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## THEORETICAL PROBLEMS

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## 50<sup>th</sup> IChO 2018

International Chemistry Olympiad  
SLOVAKIA & CZECH REPUBLIC

BACK TO WHERE IT ALL BEGAN



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## Instructions

- This theoretical exam booklet contains 62 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 $q_{\text{rev}}$ 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:

$$E/\text{eV} = \frac{E/\text{J}}{q_e/C}$$

Lambert–Beer law:

$$A = \log \frac{I_0}{I} = \epsilon l c$$

Wavenumber:

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

Reduced mass  $\mu$  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:

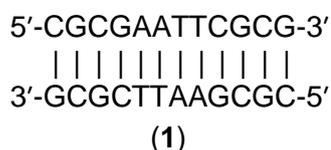
$$\frac{1}{[\text{A}]} = \frac{1}{[\text{A}]_0} + kt$$



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	<b>62</b>
	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?

The choice of the first, second, third, fourth, fifth and sixth nucleotide in one strand is arbitrary; the seventh through twelfth nucleotides in the same strand are determined by the condition of self-complementarity. There are always 4 options (C, G, A, T) for the first through six nucleotide. Hence, the total number of palindromic DNA hexanucleotides is  $4 \times 4 \times 4 \times 4 \times 4 \times 4 = 4^6 = 4\,096$ .

*5 points in total*

*Any numerical result above scores full marks.*

*No explanation of the calculation is needed to score full marks as long as the result is correct.*

*Example of a partially correct solution:*

*4 points if the student writes  $4 \times 4 \times 4 \times 4 \times 4 \times 4$  explicitly, but he/she gives an incorrect final result (e.g., due to an improper use of a calculator).*

*Examples of incorrect solutions that do not score any marks:*

*The student counts uracil as the fifth possibility, yielding 15 625 octanucleotides.*

*The student counts four possibilities for each of the twelve nucleotides, i.e. they ignore the condition of self-complementarity, yielding 16 777 216 dodecanucleotides.*

*0 points for any other result.*

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

**0.** There is no palindromic dsDNA with an odd number of base pairs.

*5 points*

*No explanation is needed.*

*0 points for any other result.*



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

The thermodynamic stability, and thus the melting temperature increases whenever an A–T pair is replaced by a G–C pair. The probability of randomly drawing one of the 4 A–T pairs from the Drew–Dickerson dodecanucleotide containing 12 base pairs is

$$4/12 = 1/3 \sim 0.333 \sim 0.33 \text{ or } 33.3\% \sim 33\%$$

4 points in total

Any of the numerical results above scores full marks.

No additional explanation is needed to score full marks.

Example of a partially correct solution:

2 points if the student declares 4/12 but they present an incorrect final result (e.g.  $4/12 = 0.25$ ).

Examples of incorrect solutions that do not score any marks:

The student counts only two A–T pairs rather than four, yielding the probability of 2/12.

The student incorrectly counts the total number of nucleotide pairs.

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:

The association reaction of a non-palindromic dsDNA reads



and the equilibrium constant of association takes the form

$$K_{\text{np}} = \frac{[\text{dsDNA}]}{\frac{c_0}{[\text{ssDNA1}]} \times \frac{c_0}{[\text{ssDNA2}]}}$$

where  $c_0$  is the standard concentration of  $1.00 \text{ mol dm}^{-3}$  and the lower index  $np$  stands for “non-palindromic”.

At  $T_m$ , one half of the initial dsDNA concentration has melted to ssDNA, so

$$[\text{dsDNA}] = [\text{ssDNA1}] = [\text{ssDNA2}] = 1/2 c_{\text{init}}$$



which yields

$$K_{np}(T_m) = \frac{\frac{1/2 c_{init}}{c_0}}{\frac{1/2 c_{init}}{c_0} \times \frac{1/2 c_{init}}{c_0}} = \frac{c_0}{1/2 c_{init}} = \frac{1.00 \{ \text{mol dm}^{-3} \}}{1/2 \times 1.00 \times 10^{-6} \{ \text{mol dm}^{-3} \}} = 2.00 \times 10^6$$

$K =$

Palindromic dsDNA

Calculation:

The association reaction of a palindromic dsDNA reads



and the equilibrium constant of association is

$$K_p = \frac{\frac{[\text{dsDNA}]}{c_0}}{\left( \frac{[\text{ssDNA}]}{c_0} \right)^2}$$

where  $c_0$  is the standard concentration, and the lower index  $p$  stands for "palindromic".

At  $T_m$ , one half of the initial dsDNA concentration has melted into two ssDNAs with identical sequences, so

$$\begin{aligned} [\text{dsDNA}] &= 1/2 c_{init} \\ [\text{ssDNA}] &= 2 \times [\text{dsDNA}] = c_{init} \end{aligned}$$

which yields

$$K_p(T_m) = \frac{\frac{1/2 c_{init}}{c_0}}{\left( \frac{c_{init}}{c_0} \right)^2} = \frac{1/2 c_0}{c_{init}} = \frac{1/2 \times 1 \times 1.00 \text{ mol dm}^{-3}}{1.00 \times 10^{-6} \text{ mol dm}^{-3}} = 5.0 \times 10^5$$

$K =$

*2 points for the association reactions (1 point each)*

*10 points for the calculation of the association constant with  $c_{init}$  (5 points each)*

*Some of the steps may be condensed or performed implicitly, and the association reactions may not be presented explicitly. As long as the derivation is correct, full marks are scored for all of the elementary steps.*

*$K$  is considered correct if given as unitless number or with the unit of  $\text{mol}^{-1} \text{ dm}^3$ . Thus, failure to introduce unitless concentrations explicitly does not lead to any deduction provided the result is numerically correct.*

*Examples of grading partially correct solutions:*

*Dissociation is considered rather than association, and the calculation is otherwise correct  
deduction of 3 points*

*Wrong numeric value of  $K(T_m)$  in spite of the correct symbolic result, due to, e.g., an improper use of a calculator  
deduction of 2 points each*

*A correct expression for  $K$  is written initially, but there is an error in the derivation  
deduction of 2 pts per each  $K$  affected, max. 2 points*

*$K$  is correct numerically, but the unit is wrong (e.g.,  $\text{mol dm}^{-3}$ )  
deduction of 2 points, enforced max. once*

*The score for any sub-task may not be negative.*



The mean contributions to the Gibbs energy of association of two single strands to form dsDNA were estimate 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:

$K$  is related to the association Gibbs energy as  $\Delta G_{np}^\circ = -RT \ln K_{np}$ , so the Gibbs energy at  $T_m$  is

$$\begin{aligned} \Delta G_{np}^\circ(T_m) &= -RT \ln K_{np}(T_m) = \\ &= -8.314 \text{ J K}^{-1} \text{ mol}^{-1} \times 330 \text{ K} \times \ln(1.00 \times 10^6) = \mathbf{-37.9 \text{ kJ mol}^{-1}} \end{aligned}$$

The shortest oligonucleotide will be obtained if C–G-only dsDNA is considered, because C–G pairs are more stable than A–T pairs.

Then, the smallest number of base pairs is obtained by dividing the Gibbs energy by the contribution of one C–G pair, which for a non-palindromic dsDNA is:

$$n_{np} = \frac{-37.9 \text{ kJ mol}^{-1}}{-6.07 \text{ kJ mol}^{-1}} = 6.2$$

The needed length of a non-palindromic dsDNA: **7**

For a palindromic dsDNA, the Gibbs energy at  $T_m$  is

$$\begin{aligned} \Delta G_p^\circ(T_m) &= -RT \ln K_p(T_m) = \\ &= -8.314 \text{ J K}^{-1} \text{ mol}^{-1} \times 330 \text{ K} \times \ln(1.00 \times 10^5) = \mathbf{-31.6 \text{ kJ mol}^{-1}}, \end{aligned}$$

and the number of base pairs is

$$n_p = \frac{-31.6 \text{ kJ mol}^{-1}}{-6.07 \text{ kJ mol}^{-1}} = 5.2$$

The needed length of a palindromic dsDNA: **6**

The shortest oligonucleotide is

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

A smaller number of base pairs was obtained under the assumption of a palindromic dsDNA. Therefore, we conclude that the shortest dsDNA that has  $T_m$  above 330 K has a palindromic sequence of 6 C–G pairs.

*5 points for the calculations of Gibbs energies*

*2 points for the consideration of C–G-only DNA (either stated explicitly, or just considering  $-6.07 \text{ kJ mol}^{-1}$  for the contribution of a single base pair to the Gibbs energy of association; not awarded if the value for A–T DNA is considered)*

*3 points for the calculation of the number of base pairs*



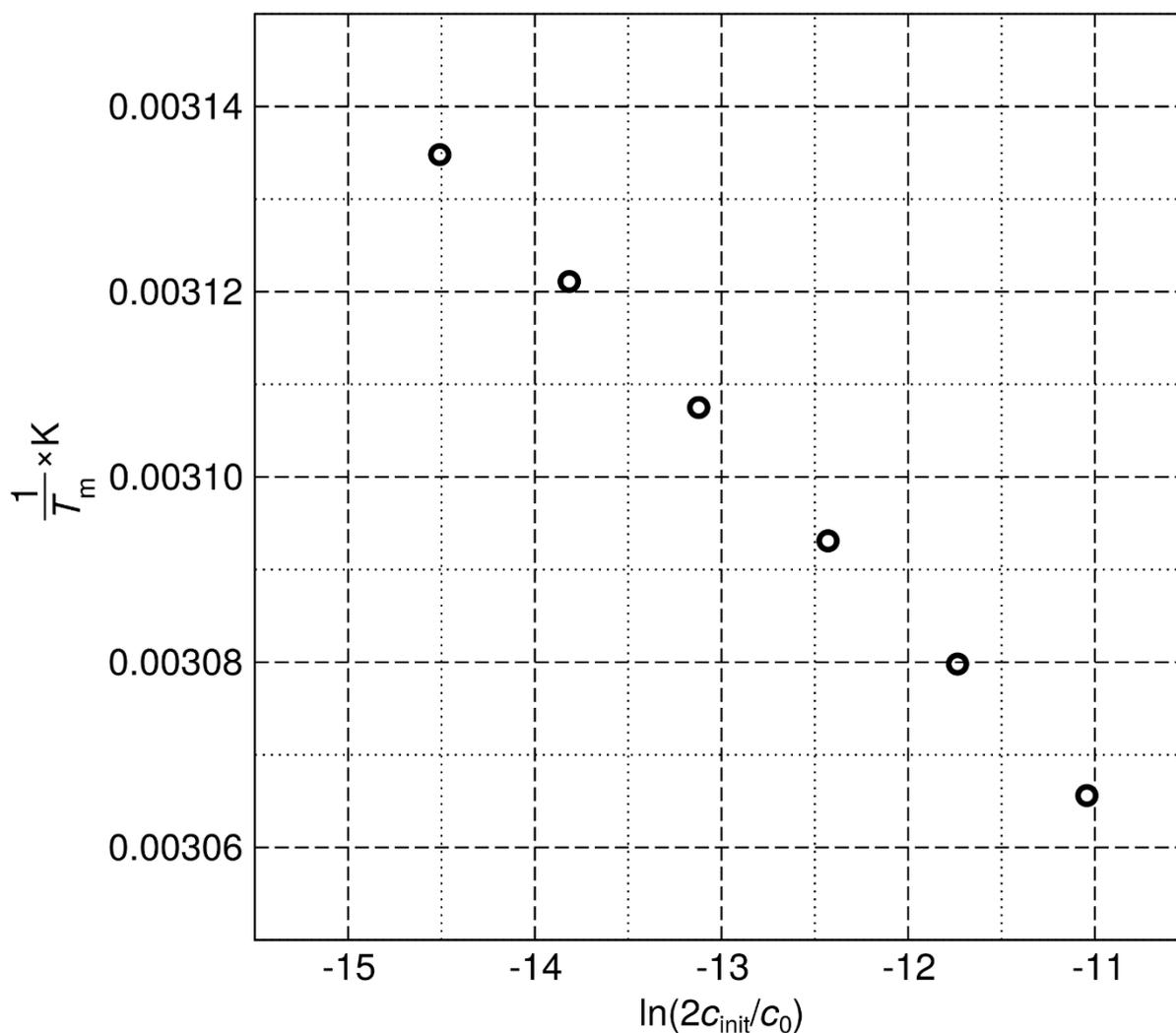
*2 points for the decision on a palindromic sequence*

*Full marks will be given if palindromic dsDNA is considered correctly. The non-palindromic case is not required explicitly.*

*If only non-palindromic case is considered, 50% of the marks may be scored for the calculation (max. 5 points in total)*

*-2 points for the wrong numeric value of  $n_p$  in spite of the correct symbolic result and logics, e.g. due to an improper use of a calculator, or due to a gross rounding error*

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  $c_{\text{init}}$  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
$T_m / \text{K}$	319.0	320.4	321.8	323.3	324.7	326.2

- 1.6 Calculate the standard enthalpy  $\Delta H^\circ$  and the standard entropy  $\Delta S^\circ$  of the association of DNA single strands to form the palindromic double-stranded Drew–Dickerson dodecanucleotide (1). Assume that  $\Delta H^\circ$  and  $\Delta S^\circ$  do not vary with temperature.

Calculation:

Start from the definition of  $\Delta G^\circ$  and its relation to the equilibrium constant:

$$\Delta G^\circ = \Delta H^\circ - T\Delta S^\circ$$

$$\Delta G^\circ = -RT \ln K$$

Combination of the expressions leads to

$$\Delta H^\circ - T\Delta S^\circ = -RT \ln K$$

Division by  $T \times \Delta H^\circ$  yields

$$\frac{1}{T} - \frac{\Delta S^\circ}{\Delta H^\circ} = -\frac{R}{\Delta H^\circ} \ln K$$

so that, specifically for  $T_m$

$$\frac{1}{T_m} = \frac{\Delta S^\circ}{\Delta H^\circ} - \frac{R}{\Delta H^\circ} \ln K_m$$

where  $K_m$  is the equilibrium constant at the melting temperature.

For the palindromic Drew–Dickerson dodecanucleotide, the concentrations of dsDNA and ssDNA at the melting temperature may be expressed in terms of the initial duplex concentration  $c_{\text{init}}$

$$[\text{dsDNA}] = 0.5 c_{\text{init}}$$

$$[\text{ssDNA}] = c_{\text{init}}$$

and the equilibrium constant at the melting temperature follows as

$$K_m = \frac{0.5 \frac{c_{\text{init}}}{c_0}}{\left(\frac{c_{\text{init}}}{c_0}\right)^2} = \frac{1}{2 \frac{c_{\text{init}}}{c_0}}$$

This may be cast into the equation above for the inverse melting temperature, yielding a linearized concentration dependence (note the “plus” sign), which corresponds to the plot in this task directly:

$$\frac{1}{T_m} = \frac{\Delta S^\circ}{\Delta H^\circ} + \frac{R}{\Delta H^\circ} \ln \left( 2 \frac{c_{\text{init}}}{c_0} \right)$$

The slope  $R/\Delta H^\circ$  and the intercept  $\Delta S^\circ/\Delta H^\circ$  may be obtained



- either graphically from the plot – **method 1**,
- or by solving a system of 2 linear equations using any 2 data points – **method 2**.

**Method 1:** The dependence in the plot is strongly linear, and it is very easy to draw a straight line passing the centre of each of the circles representing data points. Then, values of the linear function may be read, e.g., at  $\ln(2 \frac{c_{\text{init}}}{c_0}) = -15$ , ca.  $0.003145 \text{ K}^{-1}$ , and at  $\ln(2 \frac{c_{\text{init}}}{c_0}) = -11$ , ca.  $0.003065 \text{ K}^{-1}$ . From these numerical values, the slope follows as

$$\text{slope} = \frac{0.003065 \text{ K}^{-1} - 0.003145 \text{ K}^{-1}}{-11 - (-15)} = -0.000020 \text{ K}^{-1}$$

and the intercept has to be re-calculated to abscissa equal to zero, e.g., as

$$\text{intercept} = 0.003065 \text{ K}^{-1} + (0 - (-11)) \times (-0.000020 \text{ K}^{-1}) = 0.002845 \text{ K}^{-1}$$

**Method 2:** For instance, considering the first and the last point, we obtain:

$$\text{the first point: } \frac{1}{T_m} = \frac{1}{319.0 \text{ K}} = 3.135 \times 10^{-3} \text{ K}^{-1} \quad \ln(2 \frac{c_{\text{init}}}{c_0}) = \ln(2 \times 0.25 \times 10^{-6}) = -14.5$$

$$\text{the last point: } \frac{1}{T_m} = \frac{1}{326.2 \text{ K}} = 3.066 \times 10^{-3} \text{ K}^{-1} \quad \ln(2 \frac{c_{\text{init}}}{c_0}) = \ln(2 \times 8.0 \times 10^{-6}) = -11.0$$

A system of two linear equations follows as

$$3.135 \times 10^{-3} \text{ K}^{-1} = \frac{\Delta S^\circ}{\Delta H^\circ} - 14.5 \times \frac{R}{\Delta H^\circ}$$

$$3.066 \times 10^{-3} \text{ K}^{-1} = \frac{\Delta S^\circ}{\Delta H^\circ} - 11.0 \times \frac{R}{\Delta H^\circ}$$

which yields the solution

$$\frac{\Delta S^\circ}{\Delta H^\circ} = 2.849 \times 10^{-3} \text{ K}^{-1} \quad \text{and} \quad \frac{R}{\Delta H^\circ} = -2.0 \times 10^{-5} \text{ K}^{-1}$$

**Common to Methods 1 and 2:** The desired thermodynamic quantities follow from there:

$$\Delta H^\circ = \frac{R}{\text{slope}} = \frac{8.314}{-0.000020} \text{ J mol}^{-1} = -416 \text{ kJ mol}^{-1}$$

$$\Delta S^\circ = R \times \frac{\text{intercept}}{\text{slope}} = 8.314 \times \frac{0.002845}{-0.000020} \text{ J K}^{-1} \text{ mol}^{-1} = -1.18 \text{ kJ K}^{-1} \text{ mol}^{-1}$$

**Alternative route:**

It is also possible to consider the linearized dependence implicitly.

After the combination of equalities for  $\Delta G^\circ$ ,  $K_m$  may be expressed in terms of  $c_{\text{init}}$ :

$$\Delta H^\circ - T_m \Delta S^\circ = RT_m \ln(2 \frac{c_{\text{init}}}{c_0})$$

Then, a set of 2 such equations for 2 different concentrations

$$\Delta H^\circ - T_{m1} \Delta S^\circ = RT_{m1} \ln(2 \frac{c_{\text{init},1}}{c_0})$$



$$\Delta H^\circ - T_{m2}\Delta S^\circ = RT_{m2} \ln \left( 2 \frac{c_{\text{init},2}}{c_0} \right)$$

may be solved for 2 unknowns,  $\Delta H^\circ$  and  $\Delta S^\circ$ .

For instance, multiplication of the equations with  $T_{m2}$  and  $T_{m1}$ , respectively, followed by the subtraction of equations leads to

$$\Delta H^\circ = R \frac{T_{m1}T_{m2}}{T_{m2} - T_{m1}} \ln \frac{c_{\text{init},1}}{c_{\text{init},2}}$$

and a plain subtraction of equations leads to

$$\Delta S^\circ = R \frac{T_{m1} \ln \left( 2 \frac{c_{\text{init},1}}{c_0} \right) - T_{m2} \ln \left( 2 \frac{c_{\text{init},2}}{c_0} \right)}{T_{m2} - T_{m1}}$$

Or,  $\Delta S^\circ$  may be obtained by casting  $\Delta H^\circ$  into one of the equations being solved:

$$\Delta S^\circ = \frac{\Delta H^\circ}{T_{m1}} + R \ln 2 \frac{c_{\text{init},1}}{c_0}$$

The desired quantities follow as  $\Delta H^\circ = -420 \text{ kJ mol}^{-1}$  and  $\Delta S^\circ = -1.2 \text{ kJ mol}^{-1} \text{ K}^{-1}$ .

### 24 points in total

#### 15 points for the symbolic derivations

- 3 points for the combination of the expressions for  $\Delta G^\circ$
- 3 points for the rearrangement to yield the linear relationship between  $T_m$  and  $K_m$
- 3 points for the concentrations of the dsDNA and ssDNA at  $T_m$
- 3 points for the expression of  $K_m$  in terms of  $c_{\text{init}}$  for a palindromic sequence
- 3 points for the linear relationship between  $T_m$  and  $\ln 2c_{\text{init}}$

#### 9 points for the numerical calculations

Note: the least-squares linear fit to the data series leads to the following results including the standard deviations: slope =  $(-19.97 \pm 0.08) \times 10^{-6}$ , intercept =  $(2.845 \pm 0.001) \times 10^{-3}$ .

##### Method 1:

- Perform a least-squares linear fit on the pocket calculator, or
- read-off of the slope & intercept for the linear dependence (ref.: least-sq. linear fit)
- 6 points within a margin of  $5\sigma$  (i.e.,  $-20.39 < 10^6 \text{ slope} < -19.55$  &  $2.840 < 10^3 \text{ intercept} < 2.850$ )
- 3 points within a margin of  $10\sigma$  (i.e.,  $-20.81 < 10^6 \text{ slope} < -19.13$  &  $2.835 < 10^3 \text{ intercept} < 2.855$ )
- partial marks will be scored in case the slope & intercept are given with different deviations or if one is missing
- 3 points for the calculation of  $\Delta H^\circ$  &  $\Delta S^\circ$  from the slope & intercept

##### Method 2:

- 3 points for the setup of the system of two equations
- up to 6 points for the calculation of  $\Delta H^\circ$  and  $\Delta S^\circ$ , considering the accuracy requirements given above

#### Alternative route – symbolic derivations up to 18 points, numerical calculations up to 6 points

Symbolic derivations:

- 3 points for the combination of the expressions for  $\Delta G^\circ$  (a)
- 3 points for the concentrations of the dsDNA and ssDNA at the melting temperature (b)
- 3 points for the expression of  $K_m$  in terms of  $c_{\text{init}}$  for a palindromic sequence (c)



*3 points for the setup of the system of two equations (d)*

*3 points for the expression for  $\Delta H^\circ$  (e)*

*3 points for the expression for  $\Delta S^\circ$  (f)*

*9 points for a correct application of Van 't Hoff equation, yielding an expression for  $\Delta H^\circ$  (a+d+e)*

*Numerical calculations: maximum 6 points considering the accuracy requirements given above*

**General remarks**

*Some of the steps in the derivation and in the calculation may be taken implicitly or simultaneously.*

*As long as they are correct, full marks will be scored for each of the partial steps.*

*Failure to write unitless concentrations explicitly and consistently does not lead to any deduction as long as the concentrations are in  $\text{mol dm}^{-3}$  and numerically correct.*



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) ((2S,3S)-2-amino-3-methylpentanoic acid) as an example. It isomerizes on the  $\alpha$ -carbon and forms (2R,3S)-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.

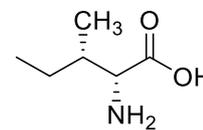
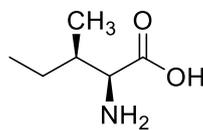
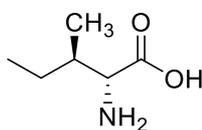
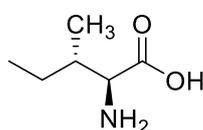
- D-*allo*-isoleucine and L-isoleucine have the same values of specific optical rotation but they have different melting points.
- D-*allo*-isoleucine has an identical absolute value of specific optical rotation as L-isoleucine but the sign is opposite. The melting point is the same for both isomers.
- 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.

1 point for the correct answer

-1 point for each incorrect answer

0 points minimum score

2.2 Assign the absolute configurations for each stereoisomer of isoleucine.



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

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

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

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

1 point for each correct answer



- 2.3 The equilibrium constant  $K_{ep}$  for L-isoleucine epimerization 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**             $\text{kJ mol}^{-1}$

**B**             $\text{kJ mol}^{-1}$

**C**             $\text{kJ mol}^{-1}$

**D**             $\text{kJ mol}^{-1}$

**A**  $G_m^\circ = 0 \text{ kJ mol}^{-1}$  (L-isoleucine)

**B**  $G_m^\circ = 0 \text{ kJ mol}^{-1}$  (**B** is a mirror image of **A** with identical physical properties)

**C**  $G_m^\circ = -RT \ln K_{ep} = -1.00 \times 10^3 \text{ J mol}^{-1}$

**D**  $G_m^\circ = -1.00 \times 10^3 \text{ J mol}^{-1}$  (**D** is a mirror image of **C** with identical physical properties)

*4 points in total, 1 point for each numerical value **A, B, C, D***

*No explanation is needed to score full marks as long as the results are correct.*

*0 points for incorrect sign.*

- 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  $2^N$ , where  $N$  is the number of stereogenic centres.

For Ile-Ile-Ile,  $N = 6$ , so there are  $2^6 = 64$  stereoisomers.

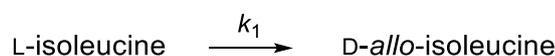
*2 points for the numerical result (either  $2^6$  or 64). No explanation is needed.*

*1 point if the student correctly declares  $2^6$  but the final result is numerically incorrect.*

*Example of an incorrect solution that do not score any marks:*

*The student incorrectly counts the number of stereocenters.*

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 at 374 K is  $k_1(374 \text{ K}) = 9.02 \times 10^{-5} \text{ h}^{-1}$  and at 421 K it 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 1 943 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:

Before boiling, the  $de$  is:

$$de = \frac{[L]_0 - [D]_0}{[L]_0 + [D]_0} \times 100(\%)$$

Because  $[D]_0 = 0$ , the  $de$  of native L-isoleucine before boiling is 100%.

$de =$             % (with three significant figures)

b) After boiling

Calculation:

First, we have to calculate the concentration ratio  $\frac{[L]}{[L]_0}$  from the first-order rate equation

$$\frac{[L]}{[L]_0} = e^{-k_1 t} = 0.839$$

$$\text{so } [D] = 0.161 [L]_0$$

and  $de = \frac{0.839 - 0.161}{0.839 + 0.161} \times 100\% = 67.8\%$  (with three significant figures)

$de =$             % (with three significant figures)

*Number of significant figures is not evaluated*

*2 points for the  $de$  before boiling*

*No additional explanation is needed to score full marks.*

*After boiling:*

*1 point for the equation for the concentration ratio from the first-order rate equation*

*1 point for the relation between the concentration of D-allo-isoleucine and L-isoleucine*

*2 points for the numerical result*

*If  $de$  is given as 0.678, full marks are scored.*

*Some of the steps may be performed implicitly. As long as the result is correct, full marks are scored for all elementary steps.*

*No points are scored if the calculations are not provided*

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

Calculation:

We need to evaluate the rate constant at 298 K. It can be evaluated from the Arrhenius equation:

$$\ln k = \ln A - \frac{E_a}{RT}$$

We get  $\ln A$  and  $E_a$  from the values of  $k$  at two temperatures (374 K and 421 K)

$$\ln k (374 \text{ K}) = \ln 9.02 \times 10^{-5} [\text{h}^{-1}] = -9.313 = \ln A - \frac{E_a}{R \times 374}$$

$$\ln k (421 \text{ K}) = \ln 1.18 \times 10^{-2} [\text{h}^{-1}] = -4.444 = \ln A - \frac{E_a}{R \times 421}$$



It follows that

$$\ln A = -9.313 + \frac{E_a}{R \times 374} = -4.444 + \frac{E_a}{R \times 421}$$

from which  $E_a = 136 \text{ kJ mol}^{-1}$ .

$\ln A$  is from the equation at 374 K

$$\ln(A[\text{h}^{-1}]) = -9.313 + \frac{E_a}{R \times 374} = 34.4$$

For  $k$  at 298 K we then have:

$$\ln(k(298 \text{ K})[\text{h}^{-1}]) = \ln A - \frac{E_a}{R \times 298} = 34.4 - \frac{136 \times 10^3}{R \times 298} = -20.5$$

$$k(298 \text{ K}) = 1.25 \times 10^{-9} \text{ h}^{-1}$$

It follows from the rate equation that

$$\ln \frac{[L]}{[L]_0} = -kt$$

$$\ln 0.90 = -1.25 \times 10^{-9} t$$

$$t = 8.42 \times 10^7 \text{ h} = 9\,610 \text{ years}$$

$t =$                       years

*2 points for the formulation of the set of two equations*

*2 points for the correct formulae for  $\ln A$  and  $E_a$  (1 point each)*

*2 points for the correct numerical values of  $\ln A$  and  $E_a$  (1 point each)*

*2 points for the calculation of the rate constant at 298 K (1 point for the formula, 1 point for the numerical value)*

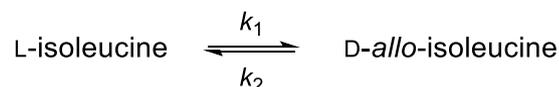
*2 points for the calculation of time*

*Full marks will be given if the time is calculated correctly using a wrong value of  $k$  based on the correct formula.*

*Some of the steps may be performed implicitly. As long as the result is correct, full marks are scored for all elementary steps. Full marks will be given for numerical calculations of time and rate constants within margins  $k(298 \text{ K}) = 1.25 \times 10^{-9} \text{ h}^{-1} \pm 0.1 \times 10^{-9} \text{ h}^{-1}$ ,  $t = 9\,610 \text{ years} \pm 850 \text{ years}$ .*

*No points are scored if the calculations are not provided.*

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  $[L]_{\text{eq}}$

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

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  $t = 0 \text{ h}$ .

2.7 Let us boil  $1.00 \text{ mol dm}^{-3}$  L-isoleucine solution for 1 943 hours at 374 K. The rate constant for the forward reaction is  $k_1(374 \text{ K}) = 9.02 \times 10^{-5} \text{ h}^{-1}$ ,  $K_{\text{ep}}$  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)  $[L]_{\text{eq}}$ , b) diastereomeric excess (*de*) after boiling.

a) Calculation:

From the definition and mass balance we know that

$$x = [L] - [L]_{\text{eq}} = [D]_{\text{eq}} - [D]$$

We can derive the formulae for  $[L]_{\text{eq}}$  (and also for  $[D]_{\text{eq}}$ ) in terms of  $[L]_0$

$$[L]_0 = [L]_{\text{eq}} + [D]_{\text{eq}}$$

$$[D]_{\text{eq}} = [L]_0 - [L]_{\text{eq}}$$

We also know that

$$K_{\text{ep}} = \frac{k_1}{k_2} = \frac{[D]_{\text{eq}}}{[L]_{\text{eq}}}$$

from which

$$[D]_{\text{eq}} = \frac{k_1}{k_2} [L]_{\text{eq}}$$

The substitution for  $[D]_{\text{eq}}$  in  $[D]_{\text{eq}} = [L]_0 - [L]_{\text{eq}}$  yields

$$[L]_{\text{eq}} = \frac{k_2}{k_1 + k_2} [L]_0$$

The rate constant  $k_2$  is calculated from the epimerization constant  $K_{\text{ep}}$  as

$$k_2 = \frac{k_1}{K_{\text{ep}}} = \frac{9.02 \times 10^{-5} \text{ h}^{-1}}{1.38} = 6.54 \times 10^{-5} \text{ h}^{-1}$$

After the substitution of the numerical values, we get (with three significant digits)

$$[L]_{\text{eq}} = \frac{6.54 \times 10^{-5} \text{ h}^{-1}}{9.02 \times 10^{-5} \text{ h}^{-1} + 6.54 \times 10^{-5} \text{ h}^{-1}} \times 1 \text{ mol dm}^{-3} = 0.420 \text{ mol dm}^{-3}$$

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

b) Calculation:

*de* is defined as

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

We can express *de* in terms of the equilibrium values as

$$de = \frac{[L]_{\text{eq}} + x - [D]_{\text{eq}} + x}{[L]_{\text{eq}} + x + [D]_{\text{eq}} - x} \times 100(\%) = \frac{[L]_{\text{eq}} - [D]_{\text{eq}} + 2x}{[L]_0} \times 100(\%)$$

We already have the formula for  $[L]_{\text{eq}}$  from task a).  $[D]_{\text{eq}}$  in terms of  $[L]_0$  is then

$$[D]_{\text{eq}} = \frac{k_1}{k_2} [L]_{\text{eq}} = \frac{k_1}{k_1 + k_2} [L]_0$$



Finally, we need to evaluate  $x$  in terms of  $[L]_0$ . We know that  $x(0) = [D]_{\text{eq}}$ , so

$$x = [D]_{\text{eq}} \times e^{-t(k_1 + k_2)} = \frac{k_1}{k_1 + k_2} [L]_0 \times e^{-t(k_1 + k_2)}$$

We can now express  $de$  as

$$de = \frac{\frac{k_2}{k_1 + k_2} [L]_0 - \frac{k_1}{k_1 + k_2} [L]_0 + 2 \frac{k_1}{k_1 + k_2} [L]_0 e^{-t(k_1 + k_2)}}{[L]_0} \times 100(\%) = \frac{k_2 - k_1 + 2k_1 e^{-t(k_1 + k_2)}}{k_1 + k_2} \times 100(\%)$$

$$de = \frac{6.54 \times 10^{-5} - 9.02 \times 10^{-5} + 2 \times 9.02 \times 10^{-5} e^{-1.943(9.02 \times 10^{-5} + 6.54 \times 10^{-5})}}{9.02 \times 10^{-5} + 6.54 \times 10^{-5}} \times 100(\%) = 69.8\%$$

(with three significant digits)

$de =$             % (with three significant figures)

a)

1 point for the mass balance equation

2 points for the equation for the equilibrium constant in terms of the rate constants and concentrations

2 points for the derivation of the formula for  $[L]_{\text{eq}}$  in terms of  $[L]_0$

1 point for the numerical value of  $k_2$

1 point for the numerical value of  $[L]_{\text{eq}}$

No points are scored if the calculations are not provided.

b)

2 points for the correct equation for  $de$  in terms of the equilibrium values

2 points for the derivation of the formulae for  $[D]_{\text{eq}}$  in terms of  $[L]_0$

2 points for the derivation of the formula for  $x$  in terms of  $[L]_0$

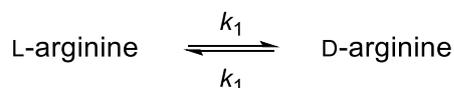
2 points for the correct equation for  $de$  in terms of  $[L]_0$

2 points for the correct numerical value of  $de$  based on correct formula

Some steps in the derivation may be taken implicitly or simultaneously. As long as they are correct, full marks will be scored for each of the partial steps. If the numerical calculation of  $k_2$  in point a) is incorrect but  $k_2$  is correctly used in task b), full marks are scored in task b).

No points are scored if the calculations are not provided.

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, immediately after his death, boiled in water (373 K) 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 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:

Let us assume the following schemes for Lothar and Richenza



where 0 is the state before boiling with  $\frac{[D]}{[L]}$  ratio  $X_0$ , 1 corresponds to the Lothar's state after boiling in water in 1137 with the  $\frac{[D]}{[L]}$  ratio  $X_1$ , 2 is the Lothar's state after the acidic hydrolysis with the  $\frac{[D]}{[L]}$  ratio  $X_2$ , and 3 is the Richenza's state after the hydrolysis with the  $\frac{[D]}{[L]}$  ratio  $X_3$ .  $k_1$  is the rate constant for racemization at 373 K,  $k'_1$  is the rate constant for acid-catalyzed racemization at 383 K.

We can write the following equations:

$$\ln \frac{1 + X_3}{1 - X_3} = 2 k'_1 t_{\text{hydrolysis}} \quad (\text{eq. 1})$$

$$\ln \frac{1 + X_1}{1 - X_1} = 2 k_1 t_{\text{boiling}} \quad (\text{eq. 2})$$

$$\ln \frac{1 + X_2}{1 - X_2} = 2 k'_1 t_{\text{hydrolysis}} + \ln \frac{1 + X_1}{1 - X_1} \quad (\text{eq. 3})$$

Combining the equations leads to

$$\ln \frac{1 + X_2}{1 - X_2} = \ln \frac{1 + X_3}{1 - X_3} + 2 k_1 t_{\text{boiling}}$$

From which the time of boiling  $t_{\text{boiling}}$  is

$$\ln \frac{(1 + X_2)(1 - X_3)}{(1 - X_2)(1 + X_3)} = 2 k_1 t_{\text{boiling}}$$

Using the values  $X_2 = 0.090$  and  $X_3 = 0.059$  we get



$$t_{\text{boiling}} = \frac{1}{2 \times 5.10 \times 10^{-3}} \ln \frac{(1 + 0.090)(1 - 0.059)}{(1 - 0.090)(1 + 0.059)} = 6.11 \text{ h}$$

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

*8 points for rate equations describing the time evolution of the ratio between the optical isomers for Lothar and Richenza (2 points for each eq. 1 and 2; 4 points for eq. 3; 1 point for eq. 3 with an incorrect evaluation of C)*

*4 points for the combination of the equations to get the time of boiling*

*2 points for the evaluation of the boiling time*

*Some steps may be taken implicitly. If the correct boiling time is provided with correct assumptions in calculations, full marks will be scored.*

*Example of a partially correct solution:*

*1 point if the boiling time is derived correctly but the result is incorrect*

*No points are scored if the calculations are not provided.*



<b>Theoretical Problem 3</b>  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	<b>Total</b>
	Points	6	10	5	2	6	<b>62</b>
	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

*2 points in total; 1 points for each correct answer (the second and fourth options in the list), - 1 points for each incorrect answer, total points scored in this question may not be negative*

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 232.15 K of pure liquid isooctane and pure gaseous hydrogen.

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

$$\Delta_c H_s^\circ(\text{C}_8\text{H}_{18}) = \frac{\Delta_c H^\circ(\text{C}_8\text{H}_{18})}{M(\text{C}_8\text{H}_{18})} = \frac{-5\,065.08 \times 10^3 \text{ J mol}^{-1}}{114.23 \times 10^{-3} \text{ kg mol}^{-1}} = -44.34 \text{ MJ kg}^{-1}$$

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

$$\Delta_c H_s^\circ(\text{H}_2) = \frac{\Delta_c H^\circ(\text{H}_2)}{M(\text{H}_2)} = \frac{-285.84 \times 10^3 \text{ J mol}^{-1}}{2.02 \times 10^{-3} \text{ kg mol}^{-1}} = -141.50 \text{ MJ kg}^{-1}$$

*6 points in total. Some of the steps may be condensed or performed implicitly. As long as this is performed correctly, full marks are scored for all of the elementary steps. Zero points will be scored for any numerical (sub)result given with wrong or missing units.*

*1 point for each numerically correct molar mass (including unit)*

*2 points for the correct way of calculation of the specific combustion enthalpy*

*1 point for each numerically correct specific combustion enthalpy (including unit)*

*-1 point for the wrong sign(s)*



- 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:

The oxidation of molecular hydrogen requires the transfer of  $z = 2$  electrons according to the equation:  $\text{H}_2 + \frac{1}{2} \text{O}_2 \rightarrow \text{H}_2\text{O}$

$$\Delta_r S^\circ = S^\circ(\text{H}_2\text{O},\text{l}) - \left( S^\circ(\text{H}_2,\text{g}) + \frac{1}{2} S^\circ(\text{O}_2,\text{g}) \right) = -164 \text{ J K}^{-1} \text{ mol}^{-1}$$

$$\Delta_r G^\circ = \Delta_r H^\circ - T \Delta_r S^\circ =$$

$$= -285.84 \times 10^3 \text{ J mol}^{-1} + 323.15 \text{ K} \times 164 \text{ J K}^{-1} \text{ mol}^{-1} = -233 \text{ kJ mol}^{-1}$$

$$EMF = - \frac{\Delta_r G^\circ}{|z|F} = - \frac{-233 \times 10^3 \text{ J mol}^{-1}}{2 \times 96485 \text{ C mol}^{-1}} = 1.21 \text{ V}$$

EMF =            V

*7 points in total for the correct result calculated in any correct way. Some of the steps may be condensed or performed implicitly. As long as this is performed correctly, full marks are scored for all of the elementary steps. Zero points will be scored for any numerical (sub)result given with wrong or missing units.*

*1 point for the correct value of  $z$  resulting from the correctly written chemical equation*

*1 point for the correct formula for the reaction entropy according to the written chemical equation*

*1 point for the numerically correct value of the reaction entropy*

*1 point for the correct formula for the reaction Gibbs energy*

*1 point for the numerically correct value of the reaction Gibbs energy*

*1 point for the correct formula for the EMF*

*1 point for the numerically correct value of the EMF*

*-1 point for incorrect sign*

- 3.4 Determine the ideal thermodynamic efficiency ( $\eta$ ) 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  $\Delta_r G^\circ = -225.85 \text{ kJ mol}^{-1}$ .

$$\eta = \frac{\Delta_r G^\circ}{\Delta_f H^\circ} = \frac{-225.85 \text{ kJ mol}^{-1}}{-281.64 \text{ kJ mol}^{-1}} \times 100\% = 80.19\%$$

$\eta =$             %

*3 points in total*

*2 points for the correct way of calculation*

*1 point for the numerically correct result*



- 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 1 090 kg of pure hydrogen. Calculate the electrolysis yield defined as the mass of produced hydrogen divided by its theoretical produced mass.

Calculations:

Electric energy produced:

$$W = P \times \tau = 10 \times 10^6 \text{ W} \times 8 \times 3\,600 \text{ s} = 2.88 \times 10^{11} \text{ J}$$

is sufficient to transfer the charge:

$$Q = \frac{W}{U} = \frac{2.88 \times 10^{11} \text{ J}}{2 \text{ V}} = 1.44 \times 10^{11} \text{ C}$$

between the electrodes. Water formation is a two-electron process. Thus, the theoretical mass of hydrogen produced is:

$$m_{\text{theory}} = \frac{Q M}{|z| F} = \frac{1.44 \times 10^{11} \text{ C}}{2 \times 96\,485 \text{ C mol}^{-1}} \times 2.02 \times 10^{-3} \text{ kg mol}^{-1} = 1\,507 \text{ kg}$$

The efficiency of the electrolysis can be evaluated as the ratio:

$$\eta_{\text{electrolysis}} = \frac{m_{\text{real}}}{m_{\text{theory}}} \times 100\% = \frac{1\,090}{1\,507} \times 100\% = 72.3\%$$

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

*7 points in total for the numerically correct final result calculated in any correct way. Some of the steps may be condensed or performed implicitly. As long as this is performed correctly, full marks will be scored for all elementary steps. If only the final equation for  $m_{\text{theory}}$  is derived correctly, but its numerical value is wrong, 4 points will be scored for  $m_{\text{theory}}$ . If a wrong numerical subresult is used in subsequent steps which are performed correctly but yield a wrong numerical value, 4 points will be scored for  $m_{\text{theory}}$ . 0 points will be scored for any numerical (sub)result given with wrong or missing units.*

*1 point for the correct formula for W*

*1 point for the numerically correct value of W*

*1 point for the correct way of calculation of Q*

*1 point for the numerically correct value of Q*

*1 point for any correct way of calculation of the theoretical amount of hydrogen*

*1 point for the numerically correct theoretical amount of hydrogen*

*1 point for the numerically correct electrolysis efficiency*

- 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<sup>-1</sup> 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:

Driving time:

$$\tau = \frac{s}{v} = \frac{330 \text{ km}}{100 \text{ km h}^{-1} / 3600 \text{ s}} = 11\,880 \text{ s}$$

determines the ideal amount of energy required to cover the given distance:

$$W_{\text{ideal}} = P \times f \times \tau = 310 \times 10^3 \text{ W} \times 0.15 \times 11\,880 \text{ s} = 5.52 \times 10^8 \text{ J.}$$

Assuming the overall non-unity efficiency, the real energy required is:

$$W_{\text{real}} = \frac{W_{\text{ideal}}}{\eta_{\text{electrolysis}} \times \eta_{\text{engine}}} = \frac{5.52 \times 10^8 \text{ J}}{0.75 \times 0.95} = 7.75 \times 10^8 \text{ J.}$$

This can be combined with the standard Gibbs energy of liquid water formation to yield the amount of hydrogen:

$$m = \frac{W_{\text{real}}}{|\Delta_r G^\circ|} \times M = \frac{7.75 \times 10^8 \text{ J}}{2.26 \times 10^5 \text{ J mol}^{-1}} \times 2.02 \times 10^{-3} \text{ kg mol}^{-1} = 6.93 \text{ kg.}$$

$m =$             kg

*8 points in total for the numerically correct final result calculated in any correct way. Some of the steps may be condensed or performed implicitly. As long as this is performed correctly, full marks will be scored for all of the elementary steps. If only the final relation for  $m$  is derived correctly, but its numerical value is wrong, 6 points will be scored in total. If a wrong numerical subresult is used in subsequent steps which are performed correctly but yield a wrong numerical value, 6 points will be scored for  $m_{\text{theory}}$ . 0 points will be scored for any numerical (sub)result given with wrong or missing units.*

*1 point for the correct formula for  $\tau$*

*1 point for the correct value of  $\tau$*

*1 point for the correct formula for  $W_{\text{ideal}}$*

*1 point for the numerically correct value of  $W_{\text{ideal}}$*

*1 point for the correct formula for  $W_{\text{real}}$*

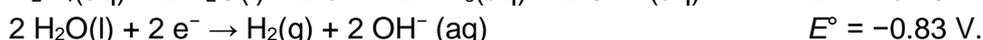
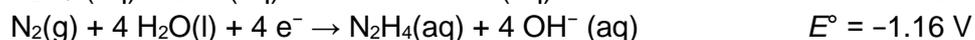
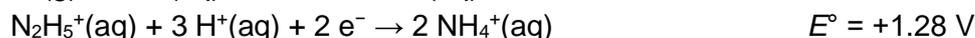
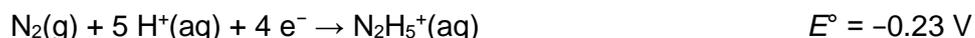
*1 point for the numerically correct value of  $W_{\text{real}}$*

*1 point for the correct formula for  $m$*

*1 point for the numerically correct value of  $m$*

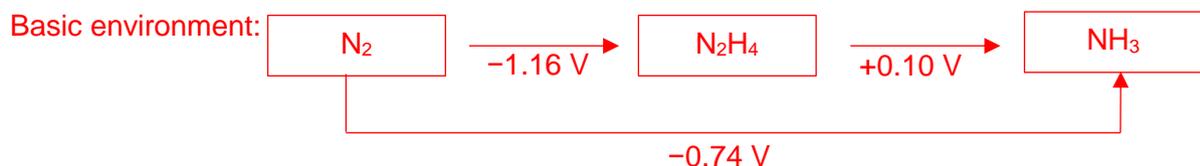
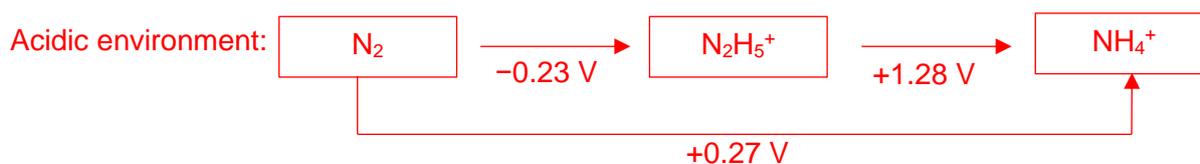
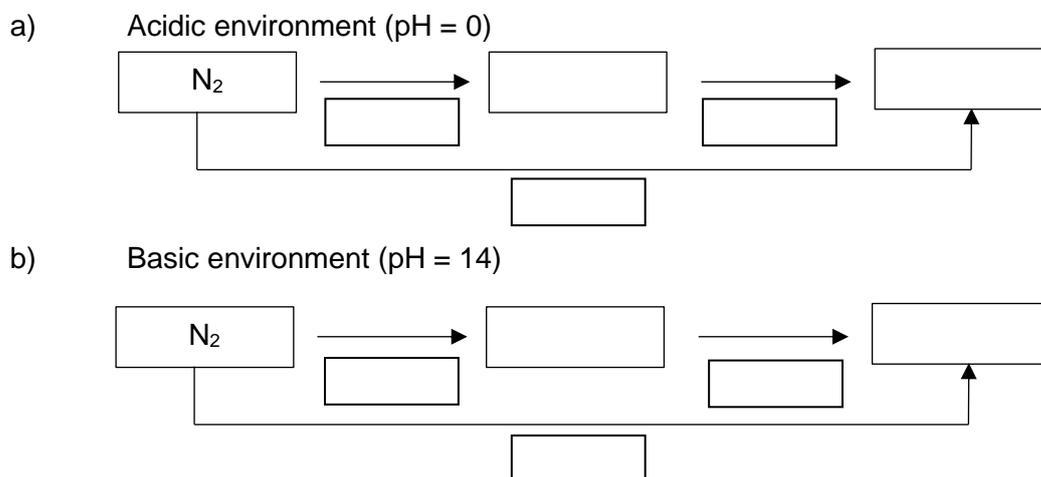
The low efficiency of hydrogen production and the safety issues connected with its storage impede spreading the hydrogen-based transportation technology. Hydrazine ( $\text{N}_2\text{H}_4$ ) fuel cells might be a suitable alternative.

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:

Redox potentials for  $\text{N}_2$  to  $\text{NH}_4^+$  and  $\text{N}_2$  to  $\text{NH}_3$ , respectively, are calculated as follows:

$$E^\circ(\text{N}_2/\text{NH}_4^+) = \frac{4 E^\circ(\text{N}_2/\text{N}_2\text{H}_5^+) + 2 E^\circ(\text{N}_2\text{H}_5^+/\text{NH}_4^+)}{6} = \frac{4 \times (-0.23) + 2 \times 1.28}{6} \text{ V} = 0.27 \text{ V}$$

$$E^\circ(\text{N}_2/\text{NH}_3) = \frac{4 E^\circ(\text{N}_2/\text{N}_2\text{H}_4) + 2 E^\circ(\text{N}_2\text{H}_4/\text{NH}_3)}{6} = \frac{4 \times (-1.16) + 2 \times 0.10}{6} \text{ V} = -0.74 \text{ V}$$

6 points in total

1 point for each diagram completely correctly filled with chemical species, no partial points given if any mistake occurs

1 point for the numerically correct value of each of the standard redox potentials  $E^\circ(\text{N}_2/\text{NH}_4^+)$  and  $E^\circ(\text{N}_2/\text{NH}_3)$ , no partial points given if any mistake occurs

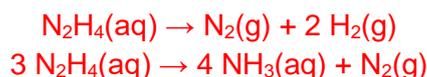
1 point for each diagram correctly filled with the remaining standard redox potentials, no partial points given if any mistake occurs



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:

$$\Delta_r G^\circ = -RT \ln K = -|z|FE^\circ \rightarrow K = \exp\left(\frac{|z|FE^\circ}{RT}\right)$$

Hydrazine decomposition to  $\text{NH}_3$  and  $\text{N}_2$  in a basic environment:

$$E^\circ = E^\circ(\text{N}_2\text{H}_4/\text{NH}_3) + (-E^\circ(\text{N}_2/\text{N}_2\text{H}_4)) = (0.10 + 1.16) \text{ V} = 1.26 \text{ V}$$

$$K = \exp\left(\frac{|z|FE^\circ}{RT}\right) = \exp\left(\frac{4 \times 96\,485 \text{ C mol}^{-1} \times 1.26 \text{ V}}{8.314 \text{ J K}^{-1} \text{ mol}^{-1} \times 298.15 \text{ K}}\right) = 1.6 \times 10^{85}$$

$K =$

Hydrazine decomposition to  $\text{H}_2$  and  $\text{N}_2$  in a basic environment:

$$E^\circ = E^\circ(\text{H}_2\text{O}/\text{H}_2) + (-E^\circ(\text{N}_2/\text{N}_2\text{H}_4)) = (-0.83 + 1.16) \text{ V} = 0.33 \text{ V}$$

$$K = \exp\left(\frac{|z|FE^\circ}{RT}\right) = \exp\left(\frac{4 \times 96\,485 \text{ C mol}^{-1} \times 0.33 \text{ V}}{8.314 \text{ J K}^{-1} \text{ mol}^{-1} \times 298.15 \text{ K}}\right) = 2.1 \times 10^{22}$$

$K =$

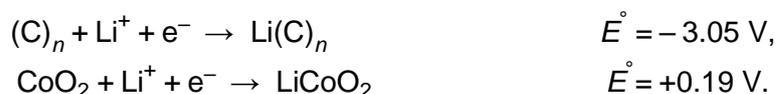
*10 points in total*

*2 points for each correctly balanced reaction (4 points in subtotal)*

*4 points for the correct way of calculation of the equilibrium constant (2 points will be scored if the correct formula for the related standard reaction Gibbs energy is given)*

*1 point for each numerically correct value of equilibrium constant (2 points in subtotal), no points will be scored if a wrong value of  $z$  is used in the calculation*

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.



Because  $E_{\text{lower}}^{\circ} > E_{\text{upper}}^{\circ}$ , the upper reaction occurs spontaneously in the opposite direction. Therefore, the discharge of the battery occurs when lithium leaves the graphite structure and its ions intercalate in the cobalt oxide:



5 points in total

1 point for each oxidation state of cobalt atom

3 points for the overall reaction

No points will be scored for the reaction written in the opposite direction.

- 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) <sub>n</sub> electrode is	<input type="checkbox"/>	cathode	<input type="checkbox"/>	because lithium ions are reduced here.
	<input checked="" type="checkbox"/>	anode	<input checked="" type="checkbox"/>	because lithium atoms are oxidized here.
LiCoO <sub>2</sub> electrode is	<input checked="" type="checkbox"/>	cathode	<input checked="" type="checkbox"/>	because cobalt ions are reduced here.
	<input type="checkbox"/>	anode	<input type="checkbox"/>	because cobalt ions are oxidized here.

2 points in total

1 point for each correct pair of boxes marked

- 3.11 Assume that a C<sub>6</sub> unit, a CoO<sub>2</sub> 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<sup>-1</sup>) and the energy density (in kWh kg<sup>-1</sup>) of such a model lithium ion battery related to the whole active battery mass.

Calculations:

The transfer of 1 mol of electrons requires at least the molar mass of the active ingredients  $M_{\text{total}} = 169.94 \text{ g mol}^{-1}$ , meaning that the specific charge capacity is:

$$c_{q,s} = \frac{F}{M} = \frac{96\,485 \text{ C mol}^{-1}}{169.94 \text{ g mol}^{-1}} = 567.76 \text{ C g}^{-1} \approx 567.76 \text{ A s g}^{-1} \approx 157.71 \text{ mAh g}^{-1}$$

Charge capacity ( $c_{q,s}$ ) = mAh g<sup>-1</sup>

Calculations:

Assuming the standard EMF (voltage) of the battery is:

$$U = E^{\circ}(\text{Li}_{x_1}\text{CoO}_2/\text{Li}_{x_2}\text{CoO}_2) - E^{\circ}(\text{Li}^+/\text{Li}^0) = 0.19 + 3.05 \text{ V} = 3.24 \text{ V},$$

the energy density of the battery can be calculated as:

$$\rho_{el} = U \times c_{q,s} = 3.24 \text{ V} \times 567.76 \text{ C g}^{-1} = 1\,839.6 \text{ W s g}^{-1} \approx 0.511 \text{ kWh kg}^{-1}$$

Energy density ( $\rho_{el}$ ) = kWh kg<sup>-1</sup>



*6 points in total for the numerically correct final result. Some of the steps may be condensed or performed implicitly. As long as this is performed correctly, full marks will be scored for all elementary steps.*

*1 point will be scored if only the correct numerical value for the Gibbs energy associated with the electron transfer is given. Zero points will be scored for any numerical (sub)result given with wrong or missing units.*

*1 point for the numerically correct value of the active molar mass*

*1 point for the correct formula for the specific charge capacity*

*1 point for the numerically correct value of the specific charge capacity*

*1 point for the numerically correct value of EMF*

*1 point for the correct formula for the energy density*

*1 point for the numerically correct value of the energy density*





Calculation:

The mole fraction is the sum of the distribution coefficients of  $[\text{CuCl}_3]^-$  and  $[\text{CuCl}_4]^{2-}$ :

$$\begin{aligned} \frac{([\text{CuCl}_3]^-) + ([\text{CuCl}_4]^{2-})}{c(\text{Cu}^{2+})} &= \frac{(\beta_3 [\text{Cl}^-]^3 + \beta_4 [\text{Cl}^-]^4)}{(1 + \beta_1 [\text{Cl}^-] + \beta_2 [\text{Cl}^-]^2 + \beta_3 [\text{Cl}^-]^3 + \beta_4 [\text{Cl}^-]^4)} \\ &= \frac{(0.69 \times 4^3 + 0.055 \times 4^4)}{(1 + 2.36 \times 4 + 1.49 \times 4^2 + 0.69 \times 4^3 + 0.055 \times 4^4)} = \\ &= 58.24 / 92.52 = 0.63 \end{aligned}$$

Mole fraction: 0.63

(answer with 2 digits after decimal point)

*4 points for completely correct answer; -1 point for the wrong mole fraction obtained by the correct procedure*

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

*1 point for the correct answer*

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

Using the simple experimental formula below, 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 the 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  $\text{cm}^3$  of both copper species and zinc species. The mass of dry resin in  $\text{OH}^-$  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:

$$V_R(\text{Cu species}) = 69.7 \text{ cm}^3 \text{ (answer with 1 digit after the decimal)}$$

$$V_R(\text{Zn species}) = 297 \text{ cm}^3 \text{ (answer with 0 digit after the decimal)}$$

*2 points in total (1 point for each  $V_R$ )*

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 a 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  $L_c = 13.0 \text{ cm}$ .

*According to the retention volumes ( $V_R$ ),  $V_{0.001}(\mathbf{A})$  corresponds to  $V_{0.001}(\text{Zn species})$  and  $V_{0.999}(\mathbf{B})$  corresponds to  $V_{0.999}(\text{Cu species})$*

$$V_{0.001}(\mathbf{A}) = 297 \text{ cm}^3 \times \left(1 - 6.91 \times \sqrt{0.125 \text{ mm}/130 \text{ mm}}\right) = 233 \text{ cm}^3$$

*2 points (1 point if  $L_c$  and  $d_p$  are used with different units;)*

$$V_{0.999}(\mathbf{B}) = 2 \times 69.7 \text{ cm}^3 - 54.8 \text{ cm}^3 = 84.6 \text{ cm}^3$$

*1 point (even with the wrong  $V_R$  and  $V_{0.001}$  for Cu species)*

$$\text{where } V_{0.001}(\text{Cu species}) = 69.7 \text{ cm}^3 \times \left(1 - 6.91 \times \sqrt{0.125 \text{ mm}/130 \text{ mm}}\right) = 54.8 \text{ cm}^3$$

*2 points (1 point if  $L_c$  and  $d_p$  are used with different units)*

It is possible to separate copper species from zinc species.

True       False

*2 points for the correct decisions based on  $V_{0.001}$  and  $V_{0.999}$  calculations*



- 4.6 Calculate the theoretical value of the total ion exchange mass capacity of the dry resin used in this problem,  $Q_{m,theor}$ , in  $\text{mmol g}^{-1}$ . 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%.

$$Q_{m,theor} = w(\text{N}) / M(\text{N}) = 0.0483 / (14.01 \text{ g mol}^{-1}) = 3.45 \text{ mmol g}^{-1}$$

*2 points (1 point if the value is in the wrong order of magnitude)*

(answer with 2 digits after decimal point)

If you cannot find the answer, use  $Q_{m,theor} = 4.83 \text{ mmol g}^{-1}$  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  $\text{Cl}^-$  form was washed with the excess of sodium sulfate solution. The effluent was collected in a  $500 \text{ cm}^3$  volumetric flask, which was then filled with water to the mark. An aliquot of  $100 \text{ cm}^3$  was potentiometrically titrated with  $0.1027 \text{ mol dm}^{-3}$  silver nitrate. The silver nitrate solution volume at the equivalence point was  $22.20 \text{ cm}^3$ . The volume of the column filled with the swollen resin,  $V_c$ , was  $10.21 \text{ cm}^3$ .

- 4.7 Calculate the  $Q_v$  of the swollen resin in  $\text{mmol}$  of active tetraalkylammonium groups per  $\text{cm}^3$  of the swollen resin.

$$Q_v = V(\text{AgNO}_3) \times c(\text{AgNO}_3) \times V_{\text{flask}} / (V_{\text{aliquot}} \times V_c) = \\ = 0.0222 \text{ dm}^3 \times 0.1027 \text{ mol dm}^{-3} \times 0.500 \text{ dm}^3 / (0.100 \text{ dm}^3 \times 0.01021 \text{ dm}^3) = 1.12 \text{ mmol cm}^{-3}$$

*3 points*

*-1 point if dilution is forgotten*

*-1 point for the wrong order of magnitude*

*(1 point for titration calculation)*

(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.

$$x = Q_v \times V_c / (Q_{m,theor} \times m_{\text{resin}}) = 1.12 \text{ mmol cm}^{-3} \times 10.21 \text{ cm}^3 / (3.45 \text{ mmol g}^{-1} \times 3.72 \text{ g}) = \\ = 0.891$$

*2 points*

(answer with 3 digits after decimal point)



<b>Theoretical Problem 5</b>	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	<b>Total</b>
	Points	5	7	3	2	6	1	1	1	<b>50</b>
	Score									

## Problem 5. Bohemian garnet

Bohemian garnet (pyrope) is a famous Czech blood 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.

$$M(\text{almandine}) = 497.75 \text{ g mol}^{-1}$$

$$\rho = m / V = (8 \times M) / (N_A \times a^3) = (8 \times 497.75) / [6.022 \times 10^{23} \times (11.50 \times 10^{-8})^3] = 4.35 \text{ g cm}^{-3}$$

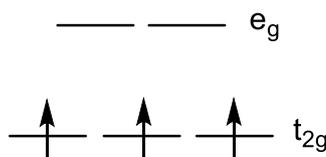
3 points in total

correct molar mass 1 point, correct equation 1 point, correct numerical calculation starting from correct equation 1 point

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 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.

Splitting diagram – configuration  $d^3$ :



3 points in total

correct orbital splitting 1 point, correct number of electrons 1 point, correct configuration according



*to Hund's rule 1 point, -1 point if only a line not indicating the electron spin is used (deducted only once per Problem); orbital marking is not evaluated*

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

**Co**

*1 point*

*correct answer 1 point, incorrect answer -1 point, minimum 0 points (the score may not be negative)*

- 5.4 The figure below shows d-orbitals splitting in the dodecahedral crystal field. Fill in the electrons for the [Fe<sup>II</sup>O<sub>8</sub>]<sup>dod</sup> chromophore for both existing arrangements.

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

*5 points in total*  
*correct number of electrons 1 point, correct high-spin configuration 2 points, correct low-spin configuration 2 points (any other configuration 0 points: high spin and low spin configurations differ in total spin. Any other configurations do not fulfil this condition.)*  
*If incorrect number of electrons is considered, then the correctness of such a configuration is taken into account.*

- 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 arrangements.

a) high-spin arrangement:                       $P > E_1 - E_3$

b) low-spin arrangement:                       $P < E_1 - E_3$

*3 points in total*

*correct BOTH inequality signs 1 point (half-points are not allowed), correct right-side terms (according to the answer in 5.4) 1 + 1 points*

- 5.6 Assuming that  $P > E_3$ , identify the 1<sup>st</sup> transition row element(s) whose divalent cation M<sup>II</sup> placed in dodecahedral position is diamagnetic in the low-spin arrangement and paramagnetic in the high-spin arrangement.

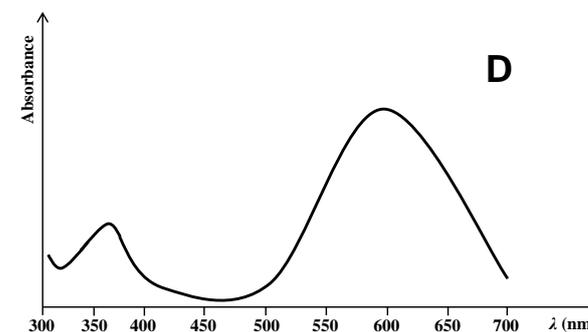
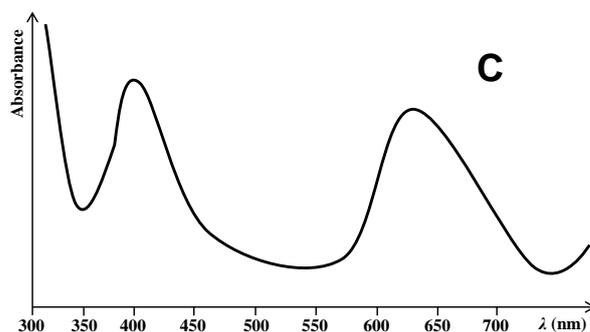
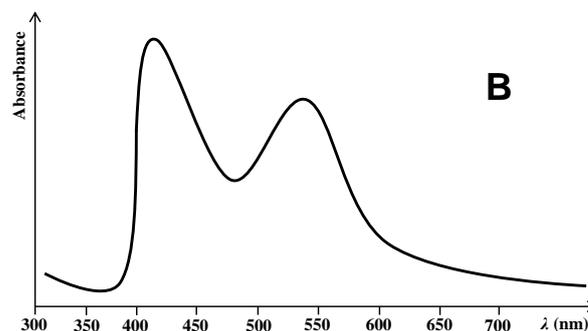
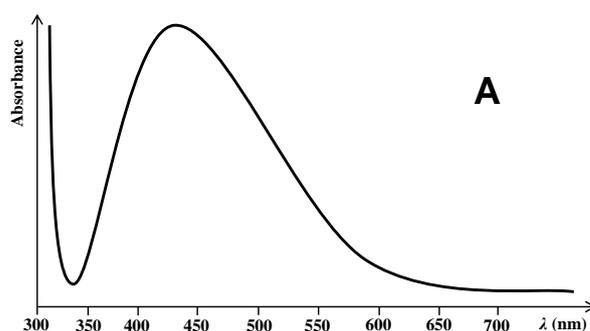


Cr, Ni

2 points

each correct metal 1 point, each incorrect metal – 1 point, minimum 0 points (the score may not be negative)

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



5.7 Match the spectra with the minerals.

Bohemian garnet: **B**

Sapphire: **D**

Uvarovite: **C**

Citrine: **A**

4 points in total, each correct assignment 1 point

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

Red

Blue

Yellow-orange

Black

Yellow

Blue-green

Violet

White

1 point



Andradite is another garnet mineral; its chemical composition is  $\text{Ca}_3\text{Fe}_2(\text{SiO}_4)_3$ . A double cation substitution –  $\text{Ti}^{\text{IV}}$  for  $\text{Fe}^{\text{III}}$  in the octahedral position and  $\text{Fe}^{\text{III}}$  for  $\text{Si}^{\text{IV}}$  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  $\text{Si}^{\text{IV}}$  ions in a sample of schorlomite that must be substituted with  $\text{Fe}^{\text{III}}$ , if we know that 5% of  $\text{Fe}^{\text{III}}$  ions in octahedral position are substituted with  $\text{Ti}^{\text{IV}}$ .

Both substitutions change the charge by 1 unit per ion. Taking total number of ions in formula into consideration we get:

$$5\% \times 2 = p \times 3$$

$$p = 3.33 \%$$

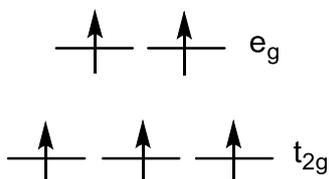
2 points

correct starting consideration in the form of an equation 1 point, correct numerical calculation 1 point

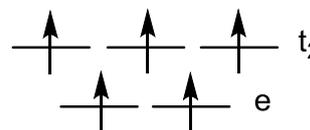
The colour of the mineral is caused by two chromophores:  $[\text{Fe}^{\text{III}}\text{O}_6]^{\text{oct}}$  and  $[\text{Fe}^{\text{III}}\text{O}_4]^{\text{tet}}$ . The central ions of both chromophores have equal number of unpaired electrons.

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

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



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



5 points in total

correct octahedral splitting 1 point, correct tetrahedral splitting 1 point, correct number of electrons 1 point, correct high-spin configurations 1 + 1 points; orbital marking is not evaluated.

Tetrahedral field causes a smaller splitting than the octahedral field ( $\Delta_{\text{tet}} = \frac{4}{9} \Delta_{\text{oct}}$ ). Surprisingly for the  $\text{Fe}^{\text{III}}$  ion, the energy of the first d–d transition (although very weak) for the octahedral chromophore is smaller ( $11\,000\text{ cm}^{-1}$ ) than for the tetrahedral one ( $22\,000\text{ cm}^{-1}$ ).

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

Because  $\Delta_{\text{oct}} < P$  (high-spin configuration in tetrahedral as well as in octahedral field), the wavenumber corresponds to electron transition from the upper to the lower level in both cases and thus:

$$11\,000\text{ cm}^{-1} = P - \Delta_{\text{oct}}$$



$$22\,000\text{ cm}^{-1} = P - \Delta_{\text{tet}} = P - \frac{4}{9} \Delta_{\text{oct}}$$

By solving the system of these equations we get:

$$P = 30\,800\text{ cm}^{-1}$$

$$\Delta_{\text{oct}} = 19\,800\text{ cm}^{-1}$$

$$\Delta_{\text{tet}} = 8\,800\text{ cm}^{-1}$$

Alternative solution comes from the assumption (independent of the result of 5.10) of the low-spin arrangement in octahedral field and high-spin arrangement in tetrahedral field:

$$11\,000\text{ cm}^{-1} = \Delta_{\text{oct}} - P$$

$$22\,000\text{ cm}^{-1} = P - \Delta_{\text{tet}} = P - \frac{4}{9} \Delta_{\text{oct}}$$

By solving the system of these equations we get:

$$P = 48\,400\text{ cm}^{-1}$$

$$\Delta_{\text{oct}} = 59\,400\text{ cm}^{-1}$$

$$\Delta_{\text{tet}} = 26\,400\text{ cm}^{-1}$$

*7 points in total*

*formulation of equations 2 + 2 points, correct energy values (i.e. correct numerical calculation starting from correct assumption) 1 + 1 + 1 points*

Synthetic garnet YAG (Yttrium Aluminium Garnet), used in optoelectronics, has the composition of  $\text{Y}_3\text{Al}_5\text{O}_{12}$ . Its structure is derived from the general garnet structure  $\text{A}_3\text{B}_2(\text{SiO}_4)_3$  by placing the ions  $\text{Y}^{\text{III}}$  and  $\text{Al}^{\text{III}}$  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:  $\text{Y}^{\text{III}}$       B:  $\text{Al}^{\text{III}}$       Si:  $\text{Al}^{\text{III}}$

*3 points in total, each correct assignment 1 point*

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

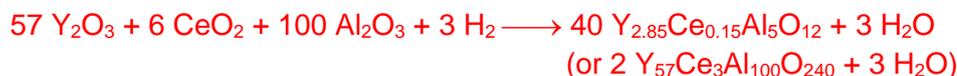
$\text{Y}_x\text{Ce}_y\text{Al}_5\text{O}_{12}$        $x = 2.85$        $y = 0.15$

*2 points in total, each value 1 point*

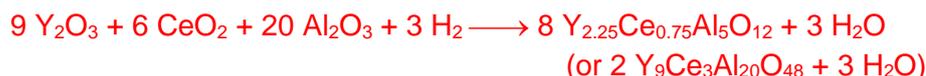
If you don't get result, use  $x = 2.25$  and  $y = 0.75$ .



- 5.14 The Ce<sup>III</sup>-doped YAG is prepared by annealing the mixture of Y<sub>2</sub>O<sub>3</sub>, Al<sub>2</sub>O<sub>3</sub> and CeO<sub>2</sub> in H<sub>2</sub> atmosphere. Use the formula from 5.13, write down a balanced equation for this reaction with the smallest whole-number stoichiometric coefficients.



for  $x = 2.25$  and  $y = 0.75$ :



*complete set of correct coefficients 6 points*

*-1 point if correct stoichiometric coefficients are only on one side of the equation*

*-1 point if stoichiometric coefficients are correct and whole-number but not the smallest*

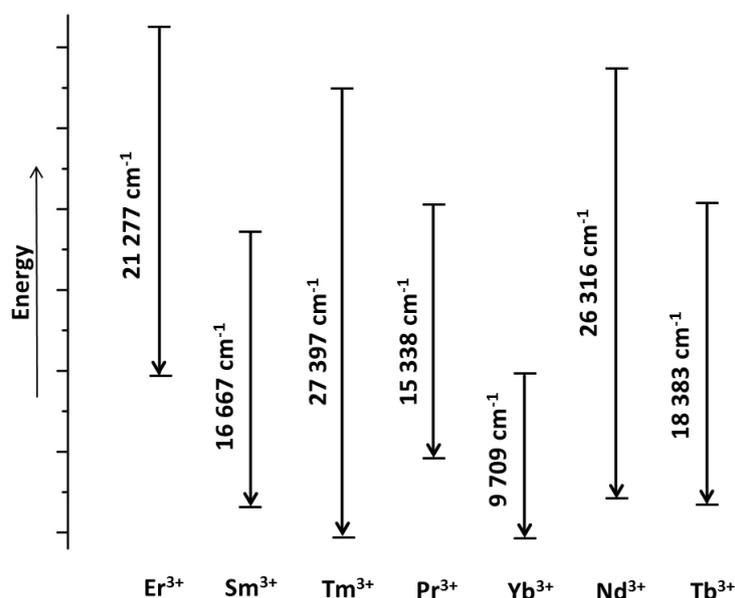
*-2 points if stoichiometric coefficients are correct but not whole-numbers*

*if hydrogen+water are omitted from the equation or when redox change was incorrect, then penalty*

*-3 point is applied*

*if incorrect formula in 5.13 is given, the answer is judged with respect to the incorrect formula*

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.

Er<sup>3+</sup>

Sm<sup>3+</sup>

Tm<sup>3+</sup>

Pr<sup>3+</sup>

Yb<sup>3+</sup>

Nd<sup>3+</sup>

Tb<sup>3+</sup>

*1 point*



5.16 Calculate the emission wavelength of this light.

$$\lambda = \frac{1}{2\,127\,700} \text{ m} = 4.70 \times 10^{-7} \text{ m} = 470 \text{ nm}$$

*1 point. The result of 5.16 is evaluated with respect to the answer in 5.15*

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-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 checked="" type="checkbox"/> Blue-green | <input type="checkbox"/> Violet        | <input type="checkbox"/> White |

*1 point*

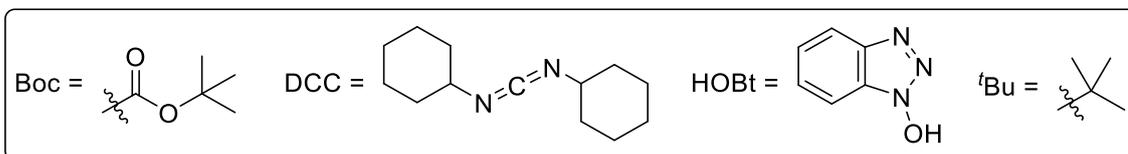
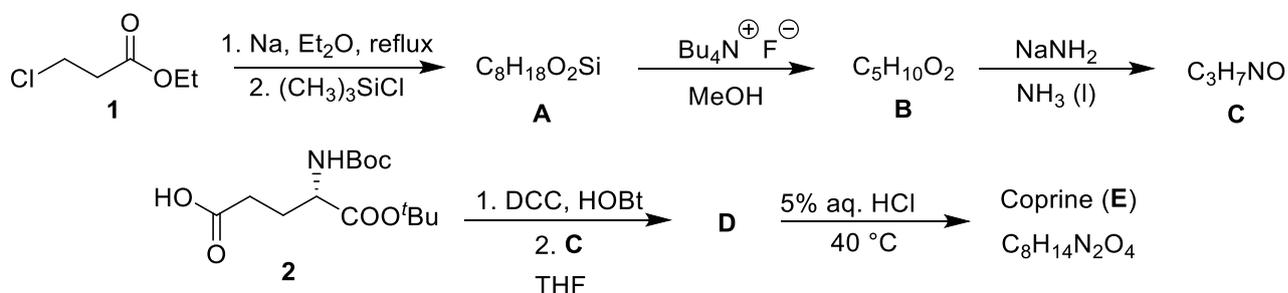


Theoretical Problem 6  7% of the total	Question	6.1	6.2	6.3	6.4	6.5	6.6	6.7	6.8	Total
	Points	18	4	8	3	4	12	16	3	<b>68</b>
	Score									

## 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 when necessary. *Hint: The first reaction affording compound **A** proceeds via an organometallic compound which then cyclizes.*

<p><b>A</b></p> <p>4 points</p>	<p><b>B</b></p> <p>2 points for TMS deprotection</p>	<p><b>C</b></p> <p>4 points for ethoxy group substitution by amino group</p>
<p><b>D</b></p> <p>4 points for amide formation 2 points for the corresponding ester formation -2 points for wrong or undefined stereo-chemistry (2 rules may apply at once)</p>		<p><b>E</b></p> <p>4 points for Boc and <sup>t</sup>Bu deprotection (zwitterionic form is also accepted with no penalty) -2 points for wrong or undefined stereo-chemistry</p>



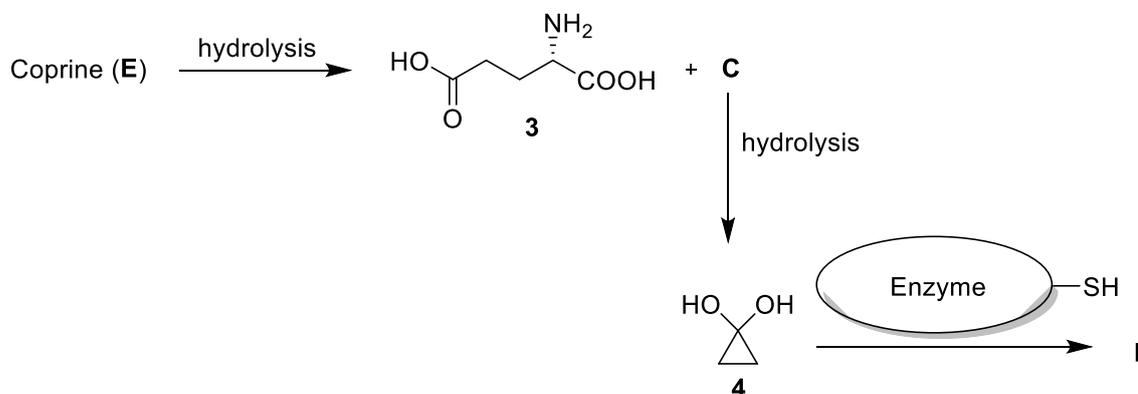
No points will be given for structure **A** if it is acyclic.

For wrong isomeric structures of compounds **A–E**, 0–2 points will be given depending on the rationality of the answer.

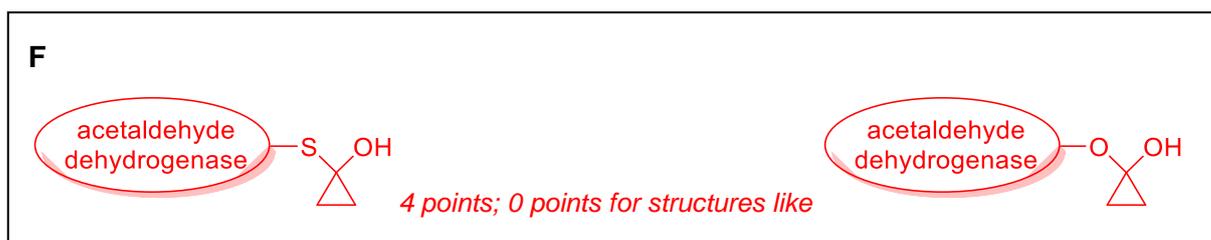
No points will be given for structures **A–C** or **E** if they do not match the given molecular formulae, except for minor mistakes (see below).

– 1 point for each atom with abnormal valence or for incorrect number of hydrogens on heteroatoms.

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**.

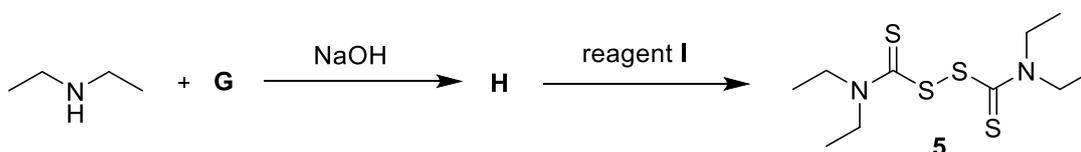


6.2 Using the pictogram for acetaldehyde dehydrogenase above, draw the structure **F** of the enzyme inhibited by compound **4**.



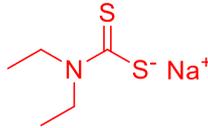
No penalty if two molecules of the enzyme are blocked by one molecule of **4**.

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.*

<p><b>G</b></p> <p><math>\text{CS}_2</math></p> <p>4 points</p> <p>No penalty for other meaningful reagents, such as halodithioformic acid, its ester or salt.</p> <p>0 points for xanthates.</p>	<p><b>H</b></p>  <p>4 points</p> <p>3 points for the above-pictured salt if the cation is wrong or missing</p> <p>2 points for the corresponding acid</p>
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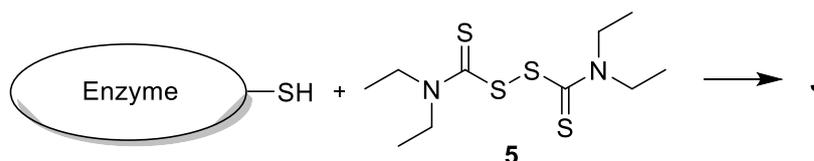
6.4 Mark all possible reagents which could be used for **I** from the following list.

- |  |  |
|--|--|
| <input checked="" type="checkbox"/> <i>m</i> -chloroperbenzoic acid ( <i>m</i> CPBA) | <input checked="" type="checkbox"/> diluted $\text{H}_2\text{O}_2$ |
| <input type="checkbox"/> $\text{Zn}/\text{CH}_3\text{COOH}$                          | <input type="checkbox"/> $\text{NaBH}_4$                           |
| <input checked="" type="checkbox"/> $\text{I}_2$                                     | <input type="checkbox"/> hot concentrated $\text{H}_2\text{SO}_4$  |
| <input type="checkbox"/> $\text{K}_2\text{CO}_3, \text{H}_2\text{O}$                 | <input type="checkbox"/> $\text{AlCl}_3$                           |

1 point for each correct answer (3 points in total).

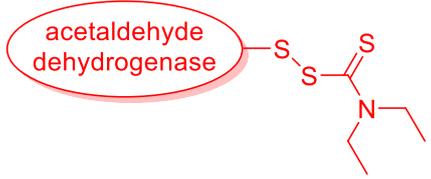
-1 point for each incorrect answer. The total score in task 6.4 may not be negative.

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



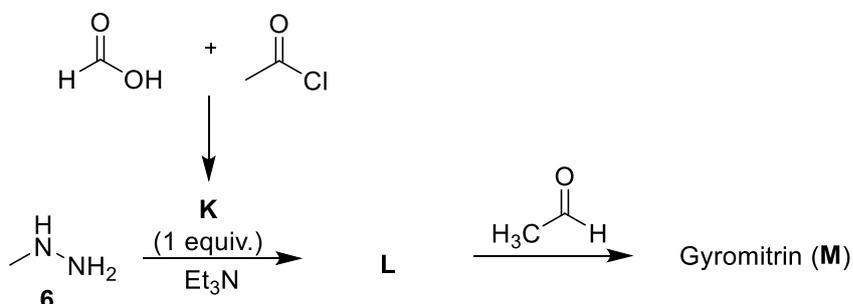
Enzyme = acetaldehyde dehydrogenase

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.*

<p><b>J</b></p>  <p>4 points (the only acceptable answer)</p>
--



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**.

<p><b>K</b></p> <p>4 points 4 points for formic anhydride 2 points for formyl chloride</p>	<p><b>L</b></p> <p>4 points for the correct structure - 1 point if acetylated - 1 point for multiple acylation - 2 points if acylated on the other nitrogen atom</p>	<p><b>M</b></p> <p>4 points for the correct structure (cis or trans isomer) - 1 point for aminal (exception down below) - 3 points if the reaction with acetaldehyde was carried out on the amidic nitrogen atom</p>
--	--	--

- 1 point for each atom with abnormal valence or for each missing hydrogen atom.

If **L** is acylated with wrong regioselectivity, then in **M** aminals, enamines, and iminium salts are accepted with no penalty.

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  $1\,293.0\text{ cm}^{-1}$  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,  $^{14}\text{N}$  with the  $^{15}\text{N}$  isotope and  $^{12}\text{C}$  with the  $^{13}\text{C}$  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 steps consider five significant digits.



C-N bond reduced mass:

$$\mu_{12\text{C}}^{14\text{N}} = \frac{14.000 \text{ g mol}^{-1} \times 12.000 \text{ g mol}^{-1}}{(14.000 + 12.000) \text{ g mol}^{-1} \times 6.0221 \times 10^{23} \text{ mol}^{-1}} = 1.0730 \times 10^{-26} \text{ kg}$$

Alternatively,  $(\mu_{12\text{C}}^{14\text{N}})' = 6.4615 \text{ g mol}^{-1}$

$$\mu_{13\text{C}}^{15\text{N}} = \frac{15.000 \text{ g mol}^{-1} \times 13.000 \text{ g mol}^{-1}}{(15.000 + 13.000) \text{ g mol}^{-1} \times 6.0221 \times 10^{23} \text{ mol}^{-1}} = 1.1565 \times 10^{-26} \text{ kg}$$

Alternatively,  $(\mu_{13\text{C}}^{15\text{N}})' = 6.9643 \text{ g mol}^{-1}$

C-N bond force constant:  $k = \left(2\pi c \tilde{\nu}_{12\text{C}}^{14\text{N}}\right)^2 \times \mu_{12\text{C}}^{14\text{N}} = 636.48 \text{ kg s}^{-2}$

C-N substituted bond wavenumber:

$$\tilde{\nu}_{13\text{C}}^{15\text{N}} = \frac{1}{2\pi c} \sqrt{\frac{k}{\mu_{13\text{C}}^{15\text{N}}}} = 1\,245.5 \text{ cm}^{-1}$$

Hypothetical kinetic isotope effect:

$$\frac{k_{12\text{C}}^{14\text{N}}}{k_{13\text{C}}^{15\text{N}}} = \exp\left(\frac{hc}{2k_{\text{B}}T} \left(\tilde{\nu}_{12\text{C}}^{14\text{N}} - \tilde{\nu}_{13\text{C}}^{15\text{N}}\right)\right) = 1.1166$$

16 points in total

2 points for the correct formula for the reduced mass, 1 point for each numerical value of the reduced mass (4 points in total), full marks will be scored if the reduced mass is given in units such as kg, g, amu, kg mol<sup>-1</sup> or g mol<sup>-1</sup>

2 points for the correct formula for the C-N force constant, 2 points for its numerical value

2 points for the correct formula for the wavenumber, 2 points for its numerical value

2 points for the correct formula for the KIE, 2 points for its numerical value

Alternative to force constant and wavenumber one can derive formula for KIE as follows

$$\tilde{\nu}_{13\text{C}}^{15\text{N}} = \tilde{\nu}_{12\text{C}}^{14\text{N}} \sqrt{\frac{\mu_{12\text{C}}^{14\text{N}}}{\mu_{13\text{C}}^{15\text{N}}}} = 1\,245.5 \text{ cm}^{-1}$$

$$E_{\tilde{\nu}_{12\text{C}}^{14\text{N}}} = \frac{hc\tilde{\nu}_{12\text{C}}^{14\text{N}}}{2} = 1.2851 \times 10^{-20} \text{ J}$$

$$E_{\tilde{\nu}_{13\text{C}}^{15\text{N}}} = \frac{hc\tilde{\nu}_{13\text{C}}^{15\text{N}}}{2} = 1.2379 \times 10^{-20} \text{ J}$$



$$\frac{k_{12\text{C}}^{14\text{N}}}{k_{13\text{C}}^{15\text{N}}} = \exp\left(\frac{E_{\tilde{\nu}_{12\text{C}}^{14\text{N}}} - E_{\tilde{\nu}_{13\text{C}}^{15\text{N}}}}{k_{\text{B}}T}\right) = 1.1166$$

*2 points for the correct formula for the wavenumber, 2 points for its numerical value*

*2 points for the correct formula for the ZPVE, 1 point for each numerical value*

*2 points for the correct formula for the KIE, 2 points for its numerical value*

*Some of the steps in the derivation may be taken implicitly or simultaneously. As long as they are correct, full marks will be scored for each of the partial steps. If the correct KIE (a dimensionless quantity) is provided, full marks will be scored for the whole 6.7 problem. If the calculation of the KIE is not completed or its wrong value is given, 0 points will be scored for any of the numerical results of the partial steps if these are given with wrong units or no units at all.*

6.8 After making these isotopic changes, the rates of hydrolysis are not significantly different. Which of the following is the most likely the rate determining step?

- Nucleophilic attack of water on a protonated amidic moiety
- C–N bond cleavage
- Protonation of the gyromitrin molecule

*3 points for the correct answer.*

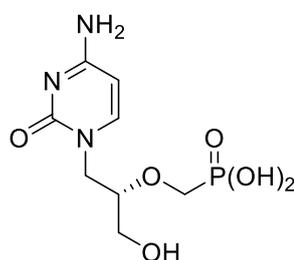
*–3 points for each incorrect answer. The total score in task 6.8 may not be negative.*



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

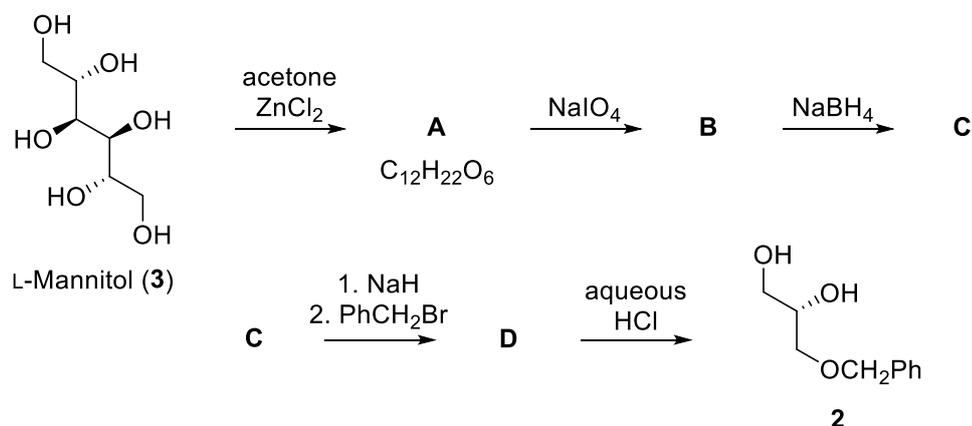
Cidofovir (**1**), originally designed and prepared by the group of Professor Holy in former Czechoslovakia, is a nucleotide analogue with antiviral activity. It is used to treat viral infections, mostly in patients with AIDS.



Cidofovir (**1**)

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

*The total for each structure/sub-problem may not be negative.*

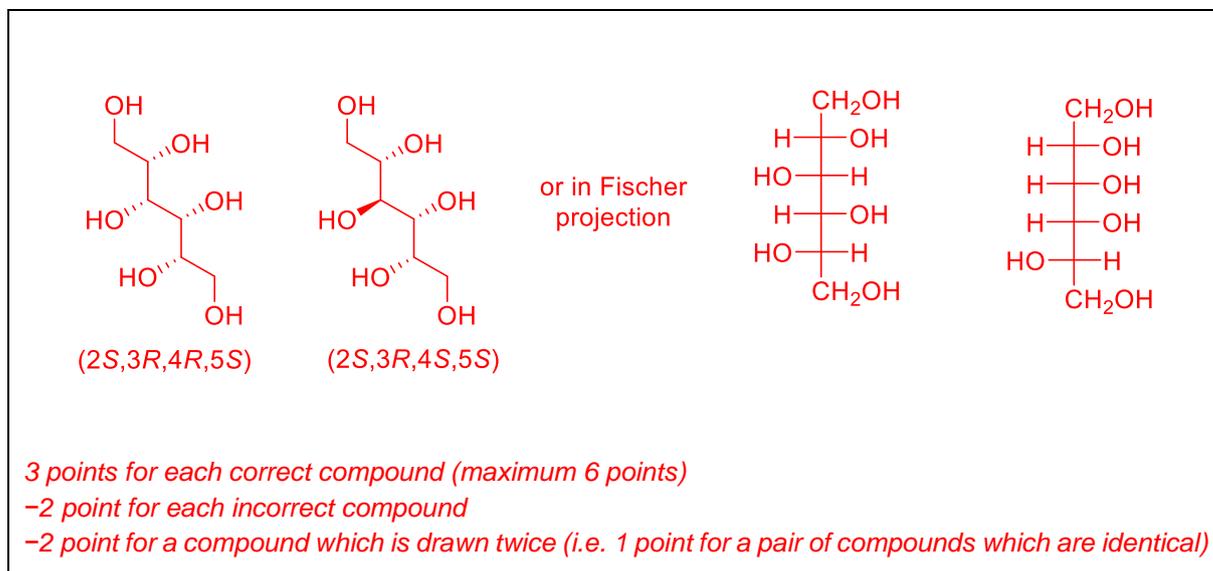


7.1 Draw the structures of compounds **A–D**, including stereochemistry. One molecule of **A** produces two molecules of **B**.

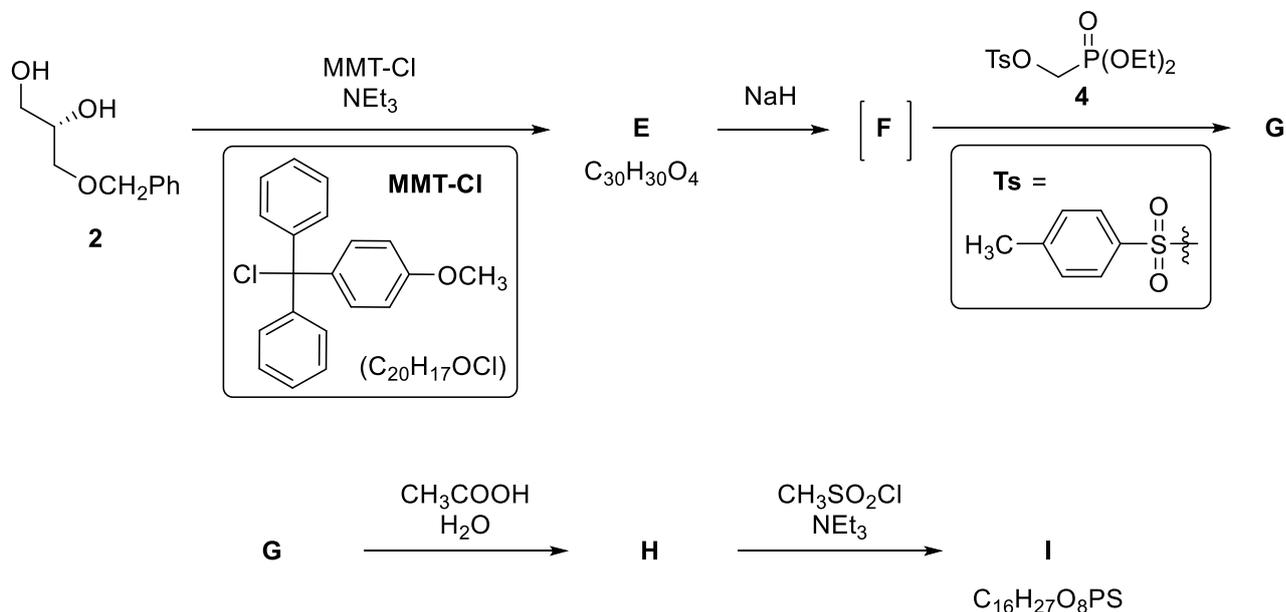
<p><b>A</b></p> <p>C<sub>12</sub>H<sub>22</sub>O<sub>6</sub></p> <p>3 points for the correct structure 2 points if the molecular formula is correct but different OH groups are protected 2 points if the correct OH groups are protected but the stereochemistry is wrong or missing 1 point if different adjacent OH groups are protected and the stereochemistry is wrong 0 points if the molecular formula is not correct</p>	<p><b>B</b></p> <p>3 points for the correct structure 3 points if any wrongly assigned compound <b>A</b> is cleaved between two adjacent free OH groups 2 points if stereochemistry is wrong or missing 1 point if compound <b>A</b> is cleaved properly but the oxidation state of C1 is wrong 1 point if <b>A</b> is not determined and <b>B</b> contains <u>one</u> CHO group 1 point if <b>B</b> contains <u>one</u> CHO group, but the protecting groups are cleaved -1 point if stereochemistry is wrong or missing</p>
<p><b>C</b></p> <p>2 points for aldehyde reduction to alcohol (ONa scores full marks) 1 point if <b>B</b> is not determined and <b>C</b> contains a primary OH group -1 point if stereochemistry is wrong or missing</p>	<p><b>D</b></p> <p>2 points for alcohol protection ("Bn" also accepted) If <b>C</b> is not correct: 2 points if <u>all</u> primary OH groups are benzyl-protected 1 point if <b>D</b> contains a benzyloxy- group (and not all primary OH groups are benzyl-protected) -1 point if stereochemistry is wrong or missing</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**.



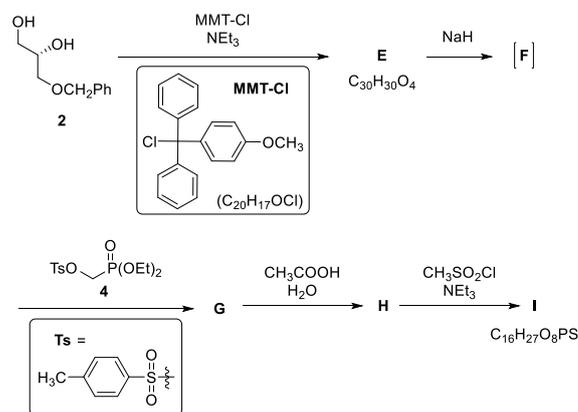
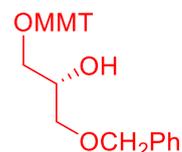
Diol **2** is further modified to provide compound **I**. The synthesis of phosphonate **4** used to convert compound **F** to **G** will be discussed later.



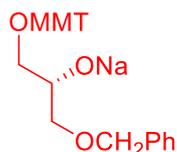


7.3 Draw the structures of compounds **E–I**, including stereochemistry. Use the abbreviation MMT for the (4-methoxyphenyl)diphenylmethyl group.

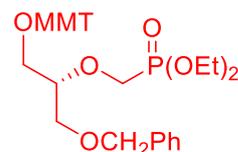
The same scheme as on the previous page, for easier orientation

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

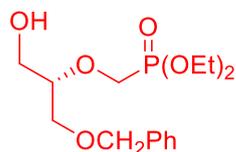
3 points for the correct structure  
 1 point if the secondary OH group is protected and the configuration on C2 is correct  
 0 points if the secondary OH group is protected and the configuration on C2 is incorrect  
 0 points if the molecular formula is not correct  
 -1 point if stereochemistry is wrong or missing

**F**

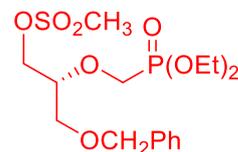
3 points for the correct structure)  
 2 points if written without the  $\text{Na}^+$  counter ion  
 1 point if the alkoxide on C2 is formed, but the configuration is inverted  
 1 point if the alkoxide on C2 is formed and any of the protecting groups is cleaved  
 -1 point if stereochemistry is wrong or missing

**G**

3 points for the correct structure  
 1 point if the substitution was performed on phosphorus and the configuration on C2 is correct  
 -1 point if stereochemistry is wrong or missing

**H**

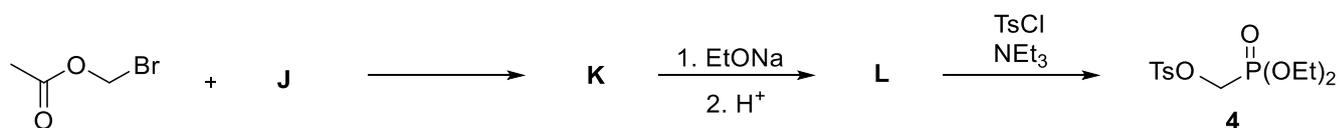
3 points for MMT cleavage  
 1 point if either benzyl or both the protecting groups are cleaved and the phosphonate is retained with the correct configuration  
 -1 point if stereochemistry is wrong or missing

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

3 points for the mesylate formation ("Ms" also accepted)  
 1 point if the molecular formula is correct, but I contains a mesylate group  
 0 points if molecular formula is not correct  
 -1 point if stereochemistry is wrong or missing



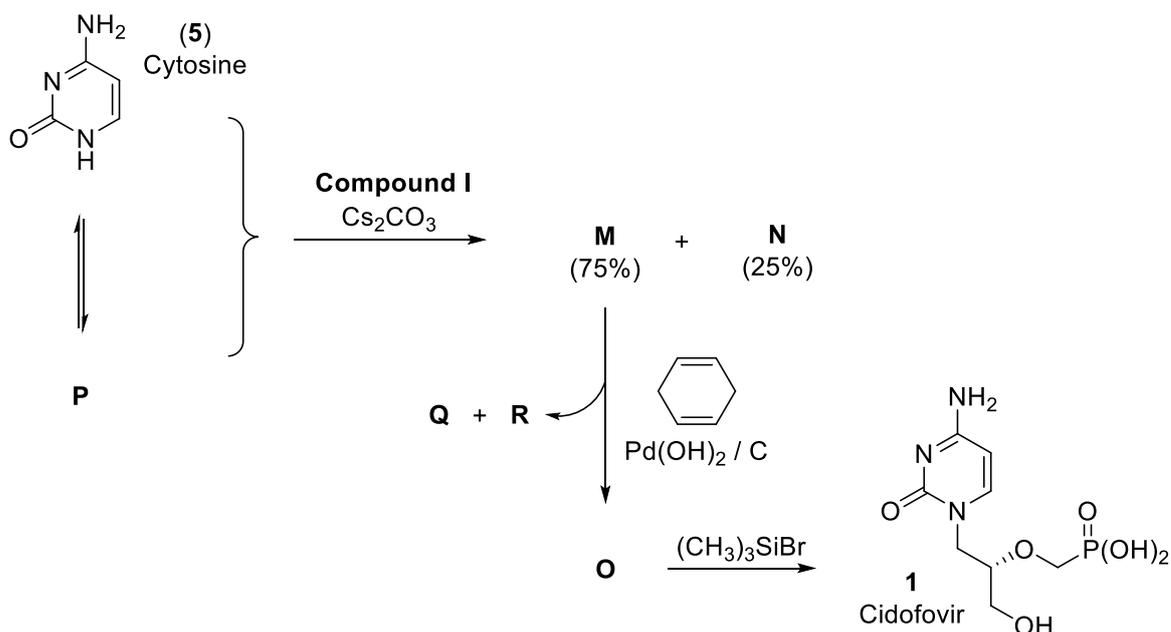
Phosfonate **4** can be prepared according to the following scheme:



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

<p><b>J</b></p> <p style="text-align: center;"> <math>\text{P}(\text{OR})_3</math> or <math>\text{Na}^+ \text{P}(\text{OR})_2^-</math> </p> <p><i>3 points for any phosphite or dialkyl phosphonate salt. Transesterification in the subsequent step would provide the required diethyl phosphonate. 1 point if all R = aryl in P(OR)<sub>3</sub></i></p>	<p><b>K</b></p> <p style="text-align: center;"> </p> <p style="text-align: center;">or</p> <p style="text-align: center;"> </p> <p><i>3 points for the correct structure</i></p>
<p><b>L</b></p> <p style="text-align: center;"> </p> <p><i>3 points for the correct structure</i></p>	

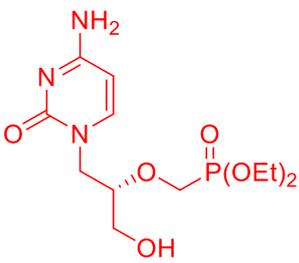
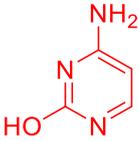
The reaction of **I** (from question 7.3) with cytosine (**5**) leads to a 3:1 mixture of isomeric compounds **M** and **N**. The formation of these two products may be understood by realizing that cytosine (**5**) can also exist as an aromatic tautomer **P**. The reaction of **M** with cyclohexa-1,4-diene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



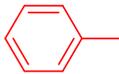
- 7.5 Draw the structures of the two isomers **M**, **N**, and of compound **O**, including stereochemistry and the structure of the aromatic tautomer **P** of cytosine (**5**). Transformation of **M** to **O** is the removal of a protecting group.

<p><b>M</b> (75%)</p> <p>3 points for the correct structure -1 point if the stereochemistry is wrong or missing</p>	<p><b>N</b> (25%)</p> <p>3 points for the correct structure 2 points if cytosine is linked via the amino group -1 point if the stereochemistry is wrong or missing 3 points in total if <b>M</b> and <b>N</b> are interchanged</p>
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<p><b>O</b></p>  <p><i>3 points for the benzyl cleavage -1 point if the stereochemistry is wrong or missing</i></p>	<p><b>P</b></p>  <p><i>2 points for the correct aromatic structure</i></p>
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7.6 Draw the structures of the two simple organic side products **Q** and **R** formed during the conversion of **M** to **O**.

<p><b>Q</b> from cyclohexadiene</p>  <p><i>3 points for the correct structure</i></p>	<p><b>R</b> from the protecting group</p>  <p><i>3 points for the correct structure</i></p>
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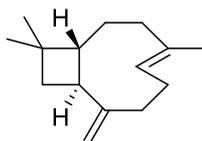


Theoretical Problem 8  9% of the total	Question	8.1	8.2	8.3	8.4	8.5	8.6	8.7	8.8	Total
	Points	14	14	2	16	6	8	9	6	<b>75</b>
	Score									

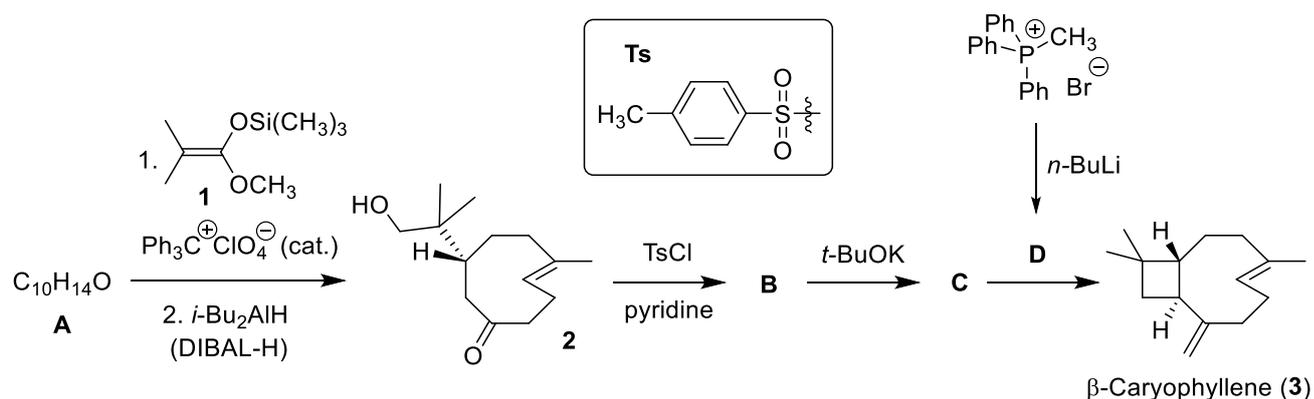
## Problem 8. Caryophyllene

$\beta$ -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.

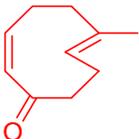
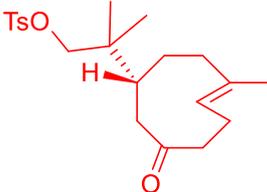
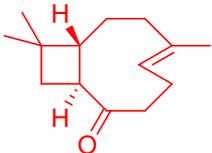
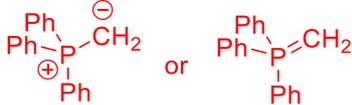
The synthesis of  $\beta$ -caryophyllene starts from a single enantiomer of dienone **A**. The reaction of **A** with silyl ketene acetal **1**, followed by immediate reduction and aqueous work-up affords ketone **2**. This intermediate then undergoes reaction with tosyl chloride, providing **B**. Basic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



$\beta$ -Caryophyllene (**3**)

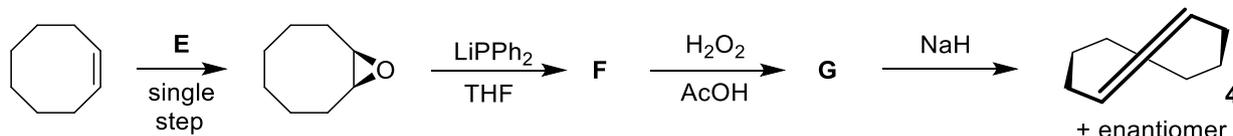


8.1 Draw the structures of compounds **A–D**, including the appropriate stereochemistry. *Hint: In transformation **A**  $\rightarrow$  **2**, the silyl ketene acetal acts as a nucleophile.*

<p><b>A</b> <math>C_{10}H_{14}O</math></p>  <p>4 points 2 points if configuration on C2-C3 double bond is (E) 1 point for the <math>\beta,\gamma</math>-unsaturated isomer of <b>A</b></p>	<p><b>B</b></p>  <p>4 points 2 points if stereo configuration is incorrect or unclear</p>
<p><b>C</b></p>  <p>4 points 2 points if stereo configuration is incorrect or unclear</p>	<p><b>D</b></p>  <p>2 points</p>



Due to the large ring size, both compounds **2** and **3** are stable, even though they contain a double bond in the *trans* configuration. *trans*-Cyclooctene (**4**) is the smallest ring that can accommodate a *trans* double bond. It can be prepared according to the following scheme:

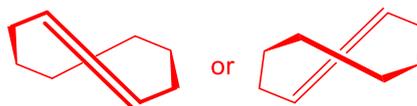
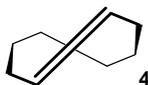


8.2 Draw the structures of reagent **E** and intermediates **F** and **G**, including the appropriate stereochemistry. For **F** and **G**, tick the box indicating the stereochemical outcome.

<p><b>E</b></p> <div style="text-align: center;"> </div> <p style="text-align: center;">2 points Other common epoxidation agents are also accepted. 1 point if a two-step epoxidation is given 0 points for H<sub>2</sub>O<sub>2</sub> (with no acid indicated)</p>	<p><b>F</b></p> <div style="text-align: center;"> </div> <p style="text-align: center;">4 points for the structure (O<sup>-</sup>Li<sup>+</sup> and OH are also accepted) 3 points when Li cation is missing from OLi 2 points if stereochemistry is incorrect or unclear</p> <p style="text-align: center;">2 points for ticking the right box (these points are additive to the points for the structure)</p> <p> <input type="checkbox"/> achiral  <input type="checkbox"/> single enantiomer  <input checked="" type="checkbox"/> racemic mixture  <input type="checkbox"/> mixture of diastereoisomers         </p>
<p><b>G</b></p> <div style="text-align: center;"> </div> <p style="text-align: center;">4 points for the structure 4 points for the oxidized product with acetylated -OH 3 points if charges and/or multiple bonds on phosphine oxide are incorrect or missing 2 points if stereochemistry is incorrect or unclear 1 point for oxidizing the alcohol to a ketone instead of or in addition to the phosphine 0 points for only acetylating -OH 2 points for ticking the right box (these points are additive to the points for the structure)</p> <p> <input type="checkbox"/> achiral  <input type="checkbox"/> single enantiomer  <input checked="" type="checkbox"/> racemic mixture  <input type="checkbox"/> mixture of diastereoisomers         </p>	

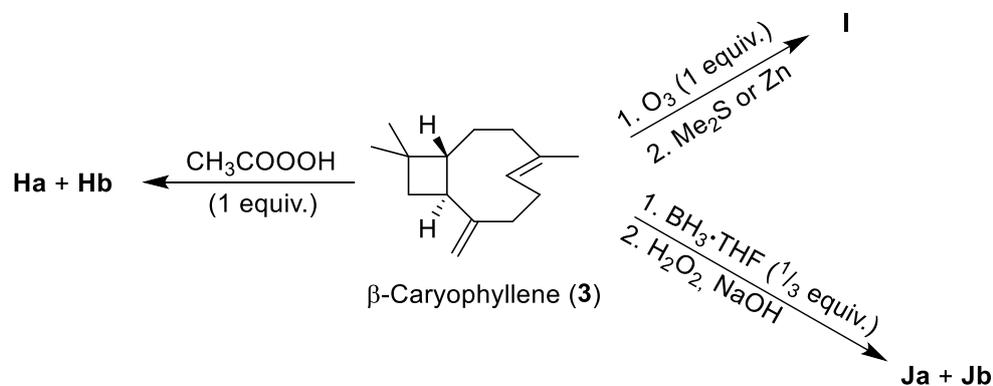


8.3 Draw the structure of the enantiomer of cycloalkene **4**.

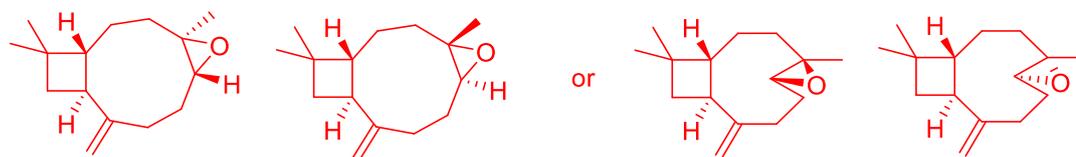


2 points (other correct drawings are also accepted)

The two double bonds in  $\beta$ -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**

6 points if both diastereomers are given

4 points if both diastereomers are given but stereochemistry of one of the two newly formed stereocenters is missing, unclear or incorrect

4 points if only one diastereomer is given (the second is missing) but stereochemistry is correct

3 points if one diastereomer is drawn correctly and the second structure is incorrect

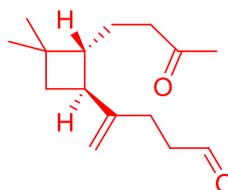
2 points if both diastereomers are given but stereochemistry is incorrect or missing

2 points if both diastereomers are given but incorrect double bond or both double bonds are syn-epoxidized

1 point if only one diastereomer is given and stereochemistry is incorrect or missing

1 point if only one diastereomer is given and incorrect double bond or both double bonds are syn-epoxidized

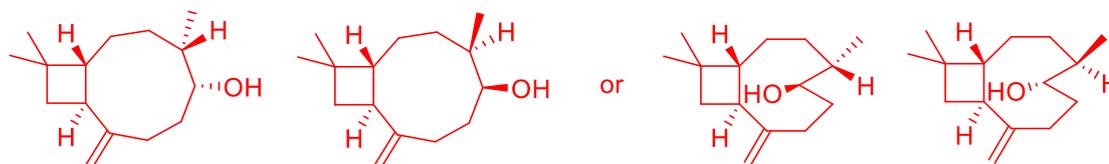
the above partial credit points are not additive

**I**

4 points

2 points if primary or secondary ozonide is drawn

1 point if the correct ozonolysis product of the exocyclic bond or of both bonds is given

**Ja + Jb**

6 points if both diastereomers are given

4 points if both diastereomers are given but stereochemistry of one of the two newly formed stereocenters is missing, unclear or incorrect

4 points if only one diastereomer is given (the second is missing) but stereochemistry is correct

3 points if one diastereomer is drawn correctly and the second structure is incorrect

2 points if both diastereomers are given but stereochemistry is incorrect or missing

2 points if both diastereomers are given but regioselectivity is incorrect

2 points if both diastereomers are given but correct hydration of the wrong double bond or of both double bonds is given

1 point if only one diastereomer is given and stereochemistry is incorrect or missing

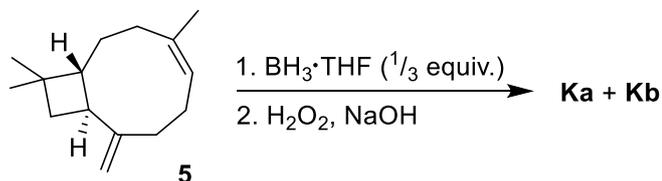
1 point if only one diastereomer is given and regioselectivity is incorrect

1 point if only one diastereomer is given and incorrect double bond or both double bonds are correctly syn-hydrated

the above partial credit points are not additive



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

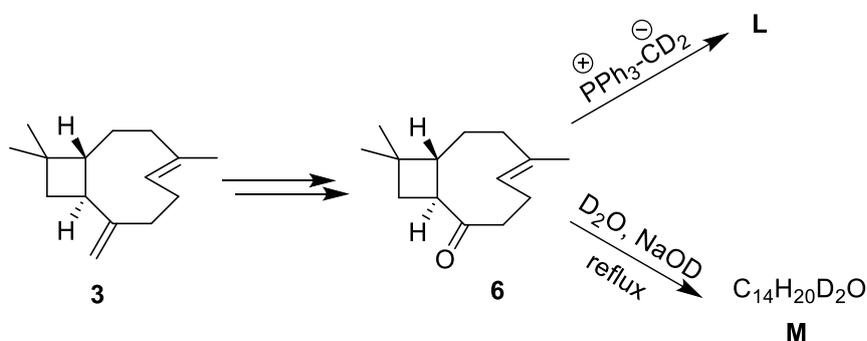


8.5 Draw the structures of compounds **Ka** and **Kb**. *Hint: **Ka** + **Kb** are a pair of diastereomers.*

**Ka + Kb**

*6 points if both diastereomers are given*  
*4 points if only one diastereomer is given (the second is missing) but stereochemistry is correct*  
*3 points if one diastereomer is drawn correctly and the second structure is incorrect*  
*2 points if both diastereomers are given but stereochemistry is incorrect or missing*  
*2 points if both diastereomers are given but regioselectivity is incorrect*  
*2 points if both diastereomers are given but correct hydration of the wrong double bond or of both double bonds is given*  
*1 point if only one diastereomer is given and stereochemistry is incorrect or missing*  
*1 point if only one diastereomer is given and regioselectivity is incorrect*  
*1 point if only one diastereomer is given and incorrect double bond or both double bonds are correctly syn-hydrated*  
*the above partial credit points are not additive*

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  $\beta$ -caryophyllene.

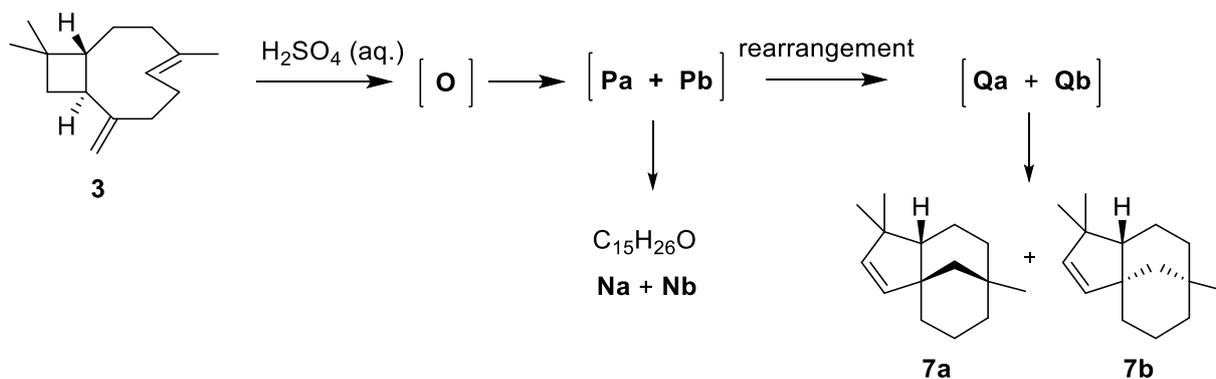


8.6 Draw the structures of compounds **L** and **M**, including the appropriate stereochemistry.



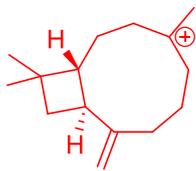
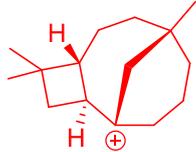
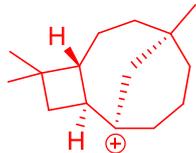
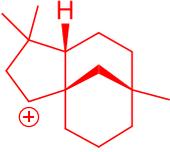
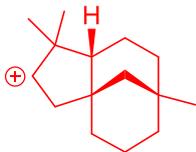
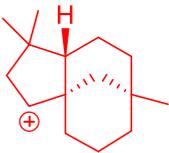
<p><b>L</b></p> <p><i>4 points</i></p>	<p><b>M</b> C<sub>14</sub>H<sub>20</sub>D<sub>2</sub>O</p> <p><i>4 points</i></p> <p><i>2 points for the structure below</i></p>
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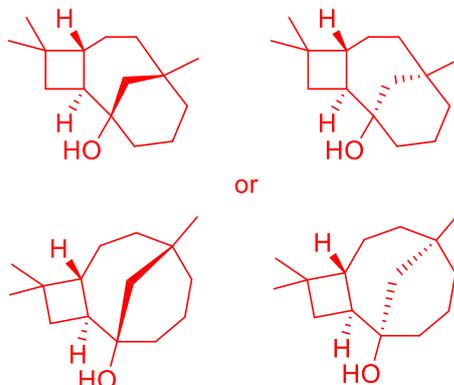
$\beta$ -Caryophyllene (**3**) undergoes acid-catalyzed cyclization, which leads to a complex mixture of products. Among them, the pair of diastereomers **Na** + **Nb** and the pair of diastereomers **7a** + **7b** are the most abundant. The reaction starts with protonation of the more reactive internal 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, including the appropriate stereochemistry, of the **three** intermediates **O**, **Pa**, **Qa** leading to the diastereomer **7a**, including the appropriate stereochemistry.



<p><b>O</b></p>  <p><b>O</b></p> <p><i>3 points for the correct structure</i>  <i>2 points if stereochemistry is missing or incomplete</i>  <i>1 point if the wrong double bond is protonated with correct regioselectivity</i>  <i>0 points if either double bond is protonated with incorrect regioselectivity</i></p>	<p><b>Pa</b></p>  <p><b>Pa</b></p> <p><i>3 points for the correct structure</i>  <i>2 points for the carbocation with incorrect regioselective ring closure</i>  <i>1 point if stereochemistry is missing or incomplete</i>  <i>2 points for structure Pb</i></p>  <p><b>Pb</b></p>
<p><b>Qa</b></p>  <p><b>Qa</b></p>  <p><b>incorrect Qa'</b></p> <p><i>3 points for the correct structure</i>  <i>2 points for the carbocation with incorrect regioselective rearrangement</i>  <i>1 point if stereochemistry is missing or incomplete</i>  <i>2 points for structure Qb</i>  <i>2 points for incorrect cation Qa'</i></p>  <p><b>Qb</b></p>	

8.8 Draw the structures of diastereomers **Na + Nb**.**Na + Nb** C<sub>15</sub>H<sub>26</sub>O

6 points if both diastereomers are given

4 points if only one diastereomer is given

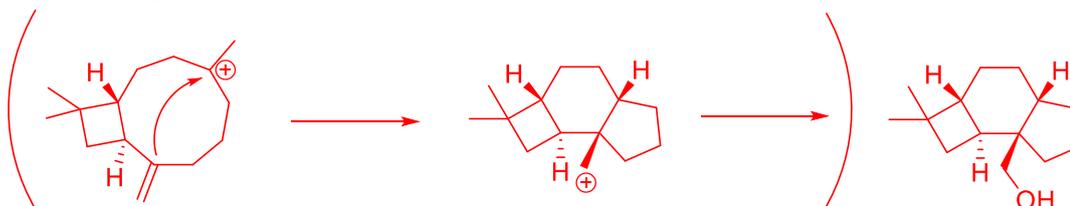
4 points if both diastereomers are given which are tricyclic compounds resulting from a regioisomeric attack on the correct carbocation (see example below)

2 points if both diastereomers are given which are tricyclic compounds resulting from an attack on incorrect carbocation (see example below)

2 points if only one diastereomer is given which is a tricyclic compound resulting from a regioisomeric attack on the correct carbocation (see example below)

1 point if only one diastereomer is given which is a tricyclic compound resulting from an attack on an incorrect carbocation (see example below)

- incorrect regioisomeric attack on the correct carbocation intermediate



- attack on the incorrect carbocation intermediate

