

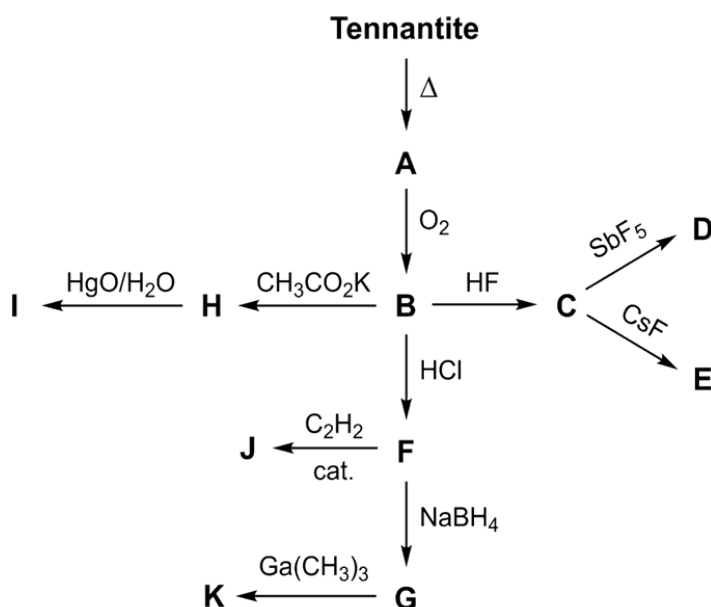
28th BChO, 2022, Vilnius, Lithuania

Problem 1 – ABC, SPECTRA, STRUCT – Some chemistry of element X

Element **X** is very important to industry where it is primarily used to manufacture semiconductor electronic devices and as an additive to lead alloys. Not long ago, different compounds of **X** were also used as pesticides and even as green pigments in paint, but these practices had to be abandoned due to the toxicity of **X**. Various minerals of this element are present in the Earth's crust and the majority of them are found in China. One such mineral is tennantite, which consists of three elements – Cu, **X**, and **Y**. Elements **X** and **Y** can be found in groups 15 and 16 of the periodic table, respectively. Crystallographic data for the tennantite unit cell: lattice parameter $a = 10.186 \text{ \AA}$, number of formula units per unit cell $Z = 2$, density $\rho = 4.6479 \text{ g cm}^{-3}$. Assume that the unit cell is cubic. Elemental composition by mass: $w_{\text{Cu}} = 51.56\%$, $w_{\text{X}} = 20.26\%$, $w_{\text{Y}} = 28.18\%$.

a) Write chemical formulas for **X**, **Y**, and tennantite.

Let us consider the production of **X**-containing compounds starting from this mineral.



The thermal decomposition of tennantite leads to another mineral **A** with a highly symmetric structure consisting of **X** and **Y** only. During the reaction, Cu_2Y and vapors of **Y** are formed as by-products. Further oxidation of **A** leads to oxide **B** ($w_{\text{X}} = 75.7\%$), which is a starting material for the synthesis of almost all **X**-containing compounds. Compound **C** reacts with SbF_5 in a 1 : 1 ratio to give salt **D** with an **X**-containing cation and Sb-containing anion. **J**, the *anti*-addition product of **F** to acetylene, is an organo-**X** compound known as Lewisite that has been manufactured for use in chemical weapons. In the reaction $\text{F} \rightarrow \text{G}$, sodium borohydride acts as a hydride donor. **K** is a semiconductor. **H** ($w_{\text{C}} = 21.26\%$, $w_{\text{H}} = 5.35\%$, $w_{\text{X}} = 66.31\%$, $w_{\text{O}} = 7.08\%$) is known as cacodyl oxide to obtain which potassium acetate has to react with **B**. During the reaction, the evolution of a gas is observed, and a potassium salt is formed as a by-product. Two equivalents of the cacodylic acid **I** are obtained by oxidizing 1 equivalent of **H**.

b) Identify the chemical formulas of **A–G** and **K**.

c) Draw the structural formulas of compounds **H–J**.

d) Write equations of the described reactions.

Similarly to heavy metal poisoning, patients who have been in contact with **J** can be given chelation therapy. A famous example of a covalent drug used specifically in the case of Lewisite poisoning is 2,3-dimercaptopropan-1-ol, also known as British anti-Lewisite (**BAL**).

- e)** Draw the structures of **BAL** and a product ($M = 258.62 \text{ g mol}^{-1}$) formed in reaction with **J**.
f) Using VSEPR theory, determine the geometries of the cation and anion of **D**.

Nuclear magnetic resonance (NMR) spectroscopy is useful beyond organic chemistry and can also be used to study inorganic species. However, this can sometimes be more complicated due to the line-broadening effects of quadrupolar nuclei (i.e. nuclei with a spin quantum number I greater than $1/2$). Just like for protons ($I = 1/2$) in ^1H NMR spectra of organic molecules, the number of lines in a multiplet can be predicted for any other NMR-active nucleus using the equation: $2nI + 1$, where n is the number of coupling nuclei. The natural abundances of ^{19}F ($I = 1/2$) and **X** ($I = 3/2$) are 100%. Two NMR-active nuclei of antimony exist: ^{121}Sb ($I = 5/2$) and ^{123}Sb ($I = 7/2$). The natural abundances of ^{121}Sb and ^{123}Sb are 57.25% and 42.75%, respectively. In the following questions, assume that any anisotropies resulting from cation-anion interactions average out over the experiment time course and only through-bond couplings are observed.

- g)** For solution-state NMR spectra of **D**, predict the number of resonances and their theoretical splitting patterns in the **i)** ^{121}Sb NMR spectrum, **ii)** **X** NMR spectrum, and **iii)** ^{19}F NMR spectrum. Include the ratios of peak intensities for any multiplets as predicted by Pascal's triangle.

Problem 2 – ELECTRO, THERMO – Thermodynamics of electrochemical CO_2 capture

Electrochemical CO_2 capture is a promising technique for direct air capture, allowing the capture of CO_2 from the atmosphere and then releasing it in pure, concentrated form for further application.

Part I. EMCS in the solution

One of the simplest systems is the electrochemically mediated complexation separation (EMCS), where the redox-active adsorbent is activated for CO_2 capture at the cathode. At the same time, at the anode, it is deactivated and releases CO_2 . A more specific case is the EMCS in the solution, where the adsorbate is dissolved directly. In the capture process, the first step is an electrochemical reaction: $\text{A}(\text{aq}) + m\text{e}^- \rightleftharpoons \text{A}^{m-}(\text{aq})$.

- a)** Using the Nernst equation, write an expression for the reduction half-cell potential E . Furthermore, the reduced A^{m-} is capturing CO_2 : $\text{A}^{m-}(\text{aq}) + m\text{CO}_2(\text{g}) \rightleftharpoons \text{A}(\text{CO}_2)_m^{m-}(\text{aq})$.
b) Write an expression for the equilibrium constant K for the given reaction, assuming the reference pressure P_0 to be 1.

For convenience, we can define *total adsorbent concentration* – A_0 : $A_0 = [\text{A}] + [\text{A}^{m-}] + [\text{A}(\text{CO}_2)_m^{m-}]$; and *activated fraction* x_A : $x_A = ([\text{A}^{m-}] + [\text{A}(\text{CO}_2)_m^{m-}])/A_0$. We are now equipped to separate expression for half-cell potential E into terms related to activated fraction and CO_2 pressure: $E = E^\circ + RT/mF \cdot f_1(x_A) + RT/mF \cdot f_2(KP_{\text{CO}_2}^m)$.

- c)** Derive expressions for $f_1(x_A)$ and $f_2(KP_{\text{CO}_2}^m)$.

Now if we define E_0 to be the potential when no CO_2 is present ($P_{\text{CO}_2} = 0$), we can consider the deviation potential E^{dev} observed at different P_{CO_2} : $E^{\text{dev}} = E(P_{\text{CO}_2}) - E_0$.

- d)** Write an expression for E^{dev} in this case.

Part II. Thermodynamic analysis

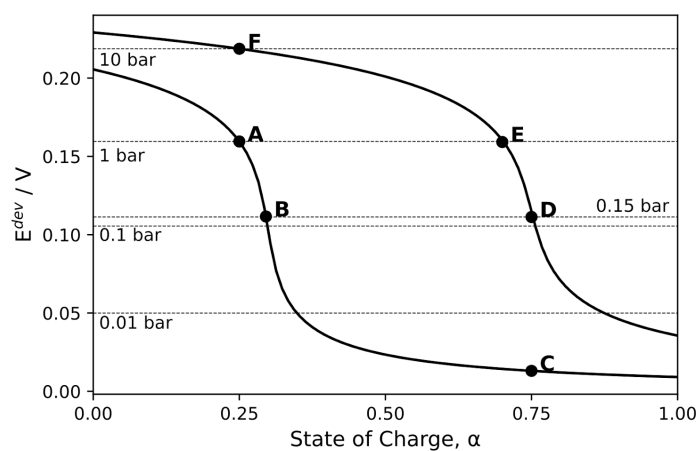
To calculate the work needed to perform the capture-release cycle, we have to consider a diagram analogous to that of the p - V diagram known from classical thermodynamics. However, in this case, we consider a diagram E^{dev} vs. α (state of charge, which describes the relative amount of reduced species). To construct this diagram, we must first understand the relation between total CO_2 content (x_{CO_2} normalized with respect to A initial concentration) and partial pressure of CO_2 (P_{CO_2}), which is given by the relation: $x_{\text{CO}_2} = \alpha \cdot K P_{\text{CO}_2} / (1 + K P_{\text{CO}_2}) + k'_{\text{h,CO}_2} P_{\text{CO}_2}$. The first term in the sum describes CO_2 which is bound to the reduced form of A, where α is the *state of charge*, which in the ECMS case coincides with the activated fraction x_A defined before. The second term, however, describes the part of CO_2 that is dissolved in the solution, where $k'_{\text{h,CO}_2}$ is normalized Henry constant. Assume that $K = 500$, $P_{\text{CO}_2} = 10^5$ Pa, and $k'_{\text{h,CO}_2} = 5 \cdot 10^{-7} \text{ Pa}^{-1}$.

e) Calculate the total CO_2 content x_{CO_2} for cases i) $\alpha = 0.25$ and ii) $\alpha = 0.75$.

During the CO_2 adsorption and desorption cycle, there are three types of thermodynamic pathways possible:

- Constant state of charge – CO_2 is adsorbed or released from A with no electrochemical reaction happening.
- Constant total CO_2 concentration – during the reduction/oxidation process, the CO_2 in the solution adsorbs to the reduced species/adsorbed CO_2 is released into the solution, while the total CO_2 concentration remains constant.
- Constant CO_2 partial pressure – the external pressure is kept constant; therefore, while the capture/release happens, the total CO_2 concentration and state of charge change while the partial pressure is constant.

The following plot shows the diagram of E^{dev} vs. α . Solid lines indicate constant total CO_2 concentration (x_{CO_2} is constant), and dashed lines indicate constant CO_2 partial pressure (P_{CO_2} is constant). The labeled points A–F show special points during the capture-release cycle, which will be described later. Note that you have already calculated the x_{CO_2} for points A and E in question e).



f) Calculate the partial pressure P_{CO_2} at point C.

The release-capture system can be considered in two extremes. In both cases, the initial state of charge is 0.25, during adsorption, the partial pressure of the feed stream is $0.15 \cdot 10^5$, and adsorption continues until the state of charge is 0.75. At the release stage, the CO_2 is released in a pure stream with a partial pressure of 10^5 .

Four-stage system:

1. As the absorbent is activated, i.e. the state of charge increases, while the total CO₂ concentration remains constant.
2. The activated absorbent is in contact with the feed gas until the partial pressure of the feed gas is reached.
3. The absorbent is deactivated as the state of charge decreases. In the end, the free CO₂ in the solution is at a partial pressure of $10 \cdot 10^5$ Pa.
4. CO₂ is removed by desorption as a gas in the flash tank at a pressure of 10^5 .

Two-stage system:

1. The adsorbent is activated and CO₂ is captured at the same time.
2. The adsorbent is deactivated and CO₂ is released at the same time.

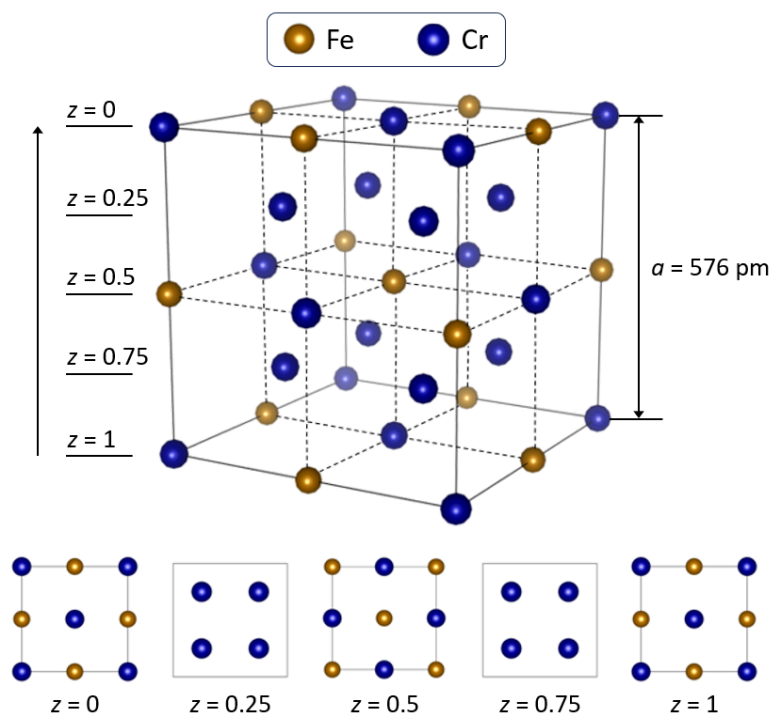
g) Assign all the described steps with points shown in the E^{dev} vs. α diagram.

The work required to perform the capture-release cycle is described as the area enclosed by the cycle in the E^{dev} vs. α diagram.

h) Which system (four-stage or two-stage) requires less work?

Problem 3 – CRYSTAL – Solution \neq liquid

We are used to the term “solution” in the context of liquid materials. But solid solutions also exist. In solid solutions, different atoms or ions form compounds with different stoichiometric compositions, but the crystal lattice remains the same. Ferrochrome has the empirical formula Fe_xCr_{1-x}. Both iron and chromium form body-centered cubic (BCC) crystal lattices; therefore, their solid solution has the same lattice if a certain amount of iron atoms are substituted by chromium atoms in the nodes of the crystal lattice. One ferrochrome cubic cell and five planar projections perpendicular to the z-axis are shown in the Figure below.



a) Calculate the x value in the empirical formula Fe_xCr_{1-x} for the structure in the Figure.

- b) Calculate the density of ferrochrome if its lattice parameter is 576 picometers.
- c) The experimental ferrochrome density value differs by 5% compared with your result. Which of the following statements can explain such a difference?

- Additional Fe or Cr atoms can be intercalated in octahedral or tetrahedral voids.
- Formation of vacancies in nodes of the crystal lattice.
- Because of the random distribution of Fe and Cr atoms in the lattice one cubic cell does not ideally correspond to the actual composition of the material.
- Chemical interactions between Fe and Cr cause a significant change of atomic radii.
- In solid solutions, lattice parameter values fluctuate significantly.

Ionic solid solutions can be obtained by combining two or more ionic compounds. Substituting cations or anions of different charges in the lattice gives rise to peculiar physical properties of such material. Forsterite is a mineral that has the empirical formula Mg_2SiO_4 . Silicon is covalently bound to oxygen atoms, and magnesium ions occupy octahedral holes in the orthorhombic lattice. The reaction between forsterite and lanthanum(III) oxide yields $\text{La}_x\text{Mg}_y\text{SiO}_4$ solid solution and one more by-product containing no lanthanum.

- d) Write the chemical formula of the by-product.
- e) Express index y as a function of x .
- f) When La^{3+} ions substitute Mg^{2+} ions, a certain concentration of vacancies is formed. Vacancies influence the electrical conductivity of the ionic solid solution. Which electric charge transfer mechanism occurs in $\text{La}_x\text{Mg}_y\text{SiO}_4$ solid solution?

- Mg^{2+} migrates to the vacancy, a new vacancy is formed in Mg^{2+} node.
- La^{3+} migrates to the vacancy, a new vacancy is formed in La^{3+} node.
- Si^{4+} migrates to the vacancy, a new vacancy is formed in Si^{4+} node.
- O^{2-} migrates to the vacancy, a new vacancy is formed in O^{2-} node.
- Mg^{2+} or La^{3+} migrates to the vacancy, a new vacancy is formed in Mg^{2+} or La^{3+} node.
- $\text{Mg}^{2+}/\text{La}^{3+}/\text{Si}^{4+}$ migrates to the vacancy, a new vacancy is formed in $\text{Mg}^{2+}/\text{La}^{3+}/\text{Si}^{4+}$ node.
- O^{2-} migrates to the vacancy, a new vacancy is formed in O^{2-} node.
- Free electrons migrate from vacancy to vacancy.

- g) By performing electrical conductivity measurements, it was calculated that the concentration of vacancies in lanthanum-doped forsterite is $6.2 \cdot 10^{17} \text{ cm}^{-3}$. The density of the material is 3.223 g cm^{-3} . One unit cell contains one silicon and four oxygen atoms. Calculate index x in the formula $\text{La}_x\text{Mg}_y\text{SiO}_4$ by assuming that all vacancies are formed because of $\text{La}^{3+}-\text{Mg}^{2+}$ exchange.

Cations can intercalate in ionic compounds via different mechanisms. For example, ferrous oxide FeO can react with lithium oxide Li_2O to yield a solid solution $\text{Li}_x\text{Fe}_{1-x}\text{O}$. During the reaction, a fraction of iron atoms oxidize to +3 oxidation state. One of the simplest methods to analyze the composition of such a solid solution is electrochemical $\text{Fe}^{3+}/\text{Fe}^{2+}$ ratio determination. We denote the ratio $r = n(\text{Fe}^{3+})/n(\text{Fe}^{2+})$, n is the molar amount. Reciprocal values of empirical formula index x and ratio r are related linearly: $x^{-1} = a \cdot r^{-1} + b$, where a and b are integer numbers.

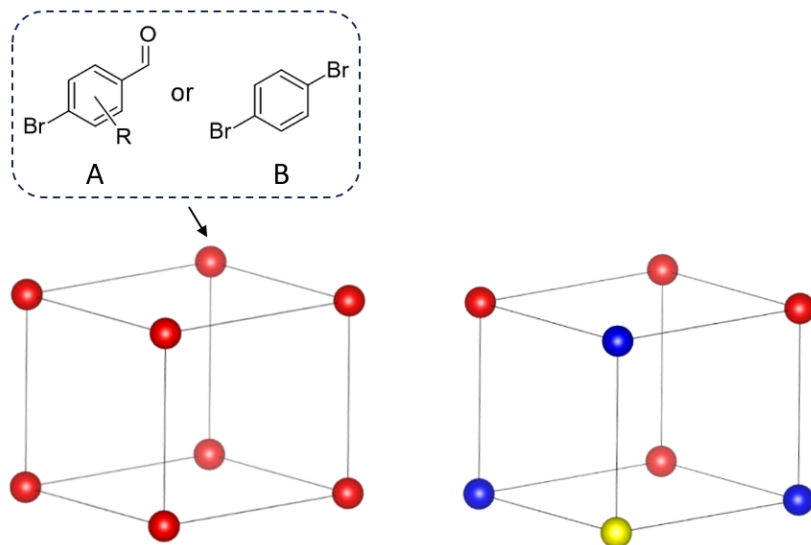
h) Calculate values a and b .

When $\text{Li}_x\text{Fe}_{1-x}\text{O}$ is dissolved in a non-oxidizing acid, an excess of sodium cyanide is added to bind all iron atoms to $[\text{Fe}(\text{CN})_6]^{4-}$ and $[\text{Fe}(\text{CN})_6]^{3-}$ complex ions. Two electrodes are immersed in this solution: a working Pt electrode and a reference $\text{AgCl} | \text{Ag}, \text{Cl}^-$ electrode, filled with saturated KCl solution. 0.092 V potential difference was measured at the starting moment of the experiment, then an increase of $[\text{Fe}(\text{CN})_6]^{4-}$ concentration was observed. Redox potentials at 298 K and 10^5 Pa are:



i) Calculate the ratio r and x from electrochemical measurement data.

Organic solid solutions are attractive because of their optical properties. For instance, *p*-bromobenzaldehyde derivatives weakly phosphoresce (emit light) in a crystalline state. However, if the *p*-bromobenzaldehyde derivative (**A**) is co-crystallized with 1,4-dibromobenzene (**B**), a solid phosphorescent solution will form. **B** molecules interrupt interactions between **A** molecules and do not allow for vibrational relaxation of excited **A** molecules. This solid solution has a primitive orthorhombic structure, where nodes can be occupied by either **A** or **B**. In the Figure below, a primitive orthorhombic cell with parameters a , b , c and nodal positions marked as red balls is shown; if the yellow molecule is the selected one, blue molecules are in the first coordination shell.



A simple kinetic model can be used to estimate the phosphorescence intensity I of the material: $I = \text{CN} \cdot k_{\text{ph}} / [k_{\text{ph}} r_0^2 + k_{\text{vib}} \sum_i (\text{CN}_i^2 r_i^2)]$, where CN is the coordination number, defining the average count of **A** molecules around selected **A** molecule, k_{ph} and k_{vib} are phosphorescence and vibrational relaxation rate constants, r_0 is a constant and CN_i are average counts of **A** molecules that are at a specific r_i distance from selected **A** molecule. r_0 and r_i are in angstroms (\AA). CN, CN_i , and r_i values should be considered only for the first coordination shell.

j) Show that for orthorhombic lattice with different unit cell lengths a , b , c , phosphorescence intensity can be calculated as $I = 9 \cdot \text{CN} \cdot k_{\text{ph}} / [9 \cdot k_{\text{ph}} r_0^2 + k_{\text{vib}} \text{CN}^2 (a^2 + b^2 + c^2)]$.

Solid solution **X** is prepared by co-crystallizing **A** and **B** in ratio $n(A) : n(B) = 1 : 1$. Solid solution **Y** is prepared by co-crystallizing **A** and **B** in ratio $n(A) : n(B) = 2 : 1$. **X** is 1.25 times more intense compared to **Y**.

k) Calculate the diagonal of the orthorhombic unit cell if $k_{ph}/k_{vib} \approx 10^{-4}$ and $r_0 = 710 \text{ \AA}$.

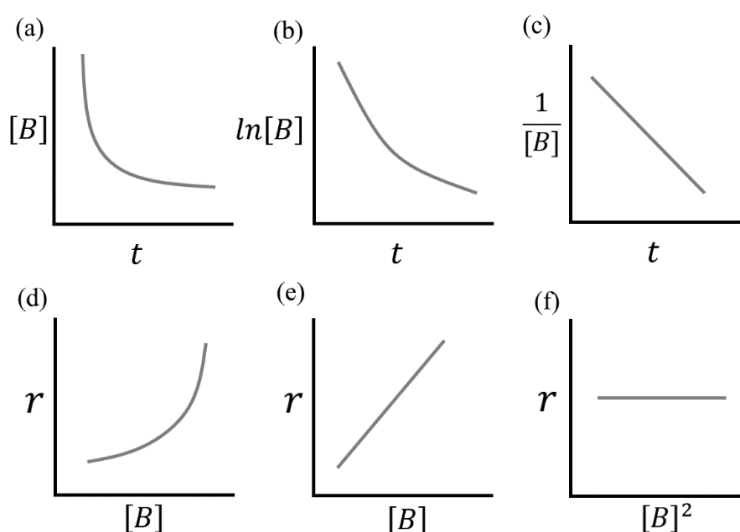
Problem 4 – KINETICS – Kinetics ABC

The following reaction proceeds via an unknown mechanism: $A + 2B \rightarrow AB_2$ (**0**).

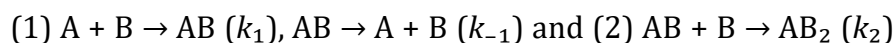
a) Choose all appropriate mechanisms that are consistent with the assumption that reaction **0** proceeds in a second-order fashion in relation to $[B]$.

- | | |
|---|---|
| i) $A + B \rightarrow AB$ slow | iii) $A + B \rightarrow AB$ fast |
| $AB + B \rightarrow AB_2$ fast | $AB + B \rightarrow AB_2$ slow |
| ii) $B + B \rightarrow B_2$ slow | iv) $A + A \rightarrow A_2$ slow |
| $A + B_2 \rightarrow AB_2$ fast | $B + B \rightarrow B_2$ slow |
| | $A_2 + B_2 \rightarrow AB_2 + A$ fast |

b) Choose graphs that could depict the relationship between $[B]$ and both time (t) and rate of reaction (r). Assume a constant state for $[A]$.



In reality, reaction (**0**) proceeds via the following mechanism:



c) For each condition listed below, determine whether the rate-limiting step of the mechanism presented above is step (1), step (2) or neither. Assume that $[A]$ and $[B]$ are much greater than $[AB]$ and $[AB_2]$.

- i)** $k_1 \gg k_{-1}$; $k_2 \gg k_1$, **ii)** $k_1 \gg k_{-1}$; $k_2 \ll k_1$, **iii)** $k_1 \gg k_{-1}$; $k_2 \cong k_1$, **iv)** $k_1 \cong k_{-1}$; $k_2 \ll k_1$

Unknown amounts of reagents A and B were added together to a container under conditions that favor reaction **0**. At time $t = t_1$, the concentration of intermediate AB has become constant, $[AB] = [AB]_{\text{const}}$ and the concentration of reagent A has reached a certain value, $[A] = [A]_1$.

d) Express the ratio k_1/k_2 in terms of $[A]_1$ and $[AB]_{\text{const}}$. Assume that $k_1, k_2 \gg k_{-1}$.

At time $t = t_2$, and at a different temperature, a certain amount of reagent C was added to the mixture. C interacts with intermediate AB via the following reaction: (3) $AB + C \rightarrow ABC$ (k_3). The experimental rate of production of ABC can be expressed as $r = ak_{\text{obs}}$, where k_{obs} is the observed rate constant for the production of ABC, and a is a product of concentration(s) of a certain compound(s).

e) Assuming that under given conditions, steps (1) and (2) proceed much slower than step (3), show that k_{obs} is approximately equal to rate constant k_1 .

The temperature of the mixture was increased to a certain value, at which rate constants k_2 and k_3 become equal.

f) Using signs $>$, $<$ and/or \cong , denote the relationship between Arrhenius pre-factors (A_2 and A_3) and activation energies (E_{a2} and E_{a3}) for reaction $AB + B \rightarrow AB_2$ and $AB + C \rightarrow ABC$. Assume that Arrhenius pre-factors and activation energies of these reactions are independent of temperature.

Certain amounts of B, C, and AB were added to a container under conditions that favor only reactions $AB + B \rightarrow AB_2$ and $AB + C \rightarrow ABC$. Assume that $[AB]_0$ is greater than $[B]_0$ and $[C]_0$.

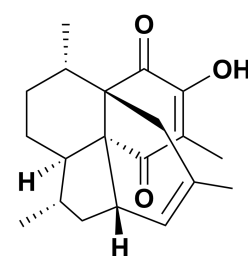
At time $t = t_3$, concentrations of compounds AB_2 and ABC became equal.

g) Express the ratio $[B]_0/[C]_0$ in terms of $[AB]_0, k_2, k_3$ and t_3 .

h) Calculate the ratio r_2/r_3 for reactions $AB + B \rightarrow AB_2$ and $AB + C \rightarrow ABC$ at time $t = t_3$ using $[AB]_0 = 1.20 \cdot 10^{-3} \text{ M}$, $k_2 = 1.40 \cdot 10^{-3} \text{ M}^{-1} \text{ s}^{-1}$, $k_3 = 5.60 \cdot 10^{-4} \text{ M}^{-1} \text{ s}^{-1}$, and $t_3 = 2.50 \cdot 10^3 \text{ s}$.

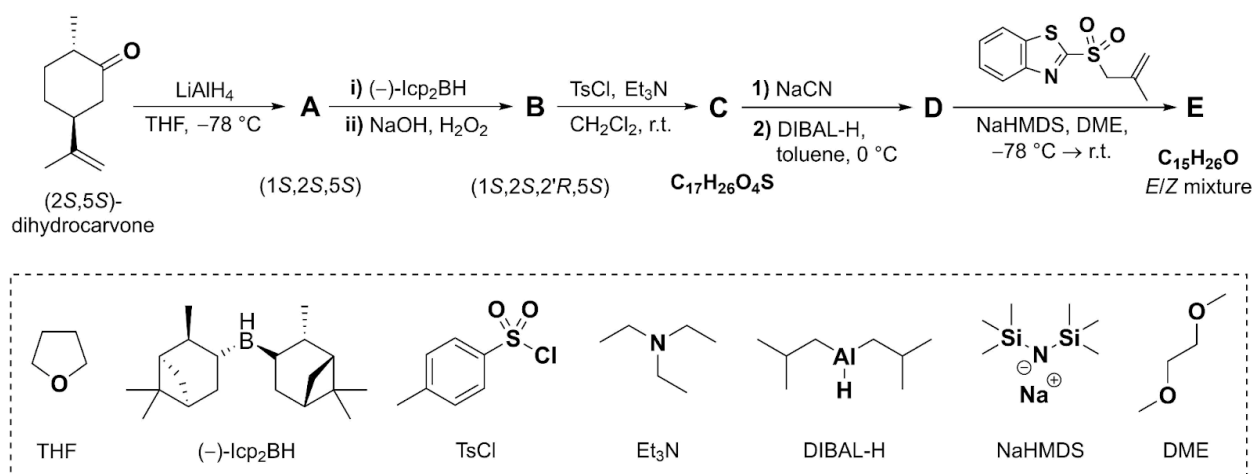
Problem 5 – MECH, SPECTRA, SYNTH – Total synthesis of (-)-Colombiasin A

(-)-Colombiasin A is a marine natural product first isolated from a species of coral found off the coast of San Andres island, Colombia. Following the initial reported total synthesis and structural assignment by K. C. Nicolaou and co-workers in 2001, Colombiasin A and structurally closely related compounds have been prepared via numerous different synthetic approaches. Construction of the carbon skeleton poses, in this case, some rather unique challenges to the synthetic chemist. Most notably, the two adjacent quaternary carbons central to Colombiasin A's carbocycles have been recognized as some of the most challenging aspects of building this natural product.



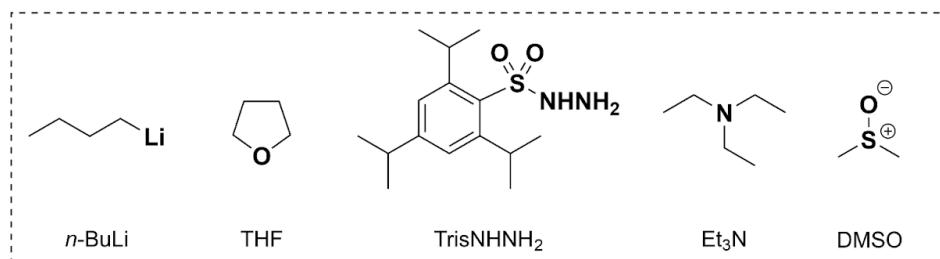
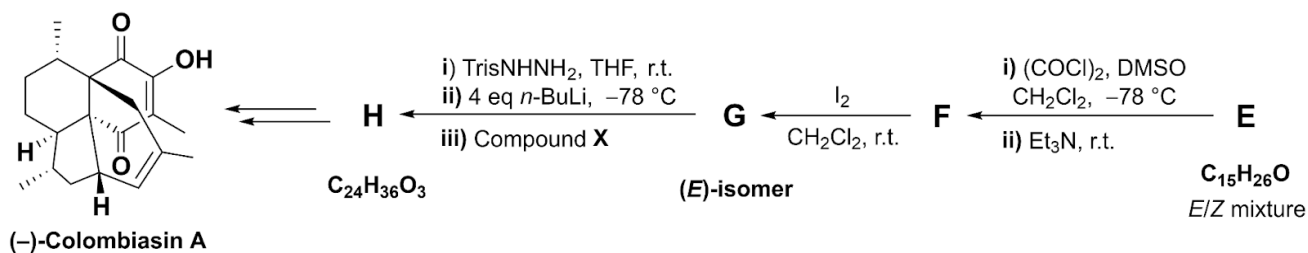
(-)-Colombiasin A

In this task, you will follow the approach of D. C. Harrowven and co-workers, which starts off simple yet concludes in a spectacular fashion. The synthesis begins from enantiomerically pure dihydrocarvone. In the first half of the sequence, a number of simple transformations eventually lead to an *E/Z* mixture of conjugated diene **E**. The stereochemical configurations of compounds **A** and **B** have been provided in the scheme below. In reaction **C** \rightarrow **D**, a partial reduction occurs over steps i)–ii). It is also known that both **C** and **D** contain a secondary hydroxyl group.



- a) Draw the structural formulas of **A–E** with stereochemistry.
- b) From the list below, choose the most suitable solvent for the reaction **C** + NaCN:
i) *n*-hexane, toluene, NH₃ (l), **ii)** 1,2-dichloroethane (DCE), **iii)** dimethylsulfoxide (DMSO),
iv) kefir, **v)** 1 : 1 MeOH/H₂O with 5% v/v H₂SO₄.
- c) Sketch the reaction mechanism for transformation **D** → **E** and clearly indicate the three by-products formed in progress. You may abbreviate parts of molecule(s) irrelevant to this transformation. *Hint: the reaction proceeds via an anionic spirocyclic intermediate. Spiro compounds are molecules containing at least two ring systems and only a single common atom.*
- d) Explain briefly, with reference to relevant ³J_{H-H} coupling constants, how the *E/Z* isomeric ratio of compound **E** could be estimated by ¹H NMR spectroscopy.

In the next part of the synthesis, the *E/Z* mixture of compound **E** is first oxidized into **F** and subsequently, with the aid of catalytic I₂, converted into stereochemically pure **G**. Compound **G** is then subjected to an interesting sequence of reactions. First, an alkenyl lithium species is formed *in situ* from **G** via a Shapiro reaction, which then undergoes a nucleophilic addition to compound **X**. Following aqueous work-up, the α-hydroxy ketone **H** is obtained. *Hint: the first step in the Shapiro reaction is the formation of a hydrazone via condensation.*



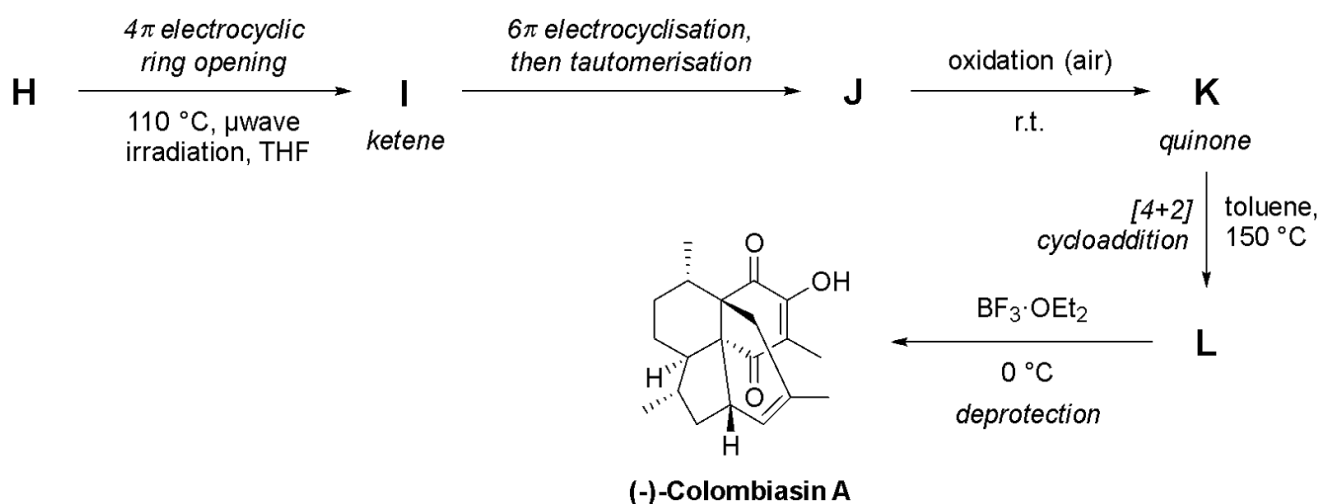
Information about compound **X**:

- Elemental composition: 64.27% C; 7.19% H; 28.54% O.
- ^1H NMR (300 MHz, CDCl_3): δ 2.19 (s, 1H), 1.62 (s, 3H) ppm. *NB! The listed integrals are relative, not absolute.*
- ^{13}C NMR (75 MHz, CDCl_3): δ 199.9, 195.9, 192.8, 182.7, 87.5, 28.7, 9.3 ppm.
- Selected IR spectroscopic data: ν_{max} (cm^{-1}) – 1799, 1748, 1584, 1395.

e) Identify the four low molecular weight by-products formed in step **E** \rightarrow **F**.

f) Draw the structures of **F**, **G**, **H** and **X** with stereochemistry.

The total synthesis of (–)-Colombiasin A from dihydrocarvone culminates in an impressive cascade, which proceeds from **H** to **K** via intermediates **I** and **J**. In the last steps, a [4+2] cycloaddition furnishes the (–)-Colombiasin A core, and deprotection using BF_3 etherate reveals the target molecule.



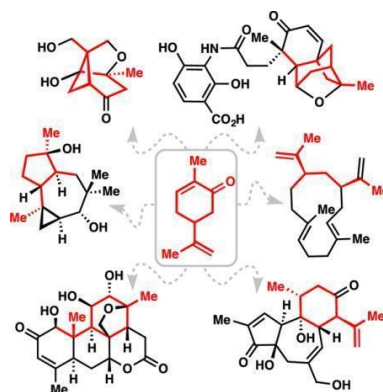
g) Draw the structural formulas of **I–L** with stereochemistry.

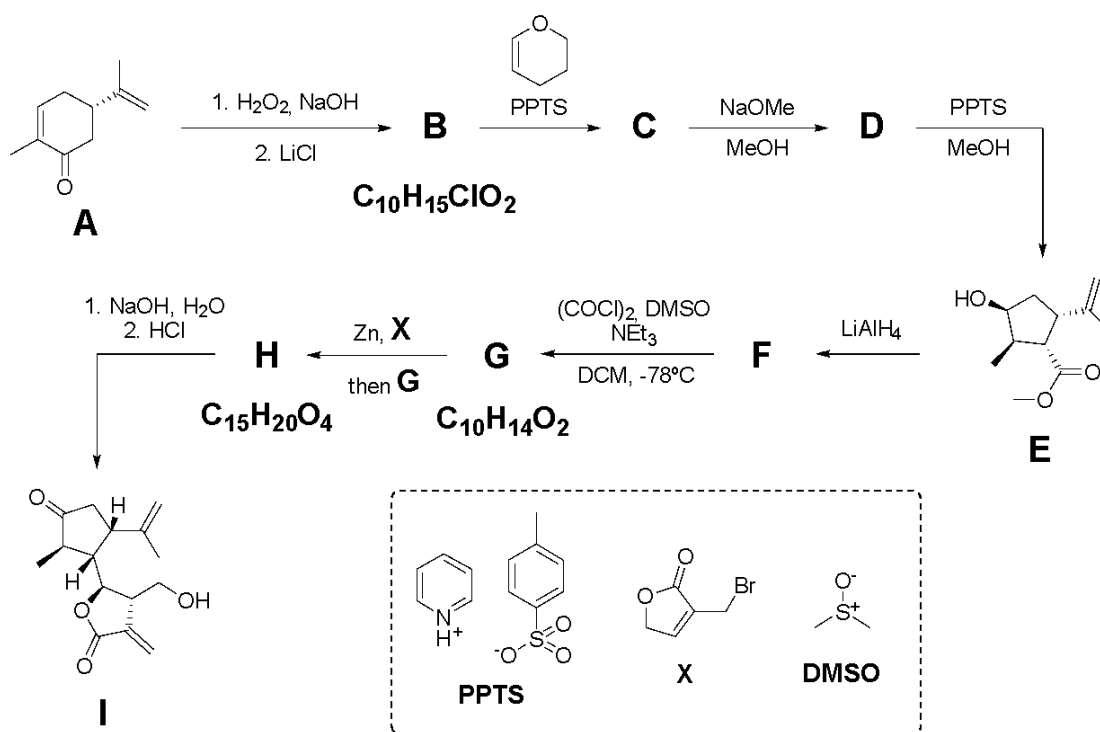
Problem 6 – SYNTH – Chiral pool

A chiral pool is a collection of enantiopure (thus chiral), cheap compounds that could be used as starting materials in synthesis, creating chiral ligands, reagents, etc. One of the most popular members of the chiral pool is a terpene Carvone. In this problem, we will take a look at the synthesis of sesquiterpene lactone 8-epigosheimin that utilizes (*S*)-carvone (**A**) as a source of chirality.

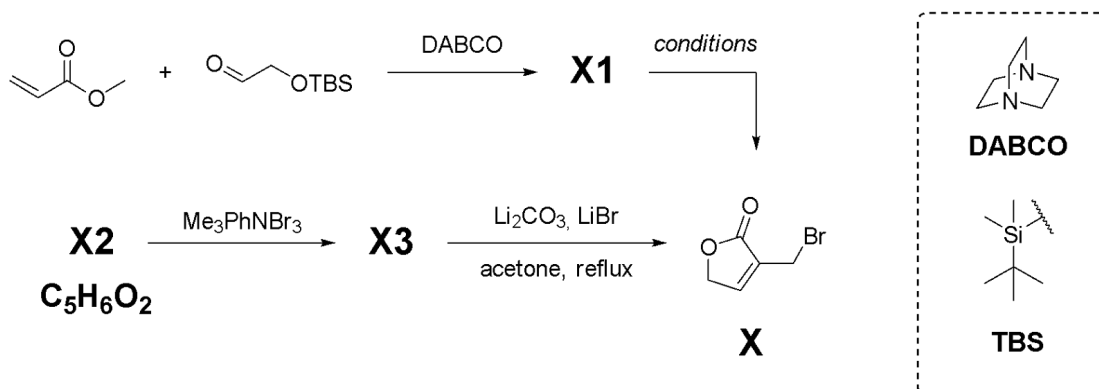
Note that 1) PPTS is a weakly acidic catalyst, and 2) in the reaction **G** \rightarrow **H**, zinc is required to create organometallic species.

a) Draw the structural formulas of compounds **B–D**, **F–H**.





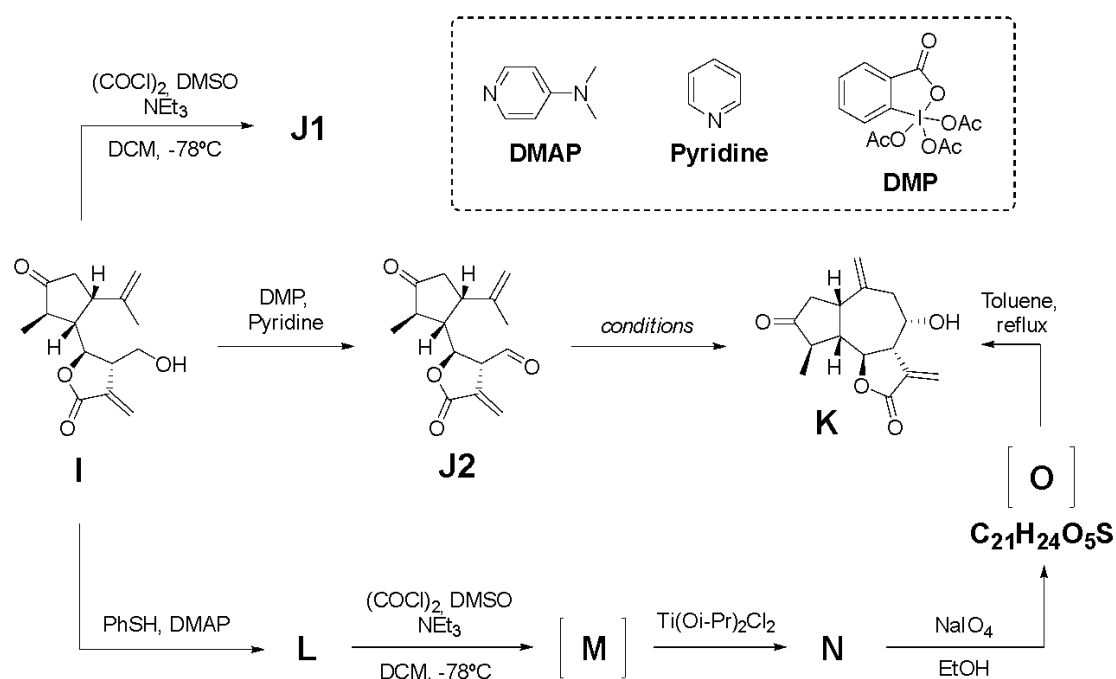
The reagent **X** could be obtained in many ways. In the scheme below, two of the most popular routes are shown.



^1H NMR spectra of **X2**: 6.08 (t, $J = 3$ Hz, 1H), 5.63 (t, $J = 3$ Hz, 1H), 4.30 (t, $J = 7$ Hz, 2H), 2.97 (m, 2H).

- Draw the structural formulas of compounds **X1**, **X2** and **X3**.
- Propose a mechanism for the synthesis of **X1**.
- Propose a reagent(s) to obtain **X** from **X1** in one step.

The endgame of the synthesis was planned through Swern oxidation followed by cyclization to obtain the 8-epigosheimin (**K**). During the oxidation, an isomer **J1** was formed instead of the necessary **J2**. Although the endgame was quite short, in order to prove the absolute configuration, a different route was taken (through **L**).



Note that Ti(IV) salts are strong oxophilic Lewis acids.

e) Draw the structural formulas of compounds **J1**, **L–O**.

f) Choose the appropriate conditions for the transformation of **J2** to **K**:

- $n\text{-BuLi}$, diethylamine
- MgSO_4 , toluene, reflux
- $\text{Et}_2\text{O} \cdot \text{BF}_3$
- NaOH , H_2O_2
- NaClO_2 , NaH_2PO_4 , $t\text{-BuOH}/\text{H}_2\text{O}$