the appropriate alphabet)

Bohemian garnet:	Sapphire:
Uvarovite:	Citrine:

5.8 If illuminated with monochromatic blue-green light, how will the Bohemian garnet look?

<input type="checkbox"/> Red	<input type="checkbox"/> Blue	<input type="checkbox"/> Yellow-orange	<input type="checkbox"/> Black
<input type="checkbox"/> Yellow	<input type="checkbox"/> Blue-green	<input type="checkbox"/> Violet	<input type="checkbox"/> White

Andradite is another garnet mineral; its chemical composition is $\text{Ca}_3\text{Fe}_2(\text{SiO}_4)_3$. A double cation substitution – Ti^{IV} for Fe^{III} in the octahedral position and Fe^{III} for Si^{IV} in the tetrahedral position – gives rise to black schorlomite. Its chemical composition can be expressed as $\text{Ca}_3[\text{Fe}, \text{Ti}]_2^{\text{oct}}([\text{Si}, \text{Fe}]^{\text{tet}}\text{O}_4)_3$.



- 5.9 Calculate the percentage of Si^{IV} ions in a sample of schorlomite that must be substituted with Fe^{III} , if we know that 5% of Fe^{III} ions in octahedral position are substituted with Ti^{IV} .

$p =$ %

The colour of the mineral is caused by two chromophores: $[\text{Fe}^{\text{III}}\text{O}_6]^{\text{oct}}$ and $[\text{Fe}^{\text{III}}\text{O}_4]^{\text{tet}}$. The central ions of both chromophores have equal number of unpaired electrons.

- 5.10 Draw the d-orbitals splitting diagrams for both chromophores and fill in the electrons.

$[\text{Fe}^{\text{III}}\text{O}_6]^{\text{oct}}$:

$[\text{Fe}^{\text{III}}\text{O}_4]^{\text{tet}}$:

Tetrahedral field causes a smaller splitting than the octahedral field ($\Delta_{\text{tet}} = \frac{4}{9}\Delta_{\text{oct}}$). Surprisingly for the Fe^{III} ion, the energy of the first d–d transition (although very weak) for the octahedral chromophore is smaller (11000 cm^{-1}) than for the tetrahedral one (22000 cm^{-1}).

- 5.11 Calculate the size of pairing energy (P) and the sizes of Δ_{oct} and Δ_{tet} splitting. Assume that the pairing energy is equal in both chromophores.

$P =$ cm^{-1}

$\Delta_{\text{oct}} =$ cm^{-1}

$\Delta_{\text{tet}} =$ cm^{-1}



Synthetic garnet YAG (Yttrium-Aluminium-Garnet), used in optoelectronics, has the composition of $Y_3Al_5O_{12}$. Its structure is derived from the general garnet structure $A_3B_2(SiO_4)_3$ by placing the ions Y^{III} and Al^{III} to the A, B and Si positions.

5.12 Based on your knowledge of the relative ion radii, determine which cation occupies which position.

A:	B:	Si:
----	----	-----

5.13 For the use in LED technology, YAG is doped with Ce^{III} . Determine the values of x and y in the formula of YAG in which 5% of yttrium atoms are substituted with cerium.

$Y_xCe_yAl_5O_{12}$	
$x =$	$y =$

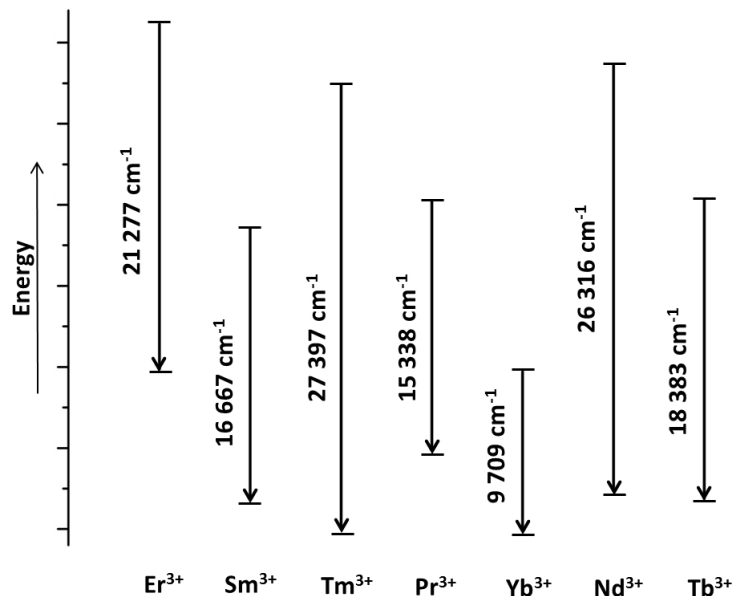
If you don't get result, use $x = 2.25$ and $y = 0.75$.

5.14 The Ce^{III} -doped YAG is prepared by annealing the mixture of Y_2O_3 , Al_2O_3 and CeO_2 in H_2 atmosphere. Use the formula from 5.13 and write down a balanced equation for this reaction with the smallest whole-number stoichiometric coefficients.

--



Doping the YAG structure with rare-earths ions enables the production of lasers with emission wavelengths ranging from the UV to the mid-IR region. In the scheme below, simplified f–f energy transitions of selected rare-earths ions are shown.



5.15 Which cation has a transition which corresponds to blue light emission.

<input type="checkbox"/> Er ³⁺	<input type="checkbox"/> Sm ³⁺	<input type="checkbox"/> Tm ³⁺	<input type="checkbox"/> Pr ³⁺
<input type="checkbox"/> Yb ³⁺	<input type="checkbox"/> Nd ³⁺	<input type="checkbox"/> Tb ³⁺	

5.16 Calculate the emission wavelength of this light.

$\lambda =$	nm
-------------	----

5.17 According to a legend, Noah used a stick with a garnet stone for illumination during his voyage. Assuming only the photoluminescence effect, determine the colour of the laser light emitted from his stick if the stone were the blood red-coloured Bohemian garnet.

<input type="checkbox"/> Red	<input type="checkbox"/> Blue	<input type="checkbox"/> Yellow-orange	<input type="checkbox"/> Black
<input type="checkbox"/> Yellow	<input type="checkbox"/> Blue-green	<input type="checkbox"/> Violet	<input type="checkbox"/> White

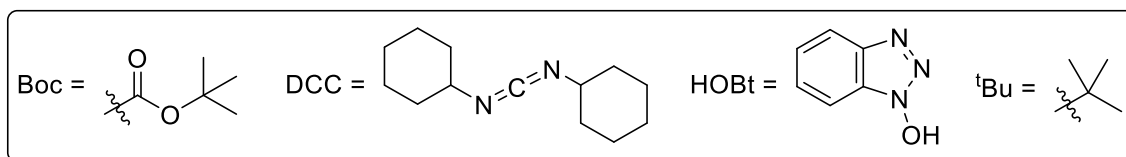
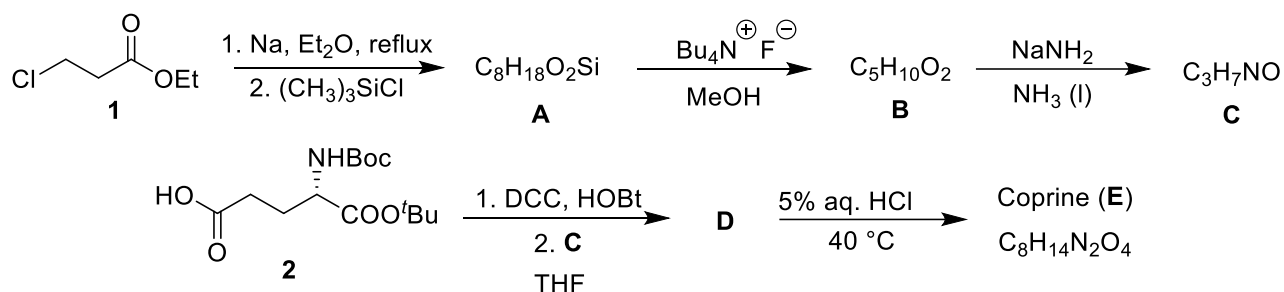


Theoretical Problem 6 7% of the total	Question	6.1	6.2	6.3	6.4	6.5	6.6	6.7	6.8	Total
	Points	18	4	8	3	4	12	16	3	68
	Score									

Problem 6. Let's go mushrooming

Mushrooming belongs to Czech and Slovak traditional pastimes. While some of our mushroom species are edible, some are inedible or even poisonous.

Inky cap (*Coprinopsis atramentaria*) is considered edible and delicious. It contains a natural compound called coprine (**E**), which can be easily synthesized from ethyl 3-chloropropanoate (**1**).

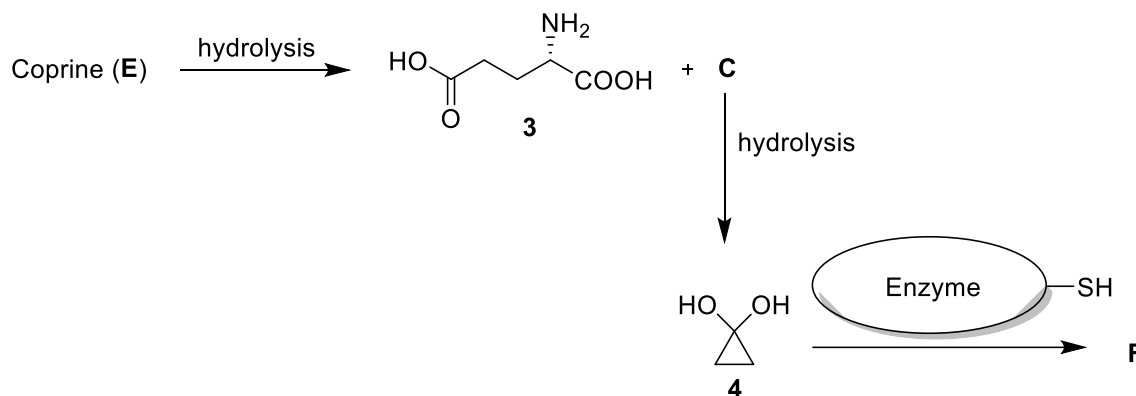


6.1 Draw the formulae of compounds **A–E** including stereochemistry where necessary. *Hint: The first reaction affording compound **A** proceeds via an organometallic compound which then cyclizes.*

A	B	C
D		E



In the human body, coprine undergoes hydrolysis to L-glutamic acid (**3**) and compounds **C** and **4**, which are responsible for the coprine adverse side-effects. They inhibit the enzyme acetaldehyde dehydrogenase, which is involved in the metabolism of alcohol. When the enzyme is inhibited, acetaldehyde formed by alcohol dehydrogenase accumulates in the body, causing strong symptoms of hangover (so called antabuse effect). The active site of the enzyme contains a cysteine SH group, which is blocked either by compound **C** or **4**.

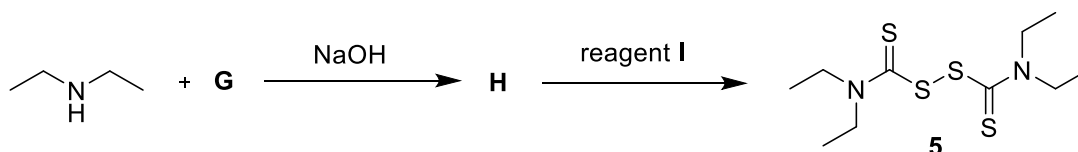


Enzyme = acetaldehyde dehydrogenase

6.2 Using the pictogram for acetaldehyde dehydrogenase above, draw the structure **F** of the enzyme inhibited by compound **4**.



The antabuse effect got its name after antabuse (**5**), the most known drug used in alcohol-addiction treatment. This drug can be synthesized according to the following scheme.





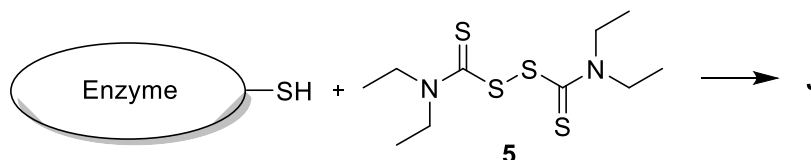
6.3 Draw the formulae of compounds **G** and **H**. *Hint: Compound H contains five carbon atoms.*

G	H
----------	----------

6.4 Mark all possible reagents which could be used for **I** from the following list.

- | | |
|--|--|
| <input type="checkbox"/> <i>m</i> -chloroperbenzoic acid (<i>m</i> CPBA) | <input type="checkbox"/> diluted H ₂ O ₂ |
| <input type="checkbox"/> Zn/CH ₃ COOH | <input type="checkbox"/> NaBH ₄ |
| <input type="checkbox"/> I ₂ | <input type="checkbox"/> hot concentrated H ₂ SO ₄ |
| <input type="checkbox"/> K ₂ CO ₃ , H ₂ O | <input type="checkbox"/> AlCl ₃ |

The way antabuse inhibits acetaldehyde dehydrogenase is similar to the effect of compounds **C** and **4**.



Enzyme = acetaldehyde dehydrogenase

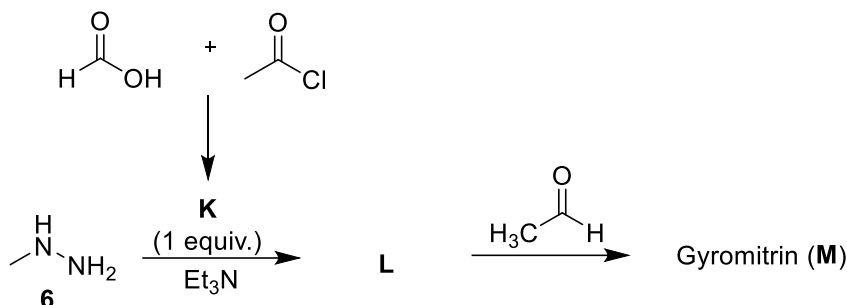
6.5 Using the pictogram for acetaldehyde dehydrogenase above, draw the structure **J** of the enzyme inhibited by antabuse (**5**). *Hint: Three sulfur atoms should be in the structure.*

J

False morel (*Gyromitra esculenta*) is another interesting mushroom. Although it was considered edible in the past (*esculentus* means edible in Latin), there is clear evidence that this mushroom is



poisonous due to the content of gyromitrin (**M**). This natural compound can be prepared from *N*-methylhydrazine (**6**):



6.6 Draw the formulae of compounds **K–M**.

K	L	M
----------	----------	----------

In human body, gyromitrin (**M**) hydrolyzes and provides *N*-methylhydrazine (**6**), which is strongly hepatotoxic. Gyromitrin (**M**) hydrolysis occurs as soon as it enters the acidic environment in human stomach where both its amide and imine groups are hydrolyzed.

Let us focus on the hydrolysis of the amide moiety within the gyromitrin molecule. The vibrational wavenumber of the stretching mode of the relevant C–N bond amounts to 1293.0 cm^{-1} and the potential energy surface does not significantly alter its shape with isotope substitution effect.

6.7 Calculate the highest possible hypothetical kinetic isotope effect at the temperature of human body, $37 \text{ }^\circ\text{C}$, for the given hydrolysis reaction assuming that both relevant nitrogen and carbon atoms were simultaneously substituted, ^{14}N with the ^{15}N isotope and ^{12}C with the ^{13}C isotope. Consider that only the zero point vibrational energy affects the rate constants. Assume that the molar masses of all isotopes are integers. In all further steps, consider **five significant figures**.



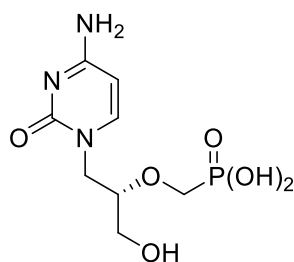
- 6.8 After making these isotopic changes, the rates of hydrolysis are not significantly different. Which of the following is the most likely rate determining step?
- Nucleophilic attack of water on a protonated amidic moiety
 - C–N bond cleavage
 - Protonation of the gyromitrin molecule



Theoretical Problem 7	Question	7.1	7.2	7.3	7.4	7.5	7.6	Total
	Points	10	6	15	9	11	6	57
7% of the total	Score							

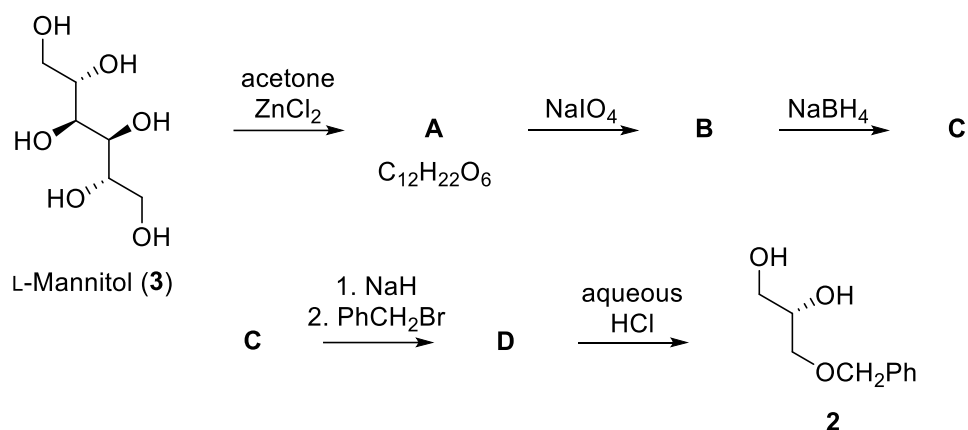
Problem 7. Cidofovir

Cidofovir (**1**), originally designed and prepared by the group of Professor Holy in former Czechoslovakia, is a nucleotide analogue with antiviral activity. It is used to treat viral infections, mostly in patients with AIDS.



Cidofovir (**1**)

The key intermediate in the synthesis of cidofovir is optically pure diol **2**, which can be prepared from L-mannitol (**3**).

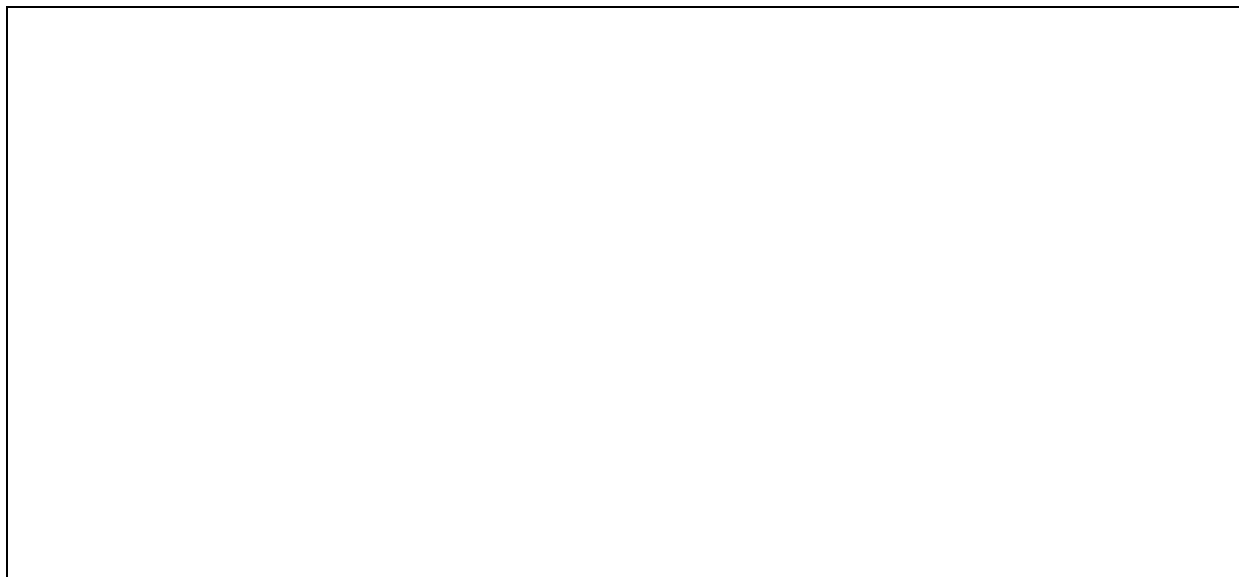


7.1 Draw the structures of compounds **A–D**, including stereochemistry. One molecule of **A** produces two molecules of **B**.

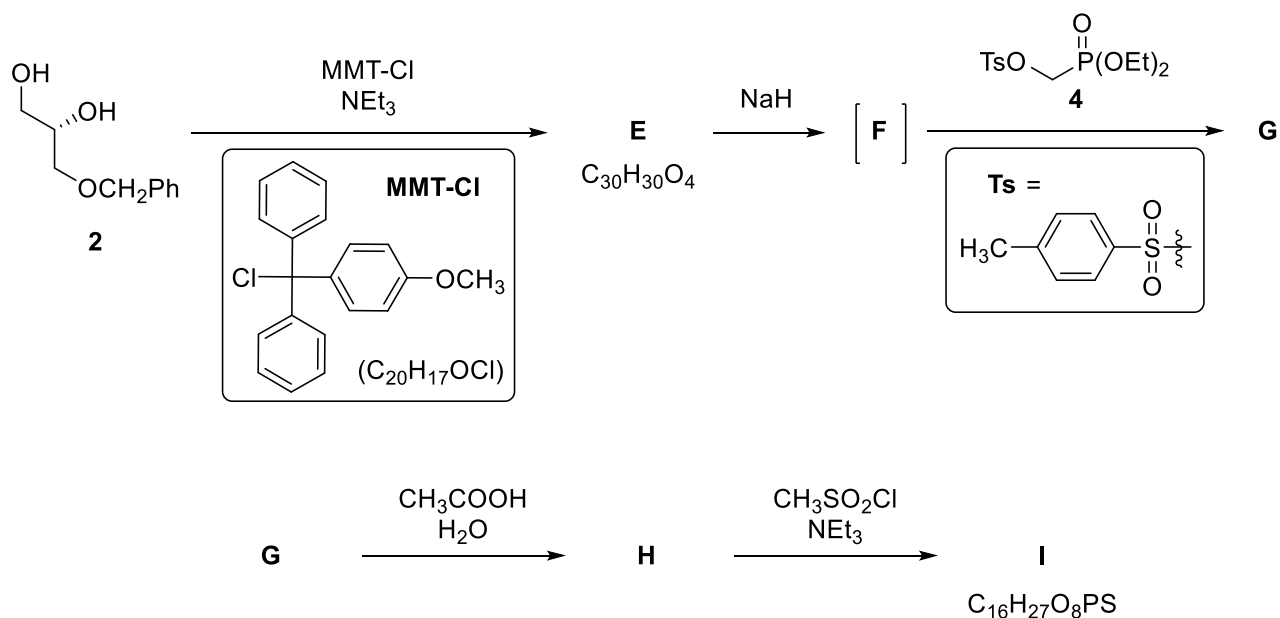
<p>A $\text{C}_{12}\text{H}_{22}\text{O}_6$</p>	<p>B</p>
<p>C</p>	<p>D</p>



- 7.2 Draw the structural formulae of all alternative stereoisomers of compound **3** which could be used in the same reaction sequence to afford only the same product **2**.



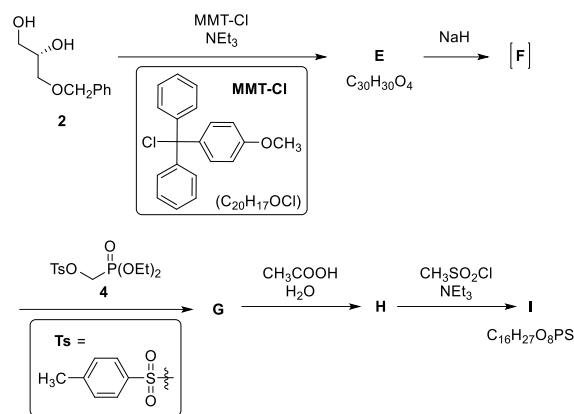
Diol **2** is further modified to provide compound **I**. The synthesis of phosphonate **4** used to convert compound **F** to **G** will be discussed later.





7.3 Draw the structures of compounds **E–I**, including stereochemistry. Use the abbreviation MMT for the (4-methoxyphenyl)diphenylmethyl group.

The same scheme as on the previous page, for easier orientation



E $\text{C}_{30}\text{H}_{30}\text{O}_4$

F

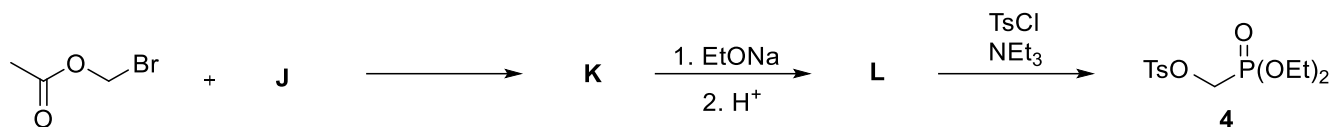
G

H

I $\text{C}_{16}\text{H}_{27}\text{O}_8\text{PS}$



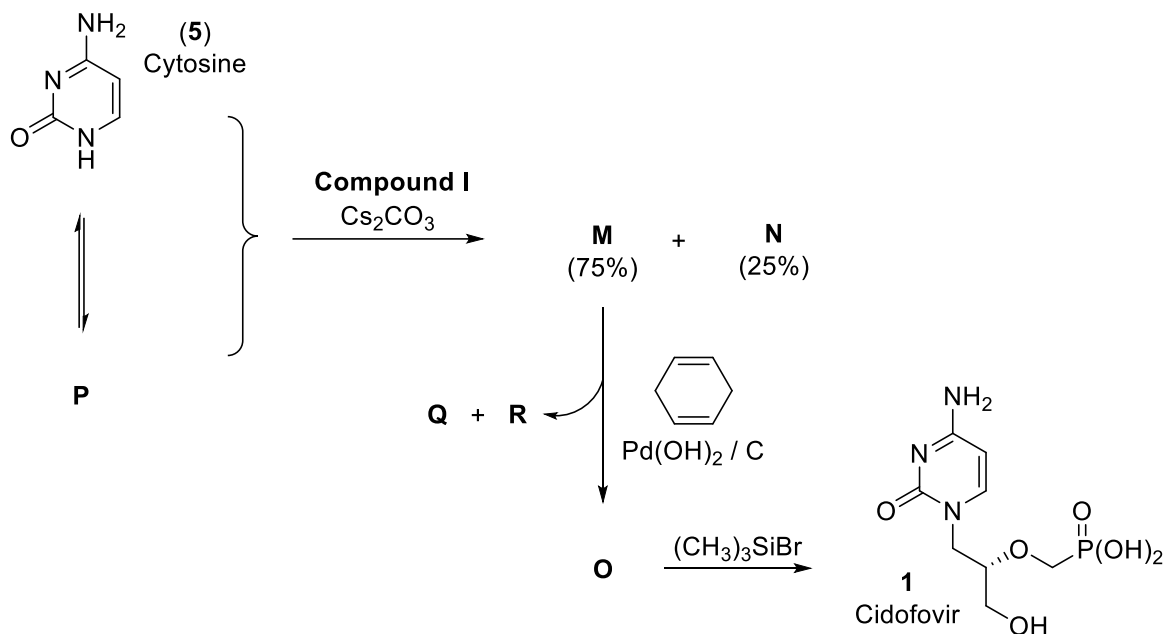
Phosphonate **4** can be prepared according to the following scheme:



7.4 Draw the structures of compounds **J–L**.

J	K
L	

The reaction of **I** (from question 7.3) with cytosine (**5**) leads to a 3:1 mixture of isomeric compounds **M** and **N**. The formation of these two products may be understood by realizing that cytosine (**5**) can also exist as an aromatic tautomer **P**. The reaction of **M** with cyclohexa-1,4-diene and palladium hydroxide on carbon leads to compound **O**. The phosphonic ester moiety in compound **O** reacts with bromotrimethylsilane to provide cidofovir (**1**).



- 7.5 Draw the structures of the two isomers **M**, **N**, and of compound **O**, including stereochemistry and the structure of the aromatic tautomer **P** of cytosine (**5**). Transformation of **M** to **O** is the removal of a protecting group.

M (75%)	N (25%)



O	P
----------	----------

7.6 Draw the structures of the two simple organic side products **Q** and **R** formed during the conversion of **M** to **O**.

Q from cyclohexadiene	R from the protecting group
------------------------------	------------------------------------

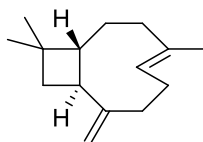


Theoretical Problem 8 9% of the total	Question	8.1	8.2	8.3	8.4	8.5	8.6	8.7	8.8	Total
	Points	14	14	2	16	6	8	9	6	75
	Score									

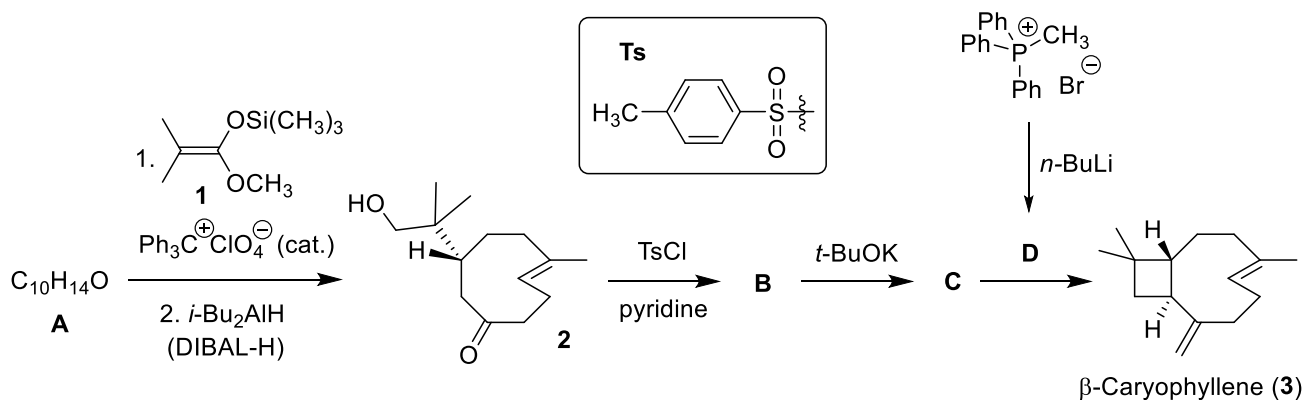
Problem 8. Caryophyllene

β -Caryophyllene (**3**) is a naturally occurring sesquiterpene present in clove tree and in some traditional Czech and Slovak plants, such as the hop plant or small-leaved linden.

The synthesis of β -caryophyllene starts from a single enantiomer of dienone **A**. The reaction of **A** with silyl ketene acetal **1** followed by immediate reduction and aqueous work-up affords ketone **2**. This intermediate then undergoes reaction with tosyl chloride, providing **B**. Basic cyclization of this compound affords **C**. Finally, the reaction of **C** with ylide **D** provides β -caryophyllene.



β -Caryophyllene (**3**)

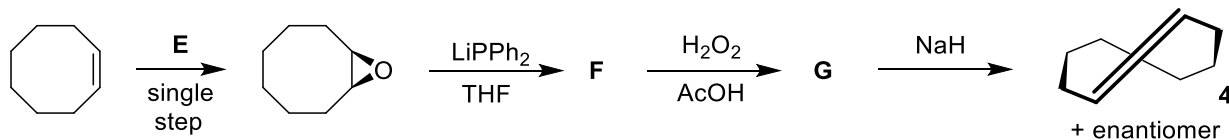


8.1 Draw the structures of compounds **A–D**, including the appropriate stereochemistry. *Hint: In transformation $\text{A} \rightarrow \mathbf{2}$, the silyl ketene acetal acts as a nucleophile.*

<p>A $C_{10}H_{14}O$</p>	<p>B</p>
<p>C</p>	<p>D</p>



One of the double bonds in **2** as well as in **3** has *trans* configuration and the scaffold is stable enough due to the large ring size. *trans*-Cyclooctene (**4**) is the smallest ring that can accommodate a *trans* double bond. It can be prepared according to the following scheme:

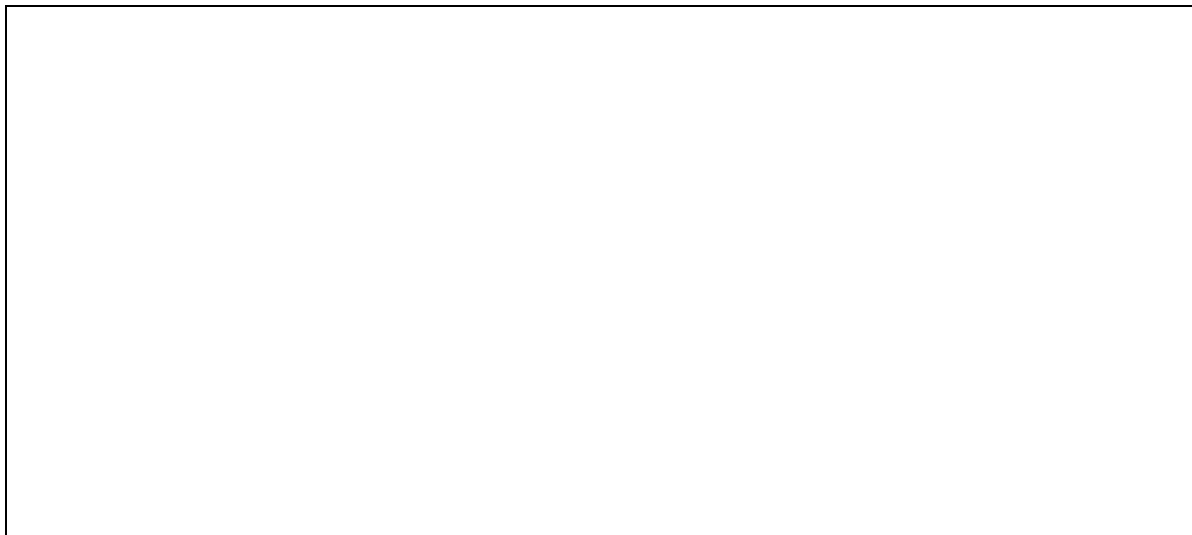
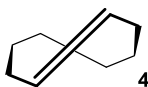


8.2 Draw the structure of reagent **E** and intermediates **F** and **G**, including the appropriate stereochemistry. For **F** and **G**, tick the box indicating the stereochemical outcome.

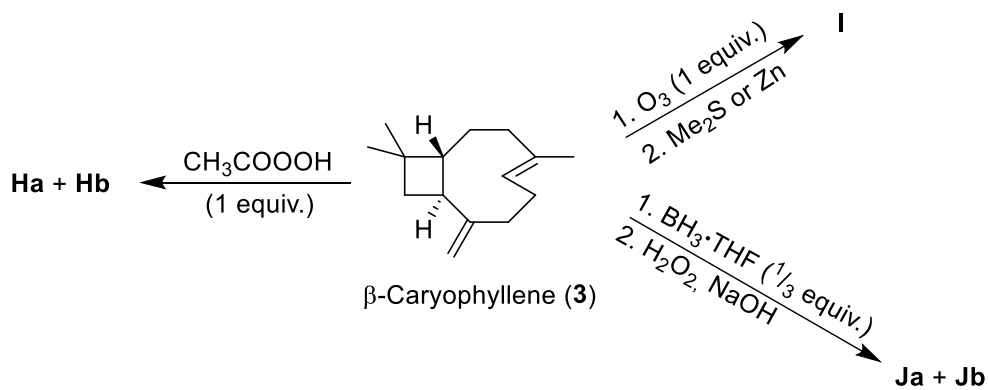
<p>E</p>	<p>F</p> <p> <input type="checkbox"/> achiral <input type="checkbox"/> single enantiomer <input type="checkbox"/> racemic mixture <input type="checkbox"/> mixture of diastereoisomers </p>
<p>G</p> <p> <input type="checkbox"/> achiral <input type="checkbox"/> single enantiomer <input type="checkbox"/> racemic mixture <input type="checkbox"/> mixture of diastereoisomers </p>	



8.3 Draw the structure of the enantiomer of cycloalkene **4**.



The two double bonds in β -caryophyllene display different reactivity: the double bond in the ring (endocyclic) is more reactive than the other one (exocyclic) due to the ring strain.



8.4 Draw the structures of compounds **Ha + Hb**, **I** and **Ja + Jb**, including the appropriate stereochemistry. *Hint: **Ha + Hb** and **Ja + Jb** are pairs of diastereomers.*



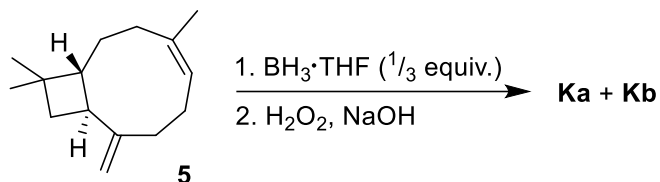
Ha + Hb

I

Ja + Jb



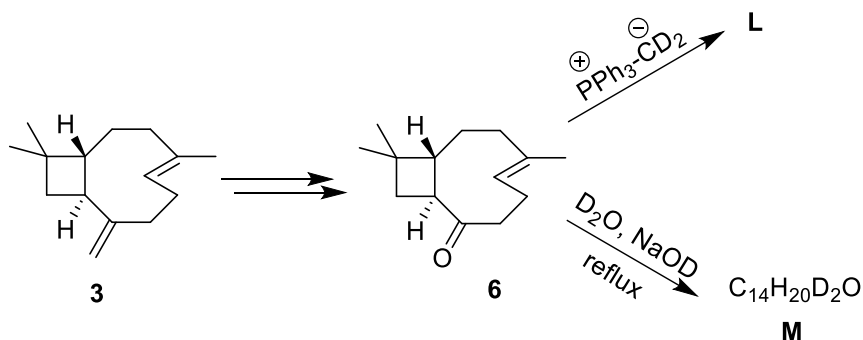
Interestingly, the reactivity of the double bonds is reversed when isocaryophyllene (**5**) is used instead of β -caryophyllene (**3**).



8.5 Draw the structures of compounds **Ka** and **Kb**. *Hint: **Ka** + **Kb** are a pair of diastereomers.*

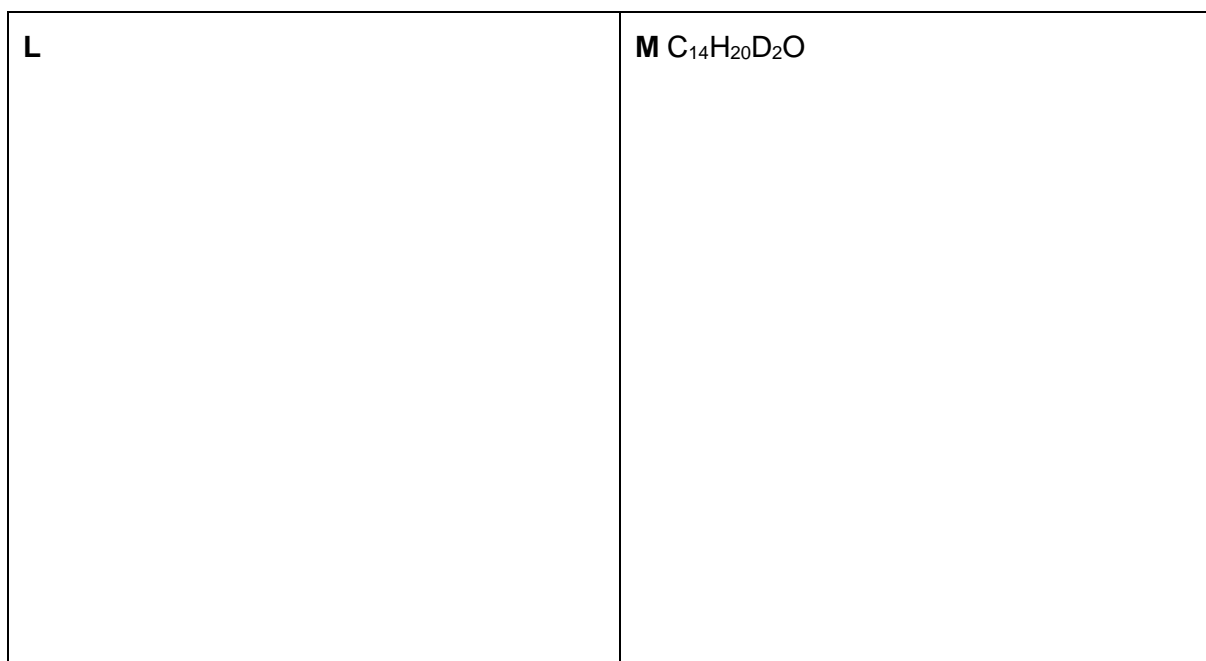


Isotope-labelled compounds are invaluable tools for reaction mechanism investigation, structure determination, and mass or NMR spectroscopy studies. Let us have a look at the synthesis of some labelled analogues of β -caryophyllene.

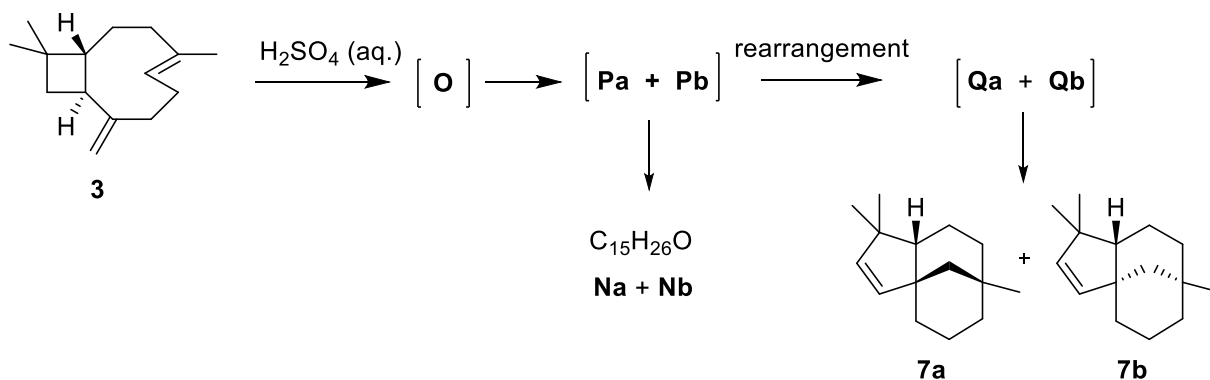




8.6 Draw the structures of compounds **L** and **M** including the appropriate stereochemistry.



β -Caryophyllene (**3**) undergoes acid-catalyzed cyclization, which leads to a complex mixture of products. Among them, the pair of diastereomers **Na + Nb** and the pair of diastereomers **7a + 7b** are the most abundant. The reaction starts with protonation of the more reactive internal double bond affording cation **O**. This cyclizes without the cleavage of a carbon-carbon single bond to yield diastereomeric tricyclic cations **Pa** and **Pb**, which undergo hydration to give the target alcohols **Na** and **Nb**. Alternatively, the cations **Pa** and **Pb** rearrange with the cleavage of a carbon-carbon single bond to cations **Qa** and **Qb**, which deprotonate to compounds **7a** and **7b**.





8.7 Draw the structures of the **three** intermediates **O**, **Pa**, **Qa** (including the appropriate stereochemistry) leading to the diastereomer **7a**.

O	Pa
Qa	

8.8 Draw the structures of diastereomers **Na + Nb**.

Na + Nb $C_{15}H_{26}O$
