Dobeles novads

Grindex

Valsts izglītības satura centrs

NACIONĀLAIS ATTĪSTĪBAS PLĀNS 2020

EIROPAS SAVIENĪBA
Eiropas Sociālais fonds

atbalsts izcilībai

IEGULDĪJUMS TAVĀ NĀKOTNĒ

8.3.2.1./16/I/002

NACIONĀLA UN STARPTAUTISKA MĒROGA PASĀKUMU ĪSTENOŠANA IZGLĪTOJAMO TALANTU ATTĪSTĪBAI

BCho

29th Baltic Chemistry Olympiad
Dobele, Latvia, April 19-21, 2023

THEORETICAL EXAM

Student code:

E	S	T	

Problem	1	2	3	4	5	6
Points						

Table for grading

April 20th, 2023
Dobele, Latvia

Equations and constants:

Avogadro's constant, $N_A = 6.0221 \cdot 10^{23}$ mol^{-1}

Boltzmann constant, $k_B = 1.381 \cdot 10^{-23}$ J·K^{-1}

Universal gas constant, $R = 8.314$ J·K^{-1}·mol^{-1} = 0.08205 atm·L·K^{-1}·mol^{-1}

Speed of light, $c = 2.9979 \cdot 10^{8}$ m·s^{-1}

Planck's constant, $h = 6.626 \cdot 10^{-34}$ J·s

Elementary charge, $e = 1.602 \cdot 10^{-19}$ C

Faraday constant, $F = 96485$ C·mol^{-1}

Mass of electron, $m_e = 9.10938215 \cdot 10^{-31}$ kg

Standard pressure, $P = 1$ bar = 10^5 Pa

Atmospheric pressure, $P_{atm} = 1.01325 \cdot 10^5$ Pa = 760 mmHg = 760 torr

Zero of the Celsius scale, 273.15 K

1 picometer (pm) = 10^{-12} m; angstrom (Å) = 10^{-10} m; nanometer (nm) = 10^{-9} m

1 eV = $1.6 \cdot 10^{-19}$ J

1 amu = $1.66053904 \cdot 10^{-27}$ kg

Ideal gas equation: $PV = nRT = Nk_BT$

Enthalpy: $H = U - PV$

Gibbs free energy: $G = H - TS$ $\quad \Delta G = \Delta G^o + RT \ln Q$

$\Delta G^\circ = -RT \ln K = -nFE^\circ_{cell}$

Entropy change: $\Delta S = \frac{q_{rev}}{T}$, where q_{rev} is heat for the reversible process

$\Delta S = nR \ln \frac{V_2}{V_1}$ (for isothermal expansion of an ideal gas)

Nernst equation: $E = E^o + \frac{RT}{nF} \ln \frac{C_{ox}}{C_{red}}$

Energy of a photon: $E = \frac{hc}{\lambda}$ $\quad$ Lambert–Beer law: $A = \log \frac{I_0}{I} = \varepsilon l c$

Integrated rate law

Zero order $[A] = [A]_0 - kt$ $\quad$ First order $\ln[A] = \ln[A]_0 - kt$

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

Arrhenius equation $k = Ae^{-E_a/RT}$

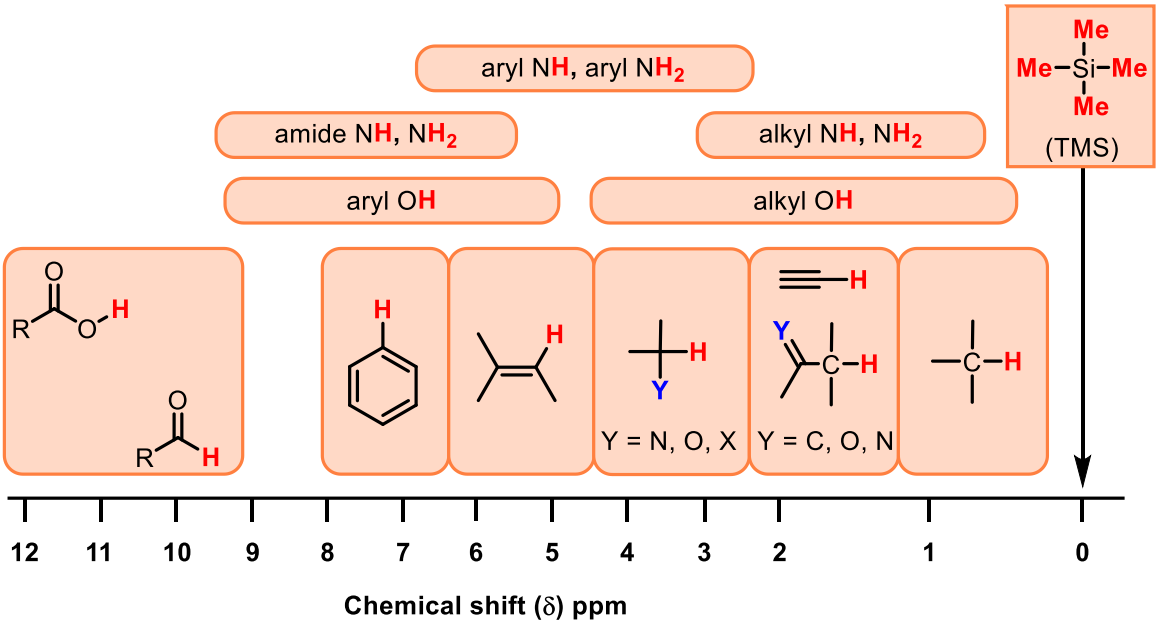
Electric current $I = \frac{Q}{t}$

Periodic table:

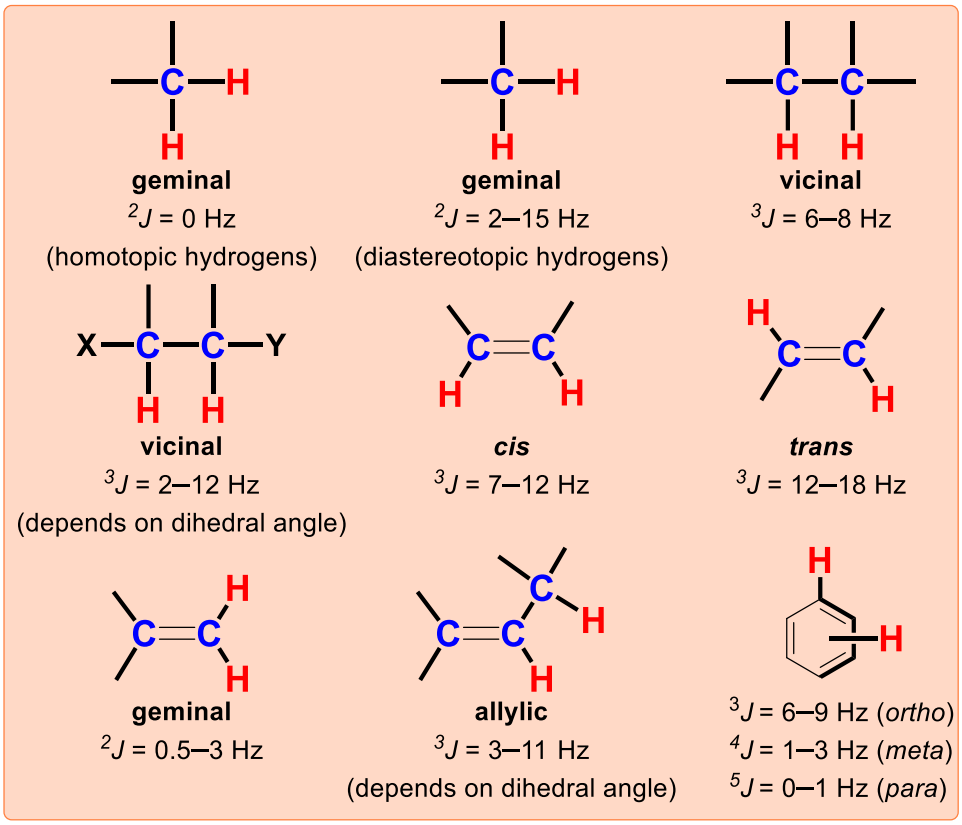
1 1.008 **H**																	2 4.003 **He**
3 6.94 **Li**	4 9.01 **Be**					Atomic number 1 1.008 **H** Atomic weight **Atomic symbol**						5 10.81 **B**	6 12.01 **C**	7 14.01 **N**	8 16.00 **O**	9 19.00 **F**	10 20.18 **Ne**
11 22.99 **Na**	12 24.31 **Mg**											13 26.98 **Al**	14 28.09 **Si**	15 30.97 **P**	16 32.06 **S**	17 35.45 **Cl**	18 39.95 **Ar**
19 39.10 **K**	20 40.08 **Ca**	21 44.96 **Sc**	22 47.87 **Ti**	23 50.94 **V**	24 52.00 **Cr**	25 54.94 **Mn**	26 55.85 **Fe**	27 58.93 **Co**	28 58.69 **Ni**	29 63.55 **Cu**	30 65.38 **Zn**	31 69.72 **Ga**	32 72.61 **Ge**	33 74.92 **As**	34 78.97 **Se**	35 79.90 **Br**	36 83.80 **Kr**
37 85.47 **Rb**	38 87.62 **Sr**	39 88.91 **Y**	40 91.22 **Zr**	41 92.91 **Nb**	42 95.95 **Mo**	43 (98) **Tc**	44 101.07 **Ru**	45 102.91 **Rh**	46 106.42 **Pd**	47 107.87 **Ag**	48 112.41 **Cd**	49 114.82 **In**	50 118.71 **Sn**	51 121.76 **Sb**	52 127.60 **Te**	53 126.90 **I**	54 131.29 **Xe**
55 132.91 **Cs**	56 137.33 **Ba**	57-71 **La–Lu**	72 178.49 **Hf**	73 180.95 **Ta**	74 183.84 **W**	75 186.21 **Re**	76 190.23 **Os**	77 192.22 **Ir**	78 195.08 **Pt**	79 196.97 **Au**	80 200.59 **Hg**	81 204.38 **Tl**	82 207.2 **Pb**	83 208.98 **Bi**	84 (209) **Po**	85 (210) **At**	86 (212) **Rn**
87 (223) **Fr**	88 (226) **Ra**	89-103 **Ac–Lr**	104 (267) **Rf**	105 (268) **Db**	106 (269) **Sg**	107 (270) **Bh**	108 (270) **Hs**	109 (278) **Mt**	110 (281) **Ds**	111 (282) **Rg**	112 (285) **Cn**	113 (286) **Nh**	114 (289) **Fl**	115 (290) **Mc**	116 (293) **Lv**	117 (294) **Ts**	118 (294) **Og**

57 138.91 **La**	58 140.12 **Ce**	59 140.91 **Pr**	60 144.24 **Nd**	61 (145) **Pm**	62 150.36 **Sm**	63 151.96 **Eu**	64 157.25 **Gd**	65 158.93 **Tb**	66 162.50 **Dy**	67 164.93 **Ho**	68 167.26 **Er**	69 168.93 **Tm**	70 173.05 **Yb**	71 174.97 **Lu**
89 (227) **Ac**	90 232.04 **Th**	91 231.04 **Pa**	92 238.03 **U**	93 (237) **Np**	94 (244) **Pu**	95 (243) **Am**	96 (247) **Cm**	97 (247) **Bk**	98 (251) **Cf**	99 (252) **Es**	100 (257) **Fm**	101 (258) **Md**	102 (259) **No**	103 (266) **Lr**

^{1}H NMR Chemical Shifts



Typical Coupling Constants



General instructions:

- You can start writing when the command Start has been given.
- You have 5 hours to complete the theoretical exam.
- The theoretical exam consists of 6 problems.
- You can use separate sheets or the other sides of the theoretical exam booklet for draft and calculation purposes.
- Show the calculation steps, even if they are not explicitly emphasized in task conditions.
- It is strictly forbidden to communicate between students during the exam.
- Raise your hand if you require to go to the bathroom.
- Write your student code on each page.
- The official English version of the exam is available on request for clarification.

Good luck!

Problem No.1 – Determination of protein content by Kjeldahl method (10% of total)

Problem No.1 (10%)	Question	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	1.10	Sum
	Points	4	2	4	2	2	6	10	7	3	4	44
	Result											

The Kjeldahl method was developed in 1883 by the Danish chemist Johan Kjeldahl. It was designed to determine the nitrogen content in organic compounds. Although 140 years have passed, this method is still used to determine protein content in food. The method consists of three stages: digestion, distillation, titration, and calculations.

I. Digestion stage

At the digestion stage, nitrogen in a sample is converted into ammonium ions. Digestion is achieved by adding excess concentrated sulfuric acid to the sample and boiling the mixture for a few hours.

*1.1. **Write** the balanced equation for the reaction between heated concentrated sulfuric acid and: a) C, b) S.*

a)
b)

*1.2. Will boiling concentrated sulfuric acid convert nitrate ions into ammonium ions? **Circle** the correct answer.*

Yes / No

Concentrated sulfuric acid is a 98% H_2SO_4 solution. Interestingly, pure, anhydrous sulfuric acid contains not only H_2SO_4 molecules. As the equilibrium is reached, HSO_4^-; $HS_2O_7^-$; $H_2S_2O_7$; H_3O^+; $H_3SO_4^+$ are also found.

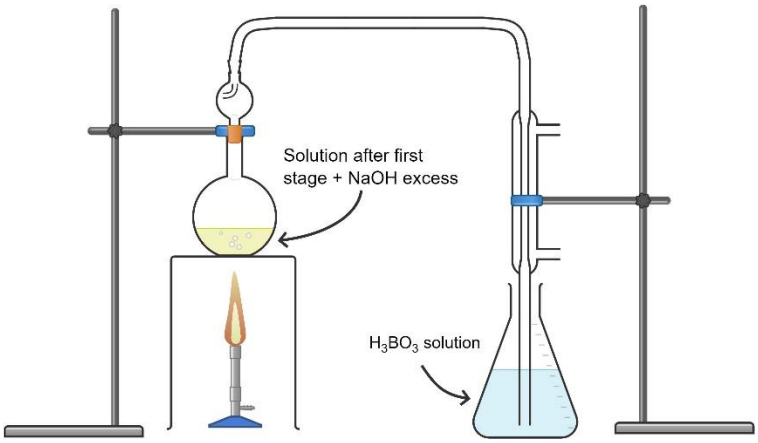
*1.3. **Fill in** the table by entering formulas.*

Compound	Quantity (mmol) in 1 kg pure H_2SO_4
	14.9
	11.3
H_3O^+	8.0
$HS_2O_7^-$	4.4
	3.6

*1.4. **Tick** the correct answer.*

☐ The addition of NaCl and/or Na_2SO_4 will increase the boiling point of H_2SO_4. There is little to no difference if NaCl or Na_2SO_4 is used.
☐ The addition of NaCl will increase the boiling point of H_2SO_4. For faster digestion it is significantly better to add NaCl than Na_2SO_4.
☐ The addition of Na_2SO_4 will increase the boiling point of H_2SO_4. For faster digestion it is significantly better to add Na_2SO_4 than NaCl.
☐ The addition of NaCl and/or Na_2SO_4 will reduce the boiling point of H_2SO_4.
☐ The addition of NaCl and/or Na_2SO_4 will reduce the boiling point of H_2SO_4, however, salt will act as a catalyst.

II. Distillation stage



At the distillation stage, the solution from the digestion stage with formed $(NH_4)_2SO_4$, is exposed to an excess of NaOH solution. Ammonium ions react with hydroxide ions:

$NH_4^+ + OH^- \rightleftarrows NH_3 + H_2O$. (1)

*1.5. Is the solution after the first stage mixed with NaOH excess is a buffer solution? **Circle** the correct answer.*

Yes / No

*1.6. **Calculate** the equilibrium constant for (1) reaction, knowing that the pH of the 0.50 mol/L $(NH_4)_2SO_4$ solution is 4.63.*

Answer = _____

Generated ammonia reacts with boric acid excess. Boric acid is very convenient to use since there is no need to know its exact concentration. After the reaction, the solution can be titrated with a strong acid. In solution, boric acid is ionized by water:

$H_3BO_3 + H_2O \rightleftarrows [H_2BO_3]^- + H_3O^+$ $pK_{a1} = 9.24$ ($pK_{a1} >> pK_{a2}$; pK_{a3}). However, studies have shown that boric acid solution contains $[H_4BO_4]^-$ ions due to the reaction below:

$H_3BO_3 + 2H_2O \rightleftarrows [H_4BO_4]^- + H_3O^+$, reaction pK = 9.14.

1.7. Assume that both reactions occur in the boric acid solution. ***Calculate*** *0.10 mol/L H_3BO_3 pH.*

Answer = _____

1.8. ***Draw*** H_3O^+, H_3BO_3 *and* $[H_4BO_4]^-$ *Lewis structures, including formal charges. Determine central atom geometry (by VSEPR) and* ***write*** *it in the table.*

	H_3O^+	H_3BO_3	$[H_4BO_4]^-$
Lewis structure			
Geometry **(IN CAPITAL LETTERS)**			

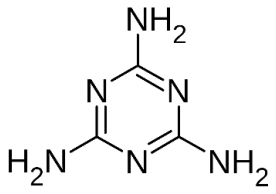
III. Titration and calculations stage

After titration is performed, amount of nitrogen in sample is calculated. To calculate amount of protein, amount of nitrogen is multiplied by specific factor. This factor for milk, rice and meat is 6.38, 5.95 and 6.25, respectively.

1.9. After testing 10.0 g of rice, 19.50 ml of the 1.00 mol/L HCl solution was used to titrate the final solution. ***Calculate*** *how much grams of protein is in the rice sample.*

Answer = _____

Knowing that the protein content is determined by the Kjeldahl method, the Chinese company "Sanlu Group" added melamine to their production for babies. The aim was to increase the amount of protein to be determined. This led to the deaths of 6 children. After investigation, imprisonments and death penalties were assigned for responsible people.



structure of melamine

1.10. Consider that all nitrogen atoms in melamine are converted to ammonium ions. ***Calculate*** *how much grams of protein 1.00 grams of melamine imitates in milk, analyzed by Kjeldahl method.*

Answer = _____

Problem No.2 – Current and future applications of the 7th group elements (10% of total)

Problem No.2 (10%)	Question	2.1	2.2	2.3	2.4	2.5	Sum
	Points	13	17	7	8	5	50
	Result						

Part I. Manganese –coryphaeus among battery materials

Manganese is predominantly used in making alloys and batteries. Interestingly, manganese compounds were used in one of the first rechargeable batteries (Leclanché cell) and are still considered promising materials for future batteries. Fill in the table to show that novel aqueous Mn-ion battery to compare it to metal-ion and lead-acid batteries from the following considerations. In the case of metal-ion batteries, neglect the electrolytes, respectively; in the case of Pb-acid, account for 35wt% H_2SO_4 aqueous electrolyte.

*2.1. **Calculate** the theoretical energy density of the batteries (electrodes and, in the case of Pb-acid battery, also the electrolyte). **Assign** letters (A–F) denoting advantages and disadvantages (pros & cons) to the corresponding batteries.*

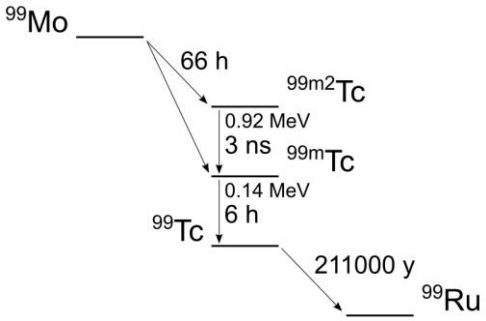
A: Electrolyte instability and high cost, low abundance of elements used.
B: Good overall safety, low electrode & electrolyte cost, high abundance of elements used.
C: Robustness, low electrode and electrolyte cost, and wide temperature range.
D: High energy density and good overall performance.
E: Low energy density and environmental issues.
F: Low voltage and moderate energy density.
X: Good safety, high abundance of Mg.
Y: Electrolyte instability and high cost, low energy density and voltage.

Battery	Reaction	EMF (V)	Theoretical energy density (Wh kg^{-1})	Pros & cons
Li-ion battery	$LiC_6 + FePO_4 \rightleftharpoons LiFePO_4 + 6C$	3.3		
Pb-acid battery	$Pb + PbO_2 + 2H_2SO_4 \rightleftharpoons 2PbSO_4 + 2H_2O$	2.1		
Mn-ion	$Mn_{0.2}V_2O_5{\cdot}H_2O + 0.8Mn \rightleftharpoons MnV_2O_5{\cdot}H_2O$	1.3		
Mg-ion	$2Mg + Mo_6S_8 \rightleftharpoons Mg_2Mo_6S_8$	1.1	134	X, Y

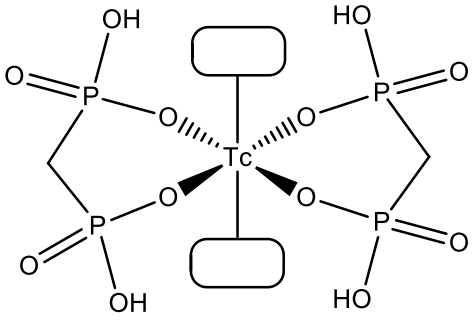
Part II. Technetium – the lightest of unstable elements

*2.2. **Fill in** the blanks in the text and **add** missing groups (O, OH, H_2O) to the structures below.*

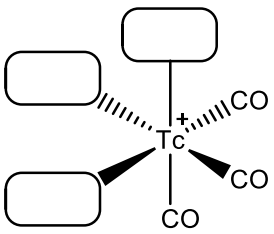
^{99m}Tc is one of the most frequently used isotopes in medicinal nuclear imaging. It is prepared in technetium-99m generators as a decay product of 99Mo, obtained in a nuclear reactor in the fission of uranium-235: $^{235}U + {}^{1}n \rightarrow$ _____ + $^{99}Mo + {}^{3}n$. Obtained ^{99}Mo undergoes _____ decay into meta-stable isomers ^{99m}Tc and ^{99m2}Tc according to the generic decay diagram (with half-lifes and energy levels).



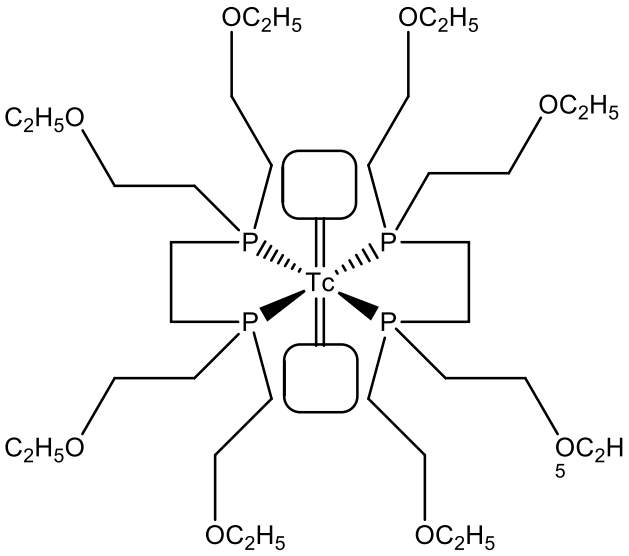
^{99m}Tc undergoes _____ decay of _____ keV comparable to 20–150 keV X-ray range used in conventional radiography. Differently from the latter, detecting the ^{99m}Tc radiation from within the patient's body in a gamma camera gives _____-dimensional images of tissues and organs. The imaging is taken before half of ^{99m}Tc decayed, i.e., within _____ hours after administrating the radiopharmaceutical. ^{99m}Tc radioactivity reduces to 1% of the initial activity in _____ hours. The radioactivity of ^{99}Tc is _____% of the initial activity of ^{99m}Tc. In most ^{99m}Tc radiopharmaceuticals, ^{99m}Tc (eluted from a technetium-99m generator) is turned into a coordination compound with specific biochemical properties: _____ attaches to hydroxyapatite and is used to scan bones, _____ penetrates lipid membranes and is used to scan the heart, _____ crosses the blood–brain barrier and is used to scan the brain.



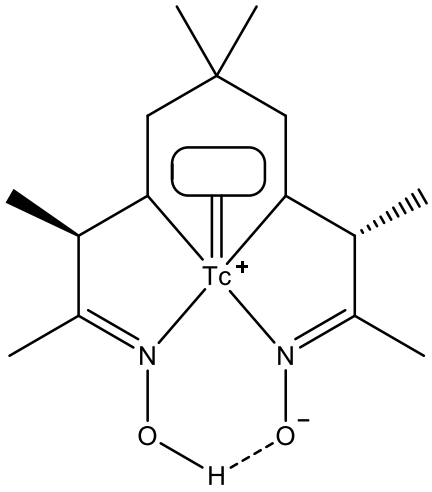
diphosphonate



carbonyl



tetrofosmin



exametazime

With more targeted imaging and therapy, the future applications of ^{99m}Tc for labeling biomolecules will likely be diverse and far-reaching. Technetium _____ is an essential precursor to specific coordination compounds; it contains two types of ligands – one is a good leaving group, and the other one is strongly bound to technetium.

Part III. Rhenium – an element of supermaterials

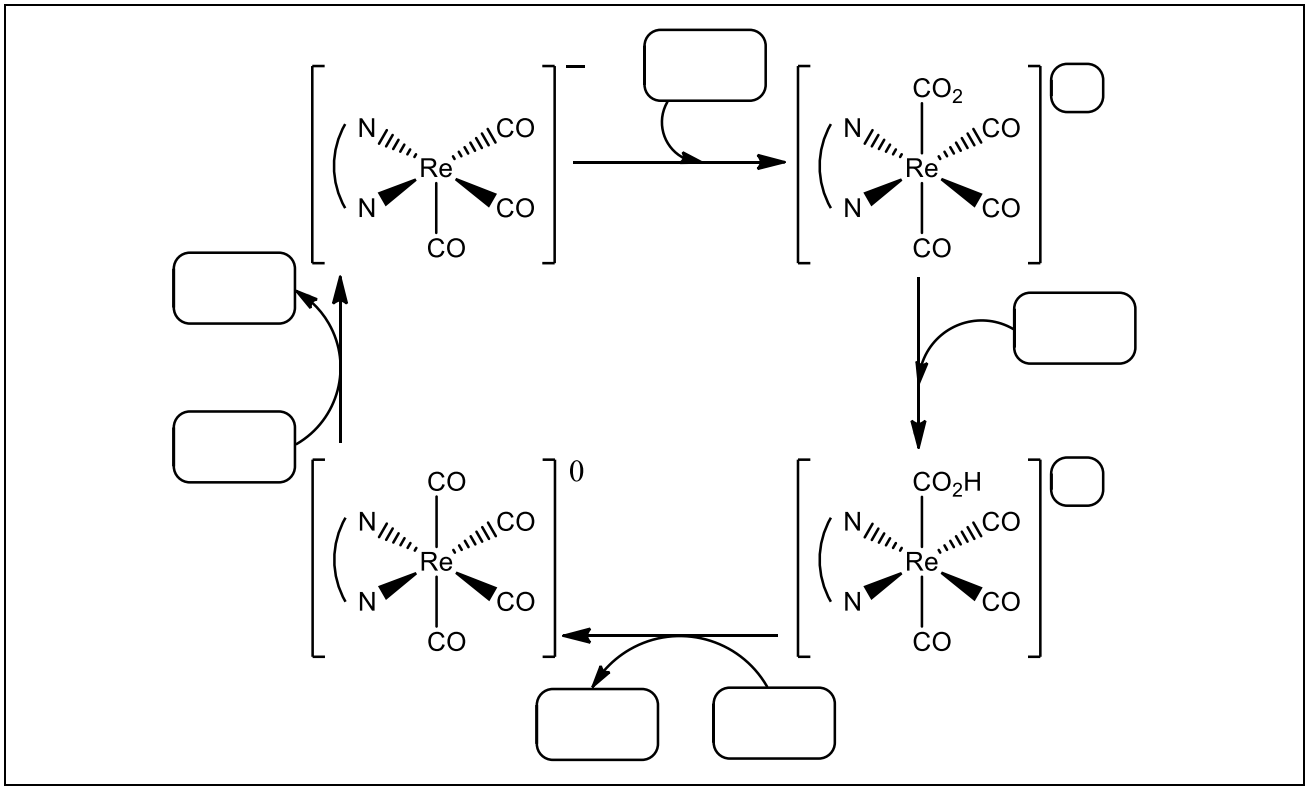
Rhenium is used in superalloys and catalysts. Rhenium chlorides are precursors for making catalytic coordination compounds. In reaction with chlorine, rhenium forms solid compound **A** (w_{Cl} = 48.77%), which thermally decomposes into molecular chloride **B** (w_{Cl} = 36.35%) and chlorine. Chloride **A** is also formed in the decomposition of molecular chloride **C**, which is unstable at room temperature. The coordination number of Re (including Re–Re bonds) is the same in molecules of **A** $[Cl_aRe(\mu\text{-}Cl)]_2$, **B** $[Cl_bRe(\mu\text{–}Cl)]_3$, and **C**, where μ denotes that chloride is bridging two rhenium atoms (Re–Cl–Re).

*2.3. **Draw** structures of the **A**–**C** molecules.*

A	**B**	**C**

Rhenium possible applications in catalysis include reduction of CO_2 to CO.

*2.4. **Fill in** in the blanks (charges, reagents, and products) in the catalytic cycle illustrating the electrochemical reduction mechanism (with H^+ and e^-).*



Part IV. Bohrium – probably the most boring element in the Universe

Bohrium belongs to the family of superheavy elements, which could act as powerful nuclear fuel, for example, for future fission-propelled space missions. Isotopes with the "magic" number of protons (114) or neutrons (184) could theoretically have half-lives large enough to be used in nuclear reactors. The half-life of synthesized isotopes (2.9 s for ^{271}Bh, 8.8 s for ^{272}Bh, and 54 s for ^{274}Bh) shows a trend for stabilization ($\log T_{1/2} = aA^{1/6} + b$) towards the **"**island of stability**"** near the double-magic ^{298}Fl.

1.5. ***Estimate*** *the half-life (in years) of the most stable isotope of Bh.* ***Make*** *a prediction on whether bohrium would find any application in the future.*

Half-life:
Prediction:

Problem No.3 – Simple Surface Chemistry (8% of total)

Problem No.3 (8%)	Question	3.1	3.2	3.3	3.4	3.5	Sum
	Points	5	4	4	3	2	18
	Result						

The surface coverage ($\theta = \frac{N_{occ}}{N_{max}}$, where N_{occ} is the number of occupied sites and N_{max} is the maximum number of adsorption sites) dependence on pressure is described by adsorption isotherms. The most used adsorption isotherm is the Langmuir adsorption isotherm. To derive the Langmuir isotherm, we consider the following rates for adsorption and desorption:

$$r_{ad} = k_{ad} p\ 1 - \theta^{\ n}$$

$$r_{des} = k_{des}\theta^{n}$$

*3.1. Assuming steady state **show** that the surface coverage **θ** dependence on pressure **p** and adsorption/desorption rate constant ratio ($\alpha = \frac{k_{ad}}{k_{des}}$) takes the form $\theta = \frac{\alpha p^{\ 1/n}}{1+ \alpha p^{\ 1/n}}$.*

Further, we will consider a special case – the non-dissociative adsorption – in which first-order rate law is observed for adsorption and desorption (n = 1).

In this case, adsorption isotherm is

$$\theta = \frac{\alpha p}{1 + \alpha p}.$$

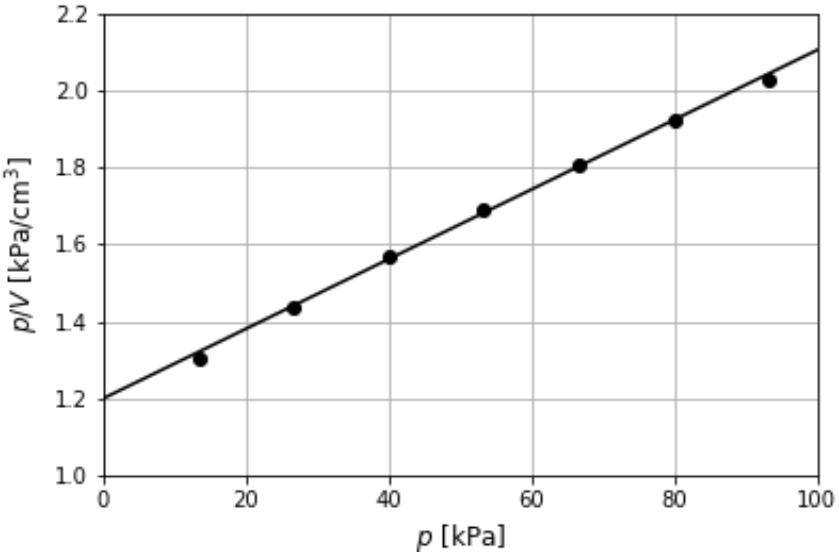
However, in experiments, we cannot measure occupied sites directly. Instead, we consider the volume of gas adsorbed V versus the volume of gas adsorbed at full coverage $V_{max,}$ and therefore, the resulting isotherm in terms of volumes is

$$\theta = \frac{V}{V_{max}} = \frac{\alpha p}{1 + \alpha p}.$$

With simple algebra, we can linearise the equation to yield that

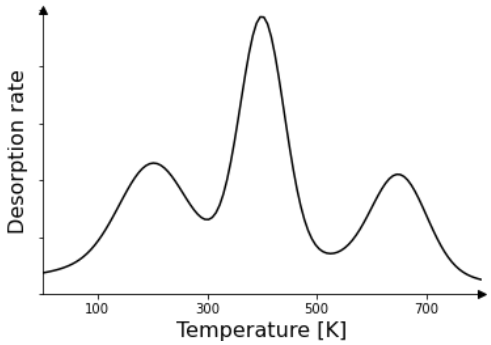
$$\frac{p}{V} = \frac{1}{\alpha V_{max}} + \frac{1}{V_{max}} \mathrm{p}.$$

The following plot was obtained in an experiment of CO adsorption on charcoal at 273 K. Solid dots show experimental data points, and the solid line shows best-fit line.



3.2. Using the plot, ***determine*** α *and* V_{max}*.*

A useful method to study the kinetics of desorption and determine the desorption activation energy is *thermal desorption spectroscopy* (TDS). In this method, a sample is heated with a linear change in temperature, and the desorption rate is observed. At the temperature where rapid desorption starts, a peak in rate is observed, but after the sample is heated further, the rate decreases due to a lack of adsorbed species. Schematic representation of spectra observed in the studies is shown in figure –



multiple peaks represent multiple adsorption sites with their respective desorption activation energies.

To extract desorption activation energy E_d, we start from the desorption rate equation and consider that the desorption rate constant follows Arrhenius law, where v is the preexponential factor,

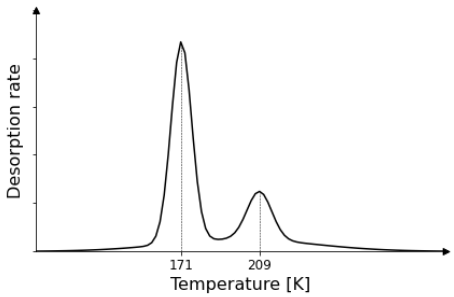
$$-\frac{d\theta}{dt} = k_{des}\theta = v\theta\exp\left(-\frac{E_d}{k_B T}\right).$$

Considering that the temperature change during the experiment is $T = T_0 + \beta t$, where β is the heating rate, and integrating the rate law, one obtains the relation, where T_{max} is the temperature at the top of the peak.

$$\frac{E_d}{k_B T_{max}^2} = \frac{v}{\beta}\exp\left(-\frac{E_d}{k_B T}\right).$$

3.3. ***Show*** *that the expression can be rewritten as* $E_d = k_B T_{max}\left(\ln\left(vT_{max}/\beta\right) - 3.64\right)$. *Hint: the quantity* $\ln\left(E_d/k_B T_{max}\right) \approx 3.64$.

TDS experiment was performed to investigate the desorption of ethylbenzene on pyrolytic graphite. Two peaks in the spectra were observed, one at 171 K and one at 209 K. Peak at 209 K corresponds to desorption from the adsorption layer directly on the surface, while the peak at 171 K corresponds to desorption from further layers.



*3.4. **Calculate** the desorption activation energies (expressed in kJ mol^{-1}) for ethylbenzene desorption from pyrolytic graphite. Assume heating rate β = 1 K s^{-1}, preexponential factor $v = 10^{12}$ s^{-1}.*

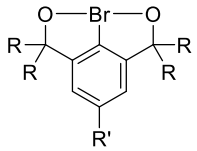
Hint: the formula from 3.3 provided results in desorption activation energy per atom.

One of the method's shortcomings is that it relies on a good guess of the preexponential factor.

*3.5. **Calculate** the error in the predicted desorption activation energy for desorption at 209 K if the actual preexponential factor is 1000 times larger.*

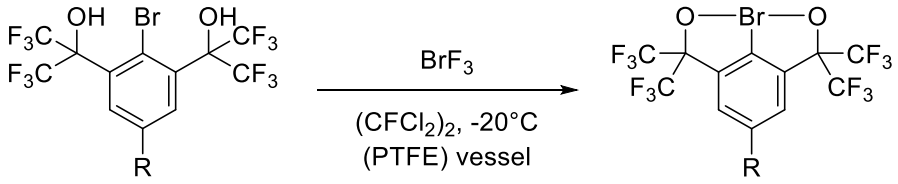
Problem No.4 – Bromine goes hyper mode (10% of total)

Problem No.4 (10%)	Question	4.1	4.2	4.3	4.4	4.5	4.6	4.7	4.8	Sum
	Points	2	12	6	2	13	9	9	11	64
	Result									



Bromine (III) reagents are fascinating compounds in the realm of organic chemistry due to their unique attributes. While their stability and high oxidizing power can make them difficult to handle, they have also served as tools for innovative synthetic conversions. In this problem, you will explore the synthesis of some hypervalent bromine (III) reagents (such as the one on the right), some of which have been investigated at the Latvian Institute of Organic Synthesis (LIOS).

Traditionally compounds like **2** have been synthesized from BrF_3 and an aryl bromide **1** according to the following scheme:



1 **2**

4.1. Preparation of BrF_3 through a chemical process is difficult since it involves using two dangerous compounds, Br_2 and F_2, which require special safety measures. Additionally, the reaction produces two other substances that need to be separated using fractional distillation, which adds to the complexity of the process. ***Write*** *the formulas for the two side products.*

Another complication arises from the fact that BrF_3 is highly reactive and can react not only with water (forming two acids and oxygen), but also with other common solvents like acetonitrile CH_3CN (yielding a fluoroalkane and 2 elementary substances) and even glass (yielding two gases and a brown liquid) at room temperature.

4.2. ***Write*** *balanced equations of the reactions of BrF_3 with a) water; b) acetonitrile; c) silicon dioxide.*

a)

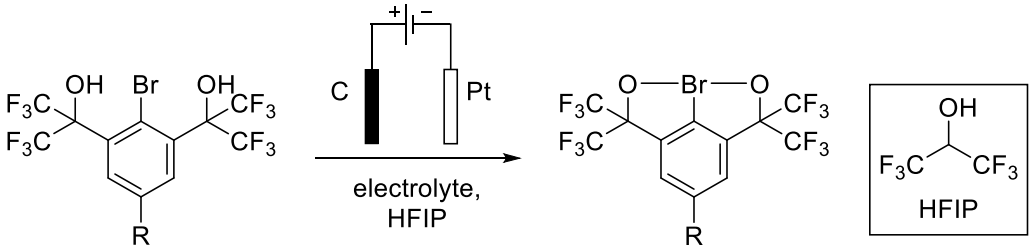
b)

c)

4.3. Another complication arises from BrF_3's ability to homolyse into radicals and promote unwanted side reactions. ***Provide*** *a radical mechanism (should consist of three separate radical reactions) of potential fluorination of a generic alkane RCH_3. Note – any other trivalent bromine compounds are highly unlikely to form!*

4.4. ***Provide*** *two more side products that might form from different termination steps.*

A novel method of synthesizing compound **2** has been developed at LIOS, which involves the oxidation of **1** in an undivided electrochemical cell:



1 **2**

4.5. Since the reaction is happening in an undivided cell, there should be a counter-reaction occurring on the opposite electrode. ***Give*** *a balanced half-reaction equation.* ***Circle*** *the correct answers in the text. Hint: Balancing the oxidation half-reaction equation might help.*

The reaction is occurring on the **(a)** electrode and it is the **(b)**.

a) carbon / platinum b) anode / cathode

In the reaction **1** → **2**, the bromine's hybridisation changes from **(c)** to **(d)**, while it's geometry (according to VSEPR) changes from **(e)** to **(f)** with the angle O-Br-C in compound **2** being close to **(g)**.

c) sp / sp^2 / sp^3 / sp^3d / sp^3d^2 / sp^3d^3

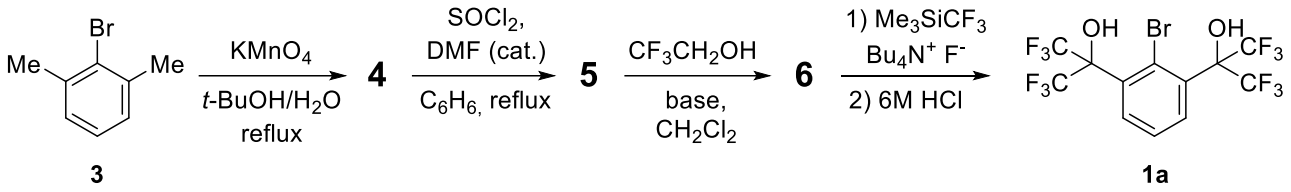
d) sp / sp^2 / sp^3 / sp^3d / sp^3d^2 / sp^3d^3

e) linear / bent / T-shaped / tetrahedral / octahedral / trigonal bipyramidal

f) linear / bent / T-shaped / tetrahedral / octahedral / trigonal bipyramidal

g) 45° / 60° / 75° / 90° / 105° / 120°

The synthesis of compound **1a** can be implemented starting from compound **3** according to the following scheme:



3 **1a**

*4.6. **Draw** the structures of the intermediate compounds **4–6**! Note: Brutto formula of compound **6** is **$C_{12}H_7BrF_6O_4$**!*

4	**5**	**6**

The electrochemical modification is also appealing due to its non-intrusive nature to monitor the reaction's progress without external interference.

By interrupting the chemical reaction and conducting a cyclic voltammetry experiment, we can obtain a cyclic voltammogram that shows the relationship between current and the electric potential. Since the same redox event is being observed, the potential will be the same, enabling the comparison of the peak current i_p at various time points. The peak current i_p is proportional to the surface area A, and the potential sweep rate v. This relationship is represented by the Randles–Sevcik equation:

$$i_p = 2.69 \cdot 10^5 \cdot z^{\frac{3}{2}} \cdot A \cdot c \cdot D^{\frac{1}{2}} \cdot v^{\frac{1}{2}},$$

where z = number of electrons transferred; A = reactive surface area; c = concentration; D = diffusion coefficient; v = potential sweep rate

*4.7. Assume that you have acquired peak currents of the oxidation of **1** before starting the experiment ($i_{p,0}$) and at a certain time point t ($i_{p,t}$). **Derive** an equation for calculating the reaction yield at a timepoint t.*

However, the Randles–Sevcik equation only applies to reversible systems. Experimental evidence suggests that the functional group R could alter whether a particular compound for this reaction will undergo reversible oxidation, therefore, rendering this method unsuitable for monitoring reaction progress.

An alternative technique involves utilizing quantitative IR spectroscopy to monitor the formation of the Br-O bond by measuring its absorption (at a constant λ) using the Beer–Lambert equation. However, there are a few issues: 1) ambiguity regarding the molar extinction coefficient and path length, 2) background absorption, 3) a synthetic chemist's laziness in calculating intermediate values.

These challenges may be overcome by 1) obtaining absorption values of the product at a known concentration, 2) acquiring background absorption, and 3) deriving the equation for them.

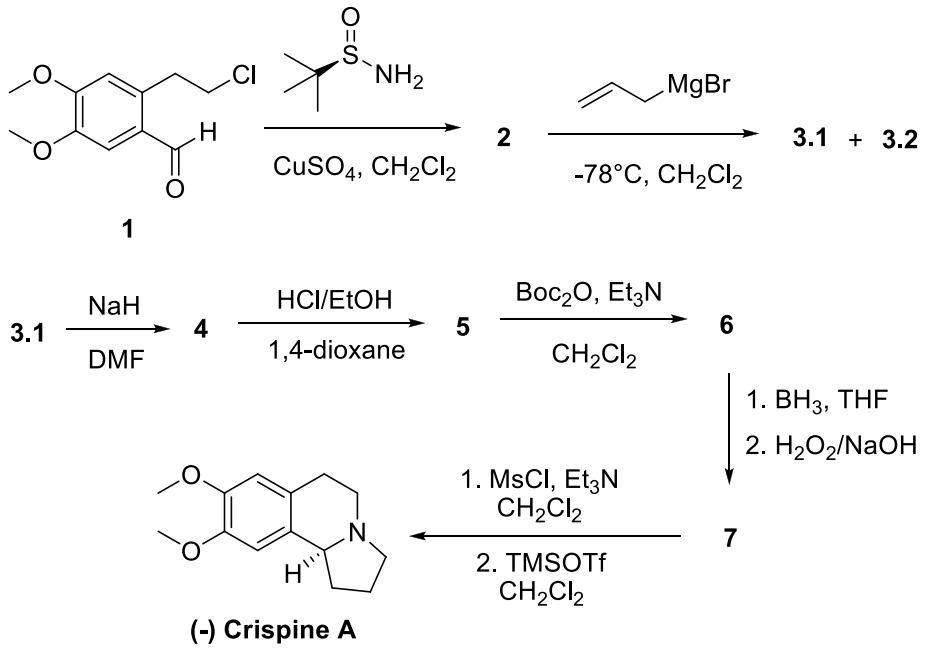
*4.8. **Derive** the equation for calculating the yield of the reaction **1** → **2** and **calculate** it for a reaction with a starting concentration of **1**, c_0 = 1 mM, where the measured absorption at a timepoint t is A_t = 0.986 AU, if the background absorption A_0 = 0.054 AU and the measured absorption of a 0.5 mM sample of **2** is A_x = 0.729 AU.*

Problem No.5 – Synthetic alkaloids (10% of total)

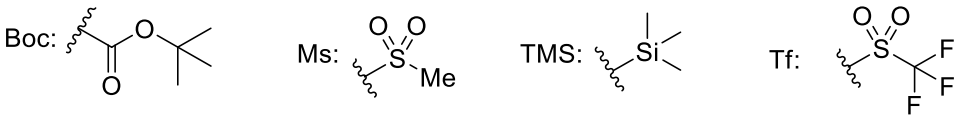
Problem No.5 (10%)	Question	5.1	5.2	5.3	5.4	5.5	5.6	5.7	5.8	5.9	5.10	5.11	Sum
	Points	12	16	2	8	4	20	12	10	8	8	4	104
	Result												

Alkaloids crispine A and crispine B have been isolated as bioactive constituents from a plant *Carduus crispus L.* which has been used for the treatment of cold, stomachache and rheumatism. Significant cytotoxic activities of these compounds on some human-cancer cells have also been reported. Crispine A and crispine B both are very similar in structure, both belong to a family of pyrroloisoquinoline alkaloids.

Synthesis of enantiopure (−) crispine A started from aldehyde **1**. Treatment of this aldehyde **1** with (R)-*tert*-butanesulfinamide in the presence of anhydrous $CuSO_4$ afforded compound **2**. Addition of allylmagnesium bromide to compound **2** at -78 ˚C in CH_2Cl_2 gave the mixture of two diastereomers **3.1** (major) and **3.2** (minor). The diastereomeric mixture was easily separated by column chromatography, and only compound **3.1** was used in further synthesis steps. Over the next several steps, compound **3.1** was finally converted to (−) crispine A, as shown in the scheme below.



DMF – dimethylformamide; THF – tetrahydrofuran



*5.1. **Provide** structures of compounds **2**, **3.1** and **3.2** with stereochemical information.*

2	**3.1**	**3.2**

*5.2. **Provide** structures of compounds **4**, **5**, **6** and **7** with stereochemical information.*

4	**5**
6	**7**

*5.3. **Give** absolute configuration of (−) crispine A stereocenter using R/S nomenclature.*

If the mixture of compounds **3.1** and **3.2** was used in the synthesis without separation, the liquid mixture of two enantiomers (−) crispine A and (+) crispine A would be finally obtained. This mixture had a specific rotation of −72.8°. Enantiopure (−) crispine A has a specific rotation of −91.0°.

Formula for enantiomeric excess calculation: *ee* = $(\omega_1 - \omega_2)/(\omega_1 + \omega_2)$
ω_1 – fraction of one enantiomer in the mixture
ω_2 – fraction of other enantiomer in the mixture

*5.4. **Calculate** enantiomeric excess of this mixture of (−) crispine A and (+) crispine A. **Calculate** the ratio of enantiomers in the mixture and clearly indicate which enantiomer is major and which is minor.*

ee = _____%

Ratio of enantiomers = _____

Major enantiomer is _____; minor enantiomer is _____;

*5.5. **Choose** correct statement(-s).*

☐ (−) enantiomer is always (R) isomer

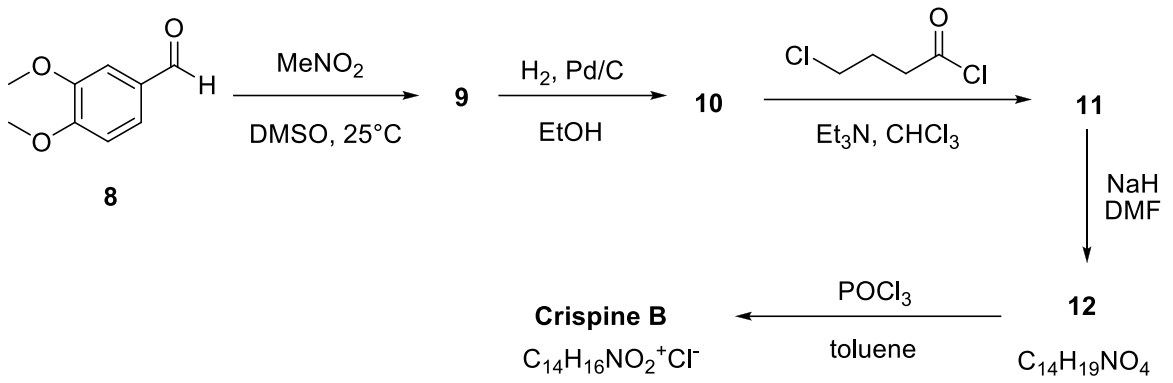
☐ (−) enantiomer is always (S) isomer

☐ (−) enantiomer always has a positive specific rotation value

☐ (−) enantiomer always has a negative specific rotation value

☐ There are no correct statements

Synthesis of crispine B started from aldehyde **8**. After several chemical transformations, crispine B was obtained. It is known that crispine B is a salt whose cation has the molecular formula $C_{14}H_{16}NO_2^+$.



DMSO – dimethyl sulfoxide

^{1}H NMR spectral data of compounds **9** and crispine B:

Compound **9** ^{1}H NMR ($CDCl_3$) δ: 2.74 (br. s., 1H), 3.88 (s, 3H), 3.90 (s, 3H), 4.50 (dd, J = 3.2, 13.2 Hz, 1H), 4.62 (dd, J = 9.6, 13.2 Hz, 1H), 5.42 (dd, J = 3.2, 9.6 Hz, 1H), 6.86-6.94 (m, 3H).

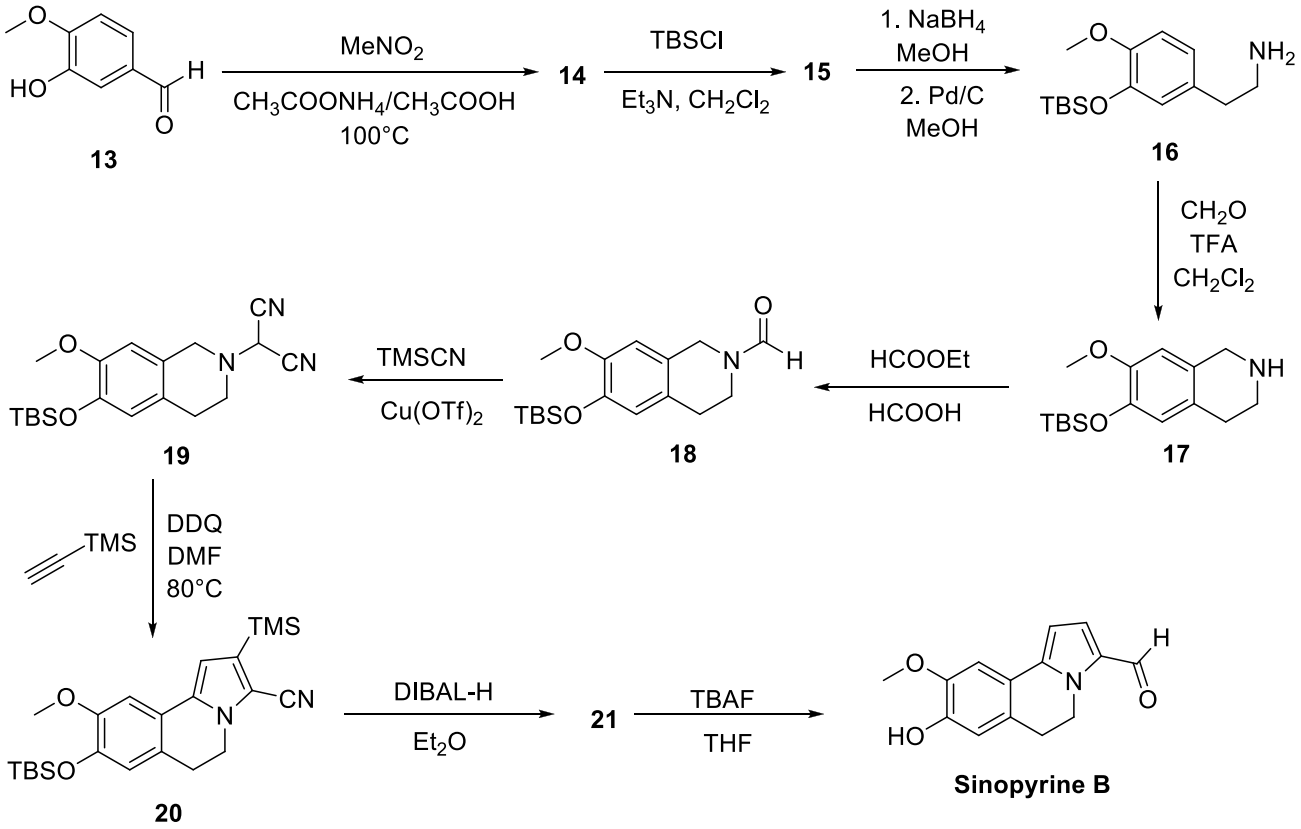
Crispine B ^{1}H NMR (deuterated MeOH) δ: 2.63 (q, 2H), 3.89 (t, 2H), 4.08 (s, 3H), 4.10 (s, 3H), 4.91 (t, 2H), 7.57 (s, 1H), 7.65 (s, 1H), 8.07 (d, J = 6.8 Hz, 1H), 8.36 (d, J = 6.8 Hz, 1H).

Meanings of abbreviations: s – singlet, br. s. – broad singlet, d – doublet, dd – doublet of doublets, t – triplet, q – quartet, m – multiplet.

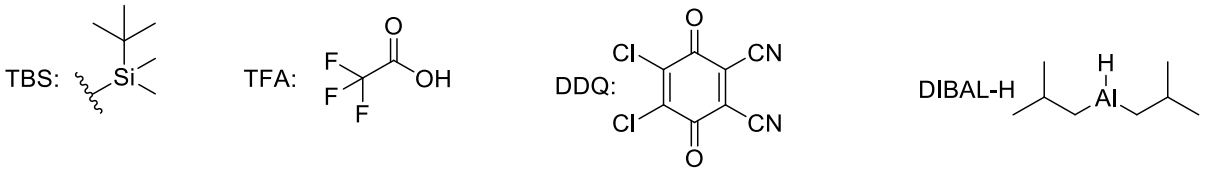
*5.6. **Provide** structures of compounds **9**, **10**, **11**, **12** and **crispine B**. Stereochemical information is not required.*

9	**10**
11	**12**
Crispine B	

Another alkaloid structurally very similar to crispine A and crispine B is sinopyrine B which is found in the plant *Sinomenium acutum*. It can be synthesized from aldehyde **13**.



TBAF – tetrabutylammonium fluoride



^{1}H NMR spectral data of compound **14**:

Compound **14** ^{1}H NMR (deuterated DMSO) δ: 3.81 (s, 3H), 6.84 (d, J = 8.2 Hz, 1H), 7.28 (d, J = 8.2 Hz, 1H), 7.46 (s, 1H), 8.01 (d, J = 13.4 Hz, 1H), 8.13 (d, J = 13.4 Hz, 1H), 10.00 (br. s., 1H).

*5.7. **Give** structures of compounds **14**, **15** and **21**.*

14	**15**	**21**

*5.8. The reaction **16** → **17** is so called Pictet-Spengler Isoquinoline Synthesis reaction. **Draw** the mechanism of **16** → **17**.*

*5.9. One of the key steps in this synthesis is a three-stage reaction **19** → **20** when pyrrole ring is formed. Everything starts with ylide formation after HCN removal. Then, a cycloaddition reaction occurs. And finally, the pyrrole ring is formed in the presence of DDQ. **Give** correct resonance structure of the most stable intermediate ylide which is formed after HCN removal and which actually participates in further reaction steps. Also, **give** the structure of the compound, which forms just after the cycloaddition reaction (before DDQ starts acting).*

Ylide:	Compound after cycloaddition:

*5.10. **Give** the name for cycloaddition reaction using two different systems by writing appropriate numbers instead of letters α, β, γ and δ. When written in parentheses (), numbers indicate amount of **atoms** in each reactant that participated in the cycloaddition reaction. When written in brackets [], numbers indicate the amount of **electrons** in each reactant that participated in cycloaddition reaction.*

(α+β) [γ+δ]

α =	γ =
β =	δ =

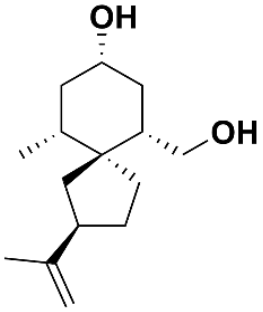
*5.11. What is the role of DDQ in this reaction? **Choose** the correct answer.*

- ☐ Oxidizing agent
- ☐ Reducing agent
- ☐ Catalyst
- ☐ Inhibitor

Problem No.6 – Toxic fungus among us (12% of total)

Problem No.6 (12%)	Question	6.1	6.2	6.3	6.4	6.5	6.6	6.7	6.8	6.9	Sum
	Points	10	5	17	2	2	2	12	2	8	70
	Result										

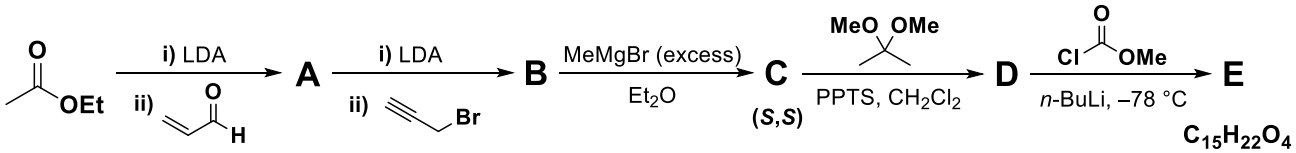
Phytoalexins are naturally occurring antimicrobial compounds produced by plants in response to pathogens at the site of infection. In this way, they serve an essential role in the general defense mechanism against plant diseases. Phytoalexins can counter the invading organism in various ways, including delaying the maturation, disrupting metabolism, breaking down cell walls, or inhibiting its reproduction.



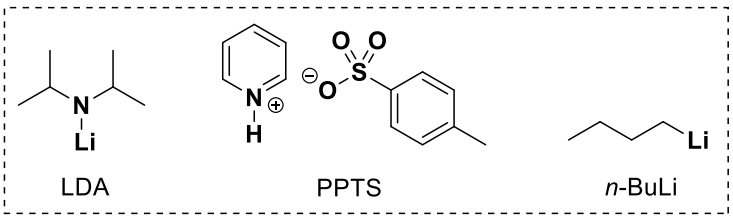
lubiminol

Lubiminol is a spirocyclic phytoalexin first isolated from potato plants infected with a particular species of fungus (*Phytophthora infestans* or *Glomeralla cingulata*). Although lubiminol has bioactive properties itself, it is an intermediate in the biosynthetic pathway of more substantial and potent antifungal agents.

In this task, you will look into the highly stereoselective total synthesis of lubiminol utilizing a radical cascade as the key step in constructing its spirocyclic core. The sequence began with a stereoselective aldol addition of ethyl acetate lithium enolate to acrolein, which gave the beta-hydroxyester **A** predominantly as its *R*-isomer. Propargylation with propargyl bromide in the presence of LDA then yielded **B**, which in turn was converted into **C** with an excess of methyl Grignard. Protection of **C** as an acetone acetal and subsequent treatment with methyl chloroformate gave compound **E**.

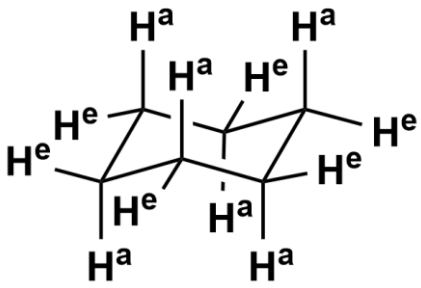


$C_{15}H_{22}O_4$



*6.1. **Draw** the structures of **A**–**E**, taking stereochemistry into account.*

A	**B**	**C**
D	**E**	*Corrections (if needed)*

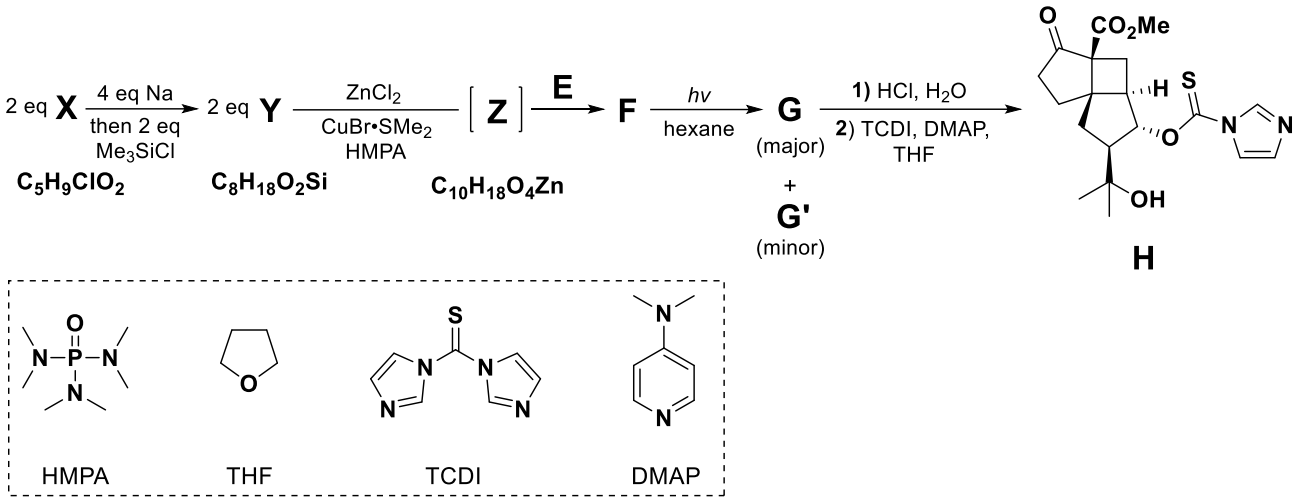


The stereoselectivity of the formation of **A** derives from the energetic differences in the two possible transition states and the outcome can be rationalized by the Zimmerman-Traxler model. By this rationale, addition of the lithium enolate proceeds via a cyclic six-membered chair-like transition state, resemblant of the chair-conformation of cyclohexane (see figure). Stereochemical outcome is ultimately determined by the spatial arrangement of the electrophile in the transition state. The lowest energy transition state is such where the electrophile's bulkiest substituent is positioned equatorially and the smallest substituent is positioned axially. In the figure, axial protons of C_6H_{12} are denoted as H^a and equatorial protons as H^e.

*6.2. **Account for** the stereochemistry of **A** by applying the Zimmerman–Traxler model. Denote bonds which are being formed or broken with a dashed line (- - -).*

Scheme depicting the lowest energy transition state:
Explanation / conclusion from the drawn transition state:

Next, compound **E** was converted into enone **F** via a formal (3+2) cycloaddition. For this purpose, a zinc homoenolate **Z** was generated *in situ* from 2 equivalents of **Y** and 1 equivalent of $ZnCl_2$. Note that 1 equivalent of **Z** can react with up to 2 equivalents of **E**. Compound **Y** can be formed by treating **X** with sodium and trapping the resulting alkoxide with trimethylsilyl chloride. It is known that **Y** is cyclic, whereas **X** and **Z** are not. Irradiation of **F** with UV light yielded **G** and **G'** as the major and minor products, respectively. Upon deprotection and carbamothioate formation, compound **H** was obtained.



*6.3. **Draw** the structures of **X**, **Y**, **Z**, **F**, **G** and **G'**, taking stereochemistry into account.*

X	**Y**	**Z**
F	**G**	**G'**

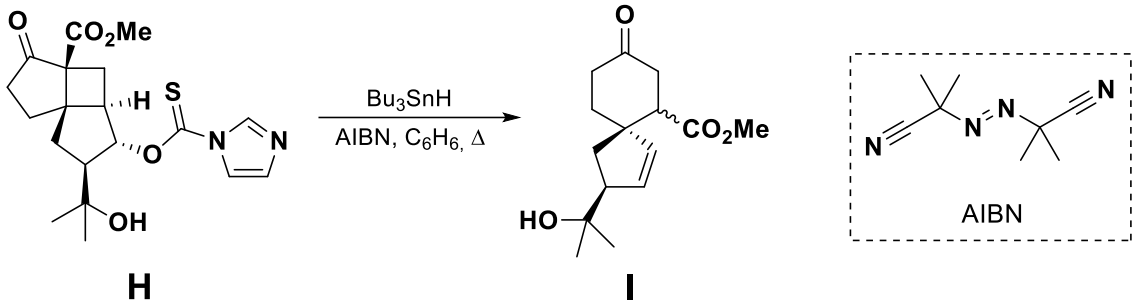
*6.4. **Circle** the correct classification for the pericyclic reaction **F→G**.*

electrocyclisation / cycloaddition / sigmatropic rearrangement / cycloreversion / cheletropic reaction / ene reaction / the correct answer is not listed

*6.5. **Circle** the correct answer. Based on Woodward-Hoffman rules, reaction **F→G** is*:

conrotatory / disrotatory / neither conrotatory nor disrotatory

Compound **H** paved the way to the key step: a radical cascade which gave access to spirocycle **I**. The first step of the cascade is a well-known name reaction.



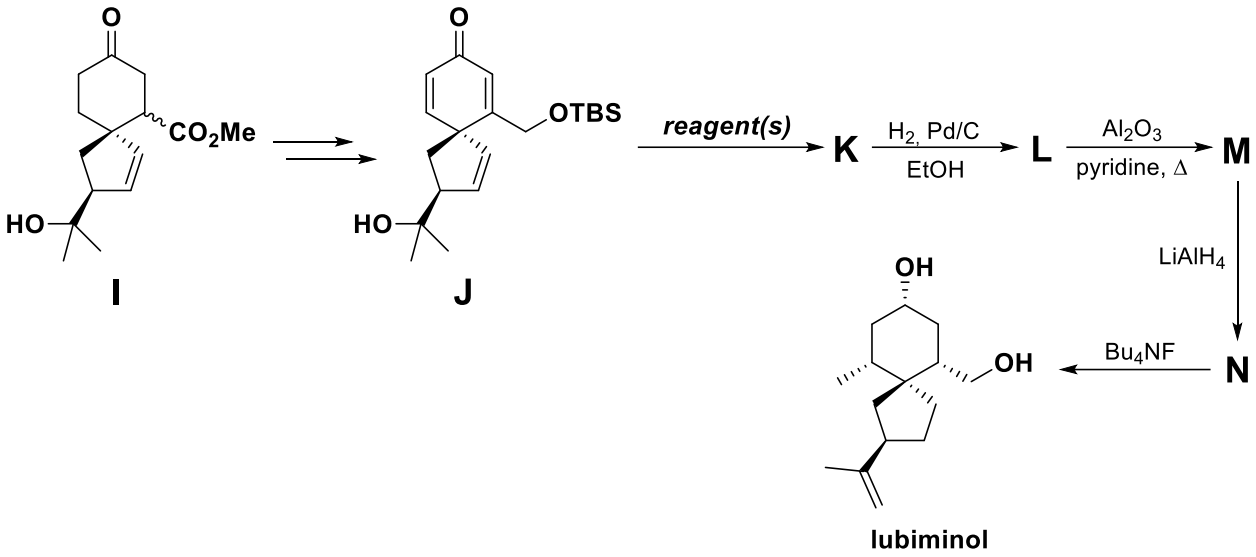
H **I**

*6.6. **Tick** the correct answer. The first step of the radical cascade is called a:*

- ☐ Barton–McCombie reaction
- ☐ Mitsunobu reaction
- ☐ Wolff–Kishner reduction
- ☐ Julia olefination
- ☐ Corey–Fuchs reaction

*6.7. **Sketch** the mechanism of the reaction **H→I** using curly fish-hook arrows to indicate the flow of electrons. Clearly **indicate** any by-products that are formed in the process.*

From compound **I**, precursor **J** was prepared over 7 steps. Subjecting **J** to **conditions** gave compound **K** stereoselectively. That was hydrogenated to give compound **L**, in which all carbon-carbon bonds are saturated. From there, only two trivial steps remained to complete the synthesis.



*6.8. **Select** the appropriate **reagent(s)** for converting **J** into **K**. There is only one correct answer.*

- ☐ i-Pr_2NLi, MeI
- ☐ MeMgBr
- ☐ $(Me_3O)BF_4$
- ☐ Me_2CuLi
- ☐ Me_3SI, NaH

*6.9. **Draw** the structures of **K**-**N**, taking stereochemistry into account.*

K	**L**
M	**N**