Problem 1 (author Khvalyuk V.N.)

1. It is unlikely that sodium was contained in the evolved gas, therefore, all of it remained in the solid residue. M(Na) = 23.0 g/mol. M(Na_2CO_3) = 106.0 g/mol.

In starting mixture there was $\frac{6.360}{106.0} \cdot 2 \cdot 23.0 = 2.760$ g of sodium.

Then the mass of solid residue is equal to $\frac{2.760}{0.2725} = 10.13$ g, and the mass of the evolved gas **B** is equal to (6.360 + 6.414 – 10.13) = 2.644 g.

The amount of gas **B** is equal to $\frac{101.7 \cdot 1.967}{8.314 \cdot (273 + 128)} = 0.0600$ mol and its molar mass is equal to $\frac{2.644}{0.0600} = 44.07$ g/mol. Given the chemical elements contained in the mixture, we can conclude that it is carbon dioxide – CO_2 (calculations 1 point, determination of gas 1 point, 2 points in total).

2. The reaction under consideration: $Na_2CO_3 + \mathbf{A} \rightarrow \mathbf{X} + \mathbf{Y} + CO_2\uparrow$.

The starting mixture contained $\frac{6.360}{106} = 0.0600$ mol Na_2CO_3 and 0.0600 mol CO_2 was evolved. It follows from this the composition of salts **X** and **Y** includes only Na, O and **A** atoms.

Since the simple substance **A** takes a part in reaction, then this reaction is redox and **A** atoms should have negative oxidation state (less than initial) in one of the salts, therefore, in the second salt **A** atoms should have positive oxidation state (higher than initial), so it is disproportionation reaction of **A**.

The salt with **A** atoms in negative oxidation state should be binary ($Na_b\mathbf{A}_c$), the second salt should contain oxygen atoms additionally ($Na_d\mathbf{A}_eO_f$).

$$Na_2CO_3 + \mathbf{A} \rightarrow Na_b\mathbf{A}_c + Na_d\mathbf{A}_eO_f + CO_2\uparrow$$

It means that the obtained solid residue contains all of remaining oxygen in $Na_d\mathbf{A}_eO_f$. In the solid residue there is (3 · 0.0600 – 2 · 0.0600) = 0.0600 mol or 0.0600 · 16.00 = 0.960 g of oxygen atoms. The mass of $Na_d\mathbf{A}_eO_f$ salt is equal to (10.13 – 6.968) = 3.162 g. The mass fraction of oxygen atoms in $Na_d\mathbf{A}_eO_f$ is equal to $\frac{0.960}{3.162} = 0.3036$.

The coefficients in formula of salt $Na_d\mathbf{A}_eO_f$ (d, e and f) are small integers. We can calculate the molar mass of this salt with different number f, then we can calculate A_r(**A**) for possible values of d and e.

$$M_r(Na_d\mathbf{A}_eO_f) = \frac{f \cdot A_r(O)}{w(O)}$$

f	1	2	3	4	5	6
M_r	52.70	105.4	158.1	210.8	263.5	316.2

When f = 3, d = 2 and e = 2 we get, A_r(**A**) = 32.05, that is close to sulfur atomic mass. The simple substance **A** is sulfur S (or S_8). The substance **Y** is sodium thiosulfate $Na_2S_2O_3$.

For synthesis it was taken 0.0600 mol Na_2CO_3, $\frac{6.414}{32.07}$ = 0.200 mol S, and it was formed 0.0600 mol CO_2 and $\frac{3.162}{158.1}$ = 0.0200 mol $Na_2S_2O_3$.

$$0.0600\ Na_2CO_3 + 0.200\ S = \mathbf{X} + 0.0200\ Na_2S_2O_3 + 0.0600\ CO_2 \quad \text{or}$$

$$3Na_2CO_3 + 10S = \mathbf{X} + Na_2S_2O_3 + 3CO_2.$$

For **X** we get Na_4S_8 or $2Na_2S_4$. The substance **X** is sodium tetrasulfide Na_2S_4 (2 points for calculation, on 1 point for **A**, **X** and **Y**, 5 points in total)

3. There is reaction (1 point):

$$3Na_2CO_3 + 10S = 2Na_2S_4 + Na_2S_2O_3 + 3CO_2\uparrow \quad \text{or}$$

$$12Na_2CO_3 + 5S_8 = 8Na_2S_4 + 4Na_2S_2O_3 + 12CO_2\uparrow$$

4. The anion S_4^{2-} has zigzag form with bond angle is close to 90°. The thiosulfate anion $S_2O_3^{2-}$ has distorted tetrahedral form, bond angles are close to tetrahedral (0.5 points for description of each anion, 1 point in total).

5. For instance:

$Na_2S + 3S = Na_2S_4$ (boiling an aqueous solution of sodium sulfide with sulfur);

$2Na + 4S = Na_2S_4$ (direct synthesis in liquid ammonia).

The other procedures exist (0.5 points for each reaction, 1 point in total).

Problem 2 (author Gulevich D.G.)

1. The number of **X** atoms in a quantum dot $N_X = \frac{4\pi r^3 \nu}{3V_u}$. Therefore the unit cell volume $V_u = \frac{4\pi r^3 \nu}{3N_X} = \frac{4 \cdot 3.14 \cdot (2.0 \cdot 10^{-9})^3 \cdot 2}{3 \cdot 598} = 1.12 \cdot 10^{-28}$ m^3. Hence the molar mass of **XY**

$$M_{XY} = \frac{\rho V_u N_A}{z} = \frac{5.67 \cdot 10^6 \cdot 1.12 \cdot 10^{-28} \cdot 6.02 \cdot 10^{23}}{2} = 191\ \text{g/mol}.$$

The density of the gas H_2**Y** in terms of the Mendeleev – Clapeyron formula:

$$pV = \nu RT \quad \Rightarrow \quad \frac{\nu}{V} = \frac{p}{RT} \quad \Rightarrow \quad \frac{m}{V} = \frac{pM}{RT} \quad \Rightarrow \quad \rho = \frac{pM}{RT}.$$

$$M(H_2Y) = \frac{3.31\ \text{g/L} \cdot 0.082\ \text{L·atm/mol·K} \cdot 298\ \text{K}}{1\ \text{atm}} = 80.9\ \text{g/mol}.$$

80.9 – 2 = 78.9 g/mol, consequently **Y** – Se. Gas H_2**Y** with a strong unpleasant odor is hydrogen selenide. M_X = 191 – 78.9 = 112.1 g/mol, therefore, **X** – Cd (determination of **Y** – 0.75 points, **X** – 1 point, 1.75 points in total).

2. (reaction equations 0.25 points, substances **C** – **G** – 0.1 point for each, 2.5 points in total)

1) $SeO_2 + 2NaOH = Na_2SeO_3 + H_2O$

2) $CdCl_2 + 4NH_3(aq) = [Cd(NH_3)_4]Cl_2$

3) $2Na_2SeO_3 + 2[Cd(NH_3)_4]Cl_2 + 3N_2H_4(aq) = 2CdSe + 8NH_3 + 3N_2 + 4NaCl + 6H_2O$

4) $CdCl_2 + 2CH_3MgCl = Cd(CH_3)_2 + 2MgCl_2$

5) $Se[Si(CH_3)_3]_2 + Cd(CH_3)_2 = CdSe + 2Si(CH_3)_4$

6) $2Se + 4NaBH_4 + 7H_2O = 2NaHSe + Na_2B_4O_7 + 14H_2$

7) $2NaHSe + H_2SO_4 = Na_2SO_4 + 2H_2Se$

8) $H_2Se + CdCl_2 + 2NaOH = CdSe + 2NaCl + 2H_2O$

C – Na_2SeO_3, **D** – $[Cd(NH_3)_4]Cl_2$, **E** – $Cd(CH_3)_2$, **F** – NaHSe, **G** – H_2Se.

3. Using λ_{max} we calculate the E_g^{nano} value for a quantum dot 2.0 nm in size: $E_g^{nano} = hc/\lambda = (6.63\cdot10^{-34} \cdot 2.998\cdot10^{8}) / (446\cdot10^{-9}) = 4.46\cdot10^{-19}$ J. Now we can calculate E_g^{bulk} of CdSe:

$$E_g^{bulk} = 4.46\cdot10^{-19} - \frac{(6.63\cdot10^{-34})^2\cdot1.37\cdot10^{31}}{8\cdot(2.0\cdot10^{-9})^2} + \frac{1.8\cdot(1.6\cdot10^{-19})^2}{4\cdot3.14\cdot8.85\cdot10^{-12}\cdot10.6\cdot2.0\cdot10^{-9}} =$$

$$= 4.46\cdot10^{-19} - 1.88\cdot10^{-19} + 1.96\cdot10^{-20} = 2.78\cdot10^{-19}\,\text{J}.$$

Then

$$E_g^{nano}(r = 3.3\text{ nm}) = 2.78\cdot10^{-19} + \frac{(6.63\cdot10^{-34})^2\cdot1.37\cdot10^{31}}{8\cdot(3.3\cdot10^{-9})^2} - \frac{1.8\cdot(1.6\cdot10^{-19})^2}{4\cdot3.14\cdot8.85\cdot10^{-12}\cdot10.6\cdot3.3\cdot10^{-9}} =$$

$$= 2.78\cdot10^{-19} + 6.91\cdot10^{-20} - 1.19\cdot10^{-20} = 3.35\cdot10^{-19}\,\text{J}.$$

$\lambda = (6.63\cdot10^{-34} \cdot 2.998\cdot10^{8})/(3.35\cdot10^{-19}) = 593$ nm. This means that CdSe quantum dots with radius 3.3 nm will luminescence in the yellow region (determination of E_g^{bulk} – 1 point, E_g^{nano} (r = 3.3 nm) – 0.5 points, λ – 0.5 points, 2 points in total).

4. a) $K_{a1} = \frac{[H^+][LH_2]}{[LH_3]}$, $K_{a2} = \frac{[H^+][LH]}{[LH_2]}$, where LH_3 – cationic form of cysteine, LH_2 – zwitterion, LH – anionic form. $K_{a1} = K_a$(–COOH), $K_{a2} = K_a$(–SH). Express $[LH_2]$ from the first equation and substitute it into the equation for K_{a2}:

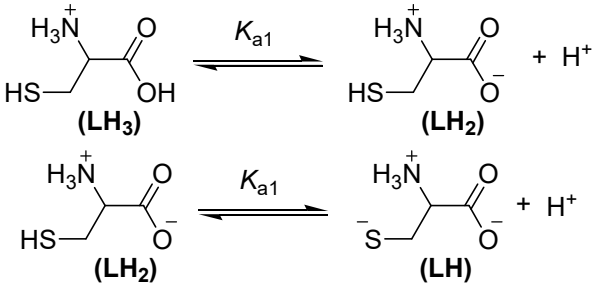
$$K_{a1}\cdot K_{a2} = \frac{[H^+]^2[LH]}{[LH_3]}.$$

At the isoelectric point, the concentrations of cationic and anionic forms are equal, therefore

$$K_{a1}\cdot K_{a2} = [H^+]^2.$$

After logarithmical conversion we obtain:

$$pH = \frac{pK_a(\text{–COOH}) + pK_a(\text{–SH})}{2} = \frac{1.9 + 8.2}{2} = 5.05 = pI$$



b) At pH = 8.5, in the cysteine molecule, the carboxyl and thiol groups are deprotonated, the total charge is –1. c) therefore, during electrophoresis, the amino acid will move to the anode (pI calculation – 1 point, total charge – 0.5 points, electrode – 0.25 points, 1.75 points in total).

5. Because of

$$\ln K = \frac{1}{R}\left(-\frac{\Delta H^\circ}{T} + \Delta S^\circ\right),$$

in the coordinates ln$K$ – 1/T, the slope of the line is $-\Delta H^0 / R$ and the free term is $\Delta S / R$.

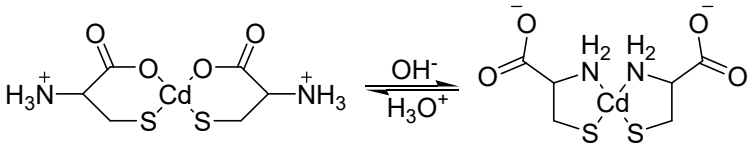
For reaction (1):

$$\Delta_r H^0 = -29348 \cdot 8.314 = -244 \text{ kJ/mol}, \ \Delta_r S^0 = -2.93 \cdot 8.314 = -24.4 \text{ J/mol·K},$$
$$\Delta_r G^0_{298} = \Delta_r H^0 - T\Delta_r S^0 = -244 \cdot 10^3 + 298 \cdot 24.4 = -237 \text{ kJ/mol}.$$

For reaction (2) (0.5 points for each calculation of $\Delta_r G^0_{298}$, 1 point in total):

$$\Delta_r H^0 = -37400 \cdot 8.314 = -311 \text{ kJ/mol}, \ \Delta_r S^0 = -3.50 \cdot 8.314 = -29.1 \text{ J/mol·K},$$
$$\Delta_r G^0_{298} = \Delta_r H^0 - T\Delta_r S^0 = -311 \cdot 10^3 + 298 \cdot 29 = -302 \text{ kJ/mol}.$$

6. Based on thermodynamic data, we can conclude that the formation of the complex is Cys–Cd–Cys preferable. Coordination depends on the pH of the solution, which determines which functional groups of the amino acid are deprotonated (0.5 points for each structure, 1 point in total).



Problem 3 (author Mezentsev-Cherkes I.V.)

1. Based on the conditions for the existence of several allotropic modifications, we can reject the consideration of halogens and focus our attention on the remaining p-elements - non-metals. Compounds of series **A** are formed with a simple substance obtained by thermal decomposition of a binary compound **D**. Of the simple substances, gaseous substances are nitrogen, oxygen, fluorine and chlorine. The condition that blue gas $\mathbf{G_1}$ can be obtained under hard conditions from gas **G**, tells us that it is oxygen O_2 (**G**) and ozone O_3 ($\mathbf{G_1}$). Accordingly, compounds of series **A** are compounds with oxygen. Define **X** using the mass fraction in $\mathbf{A_1}$ (ω(**X**) = 56.34%).

Substance	X_2O	XO	X_2O_3	XO_2	X_2O_5	XO_3
M(X)	10.32 B?	20.65 –	30.97 P	41.29 –	51.62 Cr?	61.94 –

The best variant is **X** – phosphorus, $\mathbf{X_1}$ – P_4, $\mathbf{X_2}$ – P red, $\mathbf{A_1}$ = P_4O_6. Define content of $\mathbf{A_2}$ (P_xO_y): $x:y = \frac{52.54}{30.974}:\frac{100-52.54}{15.999} = 1.70:2.97 = 4:7$. $\mathbf{A_2}$ – P_4O_7 (0.25 points for each **G**, $\mathbf{G_1}$, $\mathbf{X_1}$, $\mathbf{X_2}$; $\mathbf{A_1}$ and $\mathbf{A_2}$: 0.3 point for each calculation and 0.2 points for each formula; 2 points in total).

The condition says that in a series $\mathbf{A_2}$ – $\mathbf{A_5}$ oxidation state of phosphorus increases. It corresponds to the following sequence of compounds P_4O_7, P_4O_8, P_4O_9, P_4O_{10} (0.25 points fo formala $\mathbf{A_3}$ – $\mathbf{A_5}$, 0.75 points in total).

$$3P_4O_{10} + 2P_4 = 5P_4O_6 \text{ (0.25 points)}$$

$\mathbf{A_6}$ is produced from reaction of P_4O_6 with ozone and represents phosphorus ozonide. Mass fraction data allow to determine the formula: $\mathbf{A_6}$ – P_4O_{18} (calculation 0.3 points and determination of formula 0.2 points; 0.5 points in total). The problem says that structure fragment of central part of P_4O_{10} is saved and there are no terminal oxygen atoms. These data allow us to correctly depict the structure of the molecule.

As **D** is a binary compound, most probably, it is unstable metal oxide, because it begin to decompose at 190°C. The only substances are suitable **D** – Ag_2O, $\mathbf{D_1}$ – Ag.

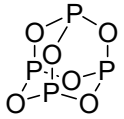
$$2Ag_2O \xrightarrow{t} 4Ag + O_2 \text{ (0.5 points)}$$

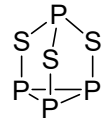
A similar class of binary compounds of phosphorus could be sulfides. From equality of molar mass of $\mathbf{B_1}$ and $\mathbf{A_1}$, we can calculate that $\mathbf{B_1}$ – P_4S_3, This also confirms the conclusion, that **Y** is **S** (0.25 points for each $\mathbf{B_1}$ and **Y**; 0.5 point in total).

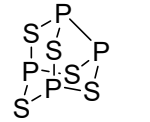
$$4P_{(red)} + 3S = P_4S_3 \text{ (0.25 points)}$$

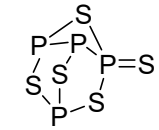
From equality of molar mass of $\mathbf{A_5}$ and $\mathbf{B_2}$, we can define that $\mathbf{B_2}$ – P_4S_5. From calculation of mass fraction for $\mathbf{B_4}$ we can define that $\mathbf{B_4}$ – P_4S_9. Compound $\mathbf{B_4}$ can be produced by comproportionation $\mathbf{B_5}$ and $\mathbf{B_3}$. From this condition we can definitely determine $\mathbf{B_5}$ – P_4S_{10}, and $\mathbf{B_3}$ can be P_4S_6, P_4S_7, P_4S_8. Using number and types of bonds in molecules we can conclude that $\mathbf{B_3}$ – P_4S_7 (0.25 points for each formula determination of $\mathbf{B_2}$, $\mathbf{B_3}$, $\mathbf{B_5}$; 0.3 points for calculation and 0.2 points for formula determination of $\mathbf{B_4}$; 1.25 points in total).

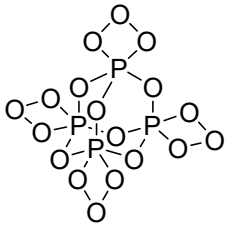
2. Structural formulas of compounds (0.25 points for each $\mathbf{A_1}$, $\mathbf{B_1}$, $\mathbf{B_4}$, $\mathbf{B_5}$; 0.75 points for each $\mathbf{B_2(1)}$, $\mathbf{B_2(2)}$, $\mathbf{A_6}$ and $\mathbf{B_3}$; 4 points in total):

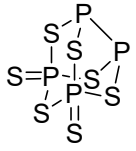
$\mathbf{A_1}$ – P_4O_6 

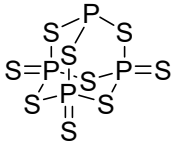
$\mathbf{B_1}$ – P_4S_3 

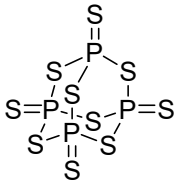
$\mathbf{B_2(1)}$ – P_4S_5 

$\mathbf{B_2(2)}$ – P_4S_5 

$\mathbf{A_6}$ – P_4O_{18} 

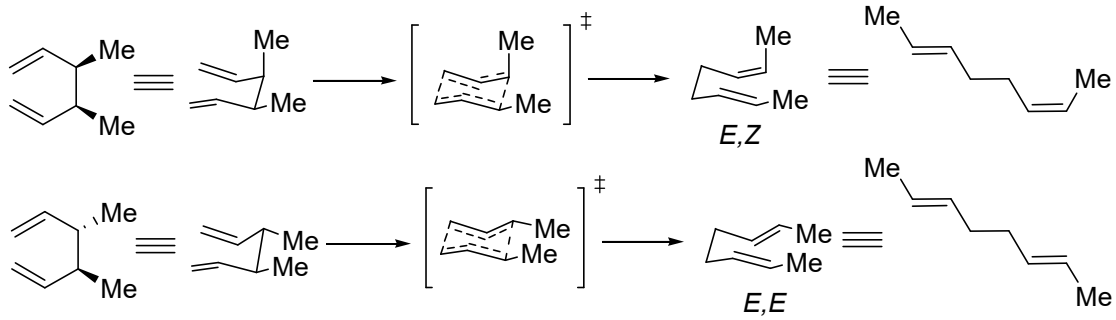
$\mathbf{B_3}$ – P_4S_7 

$\mathbf{B_4}$ – P_4S_9 

$\mathbf{B_5}$ – P_4S_{10} 

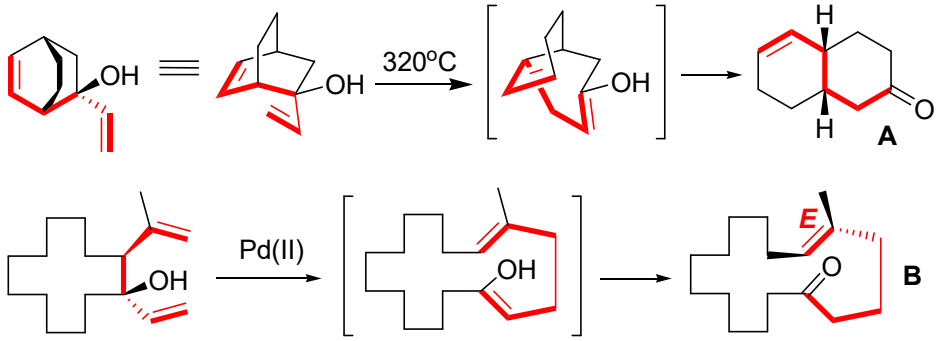
Problem 4 (authors Ilievski F.Z., Volochnyuk D.M.)

1. To prove the concert transition state of the reaction, Doering and Roth in 1962 investigated the Cope rearrangement of two diastereomeric 3,4-dimethyl-1,5-hexadienes (both C_8H_{14}) which gives two different reaction products (Scheme 1)[1] (0.25 points for each correct hydrocarbon structure and correct rearranged product, 1 point in total).

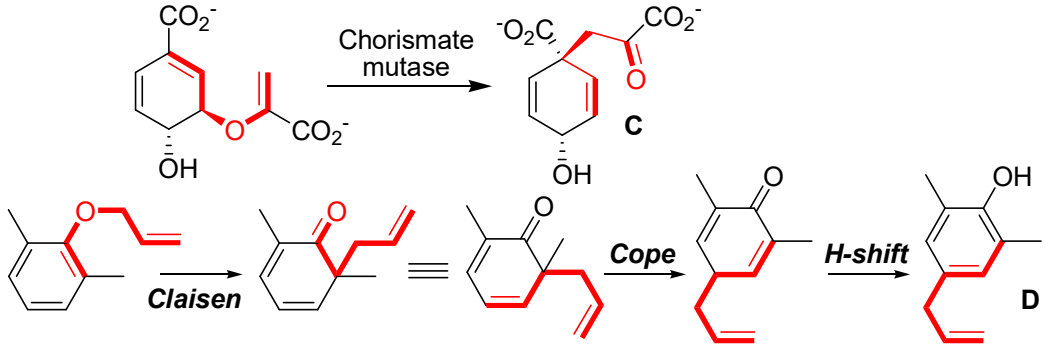


Scheme 1. Cope rearrangement of the two diastereomeric 3,4-dimethyl-1,5-hexadienes.

2. To correctly answer this question, one needs to recognize the fragments of 1,5-hexadiene (in a case of Cope rearrangement) or its hetero-analogue (in a case of Claisen rearrangement). **A** and **B** fall into the class of oxy-Cope rearrangement, where the mentioned fragment is easily recognized as showed on Scheme 2, labeled in red. As a result of oxy-Cope rearrangement, the corresponding enoles are formed, which are transformed into corresponding ketones. It should be noted that Pd-based catalysis allows carrying out the reaction at room temperature. In the referred case, the exclusively *E*-isomer of final product **B** formed (Scheme 2)[2]



Scheme 2. Oxy-Cope rearrangement.



Scheme 3. Claisen and tandem Claisen-Cope rearrangement.

C and **D** are products of the Claisen rearrangement. As in the case of oxy-Cope rearrangement, the key fragments can also be easily recognized in **Scheme 3**. In the case of chorismate, the enzymatic Claisen rearrangement leads to prephenate (compound **C**). In a case of allyl phenols the Claisen rearrangement leads to cyclohexadienone intermediate, which in absence of *ortho*-

substituents quickly tautomerizes to an *ortho*-substituted phenol. But in a case of two *ortho*-subsituents the tautomerisation impossible and the followed Cope rearrangement occurs. The final aromatization dives the *para*-substituted phenol **D** (Scheme 3)[3] (each correct structure A – D – 1 point, 4 points in total).

3. Firstly, one needs to solve the structure of ***barbaralane***. The compound has a degree of unsaturation $[(9 \cdot 2 + 2) - 10] / 2 = 5$ and must contain a 1,5-diene fragment, as it can be inferred from the nature of the problem. Therefore ***barbaralane*** is tricyclic molecule. Monocyclic molecules with the proposed formula cannot enter degenerate Cope rearrangement. From the bicyclic molecules, bicyclo[5.1.0]octadiene could do it (See Fig 1). Analysis of the formulas of bicyclo[5.1.0]octadiene (C_8H_{10}) and ***barbaralane*** (C_9H_{10}) show that these structures differ in one methylene bridge. The addition of methylene bridge into bicyclo[5.1.0]octadiene structure keeps the planar symmetry, leading us to the ***barbaralane*** structure – tricyclo[3.3.1.$0^{2,8}$]nona-3,6-diene[4] (1 point).

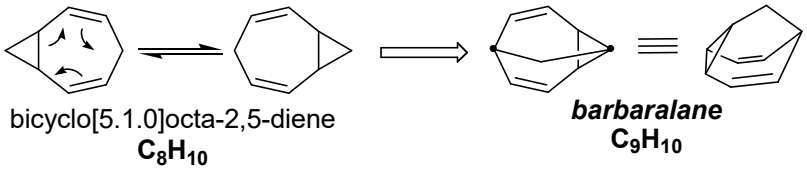
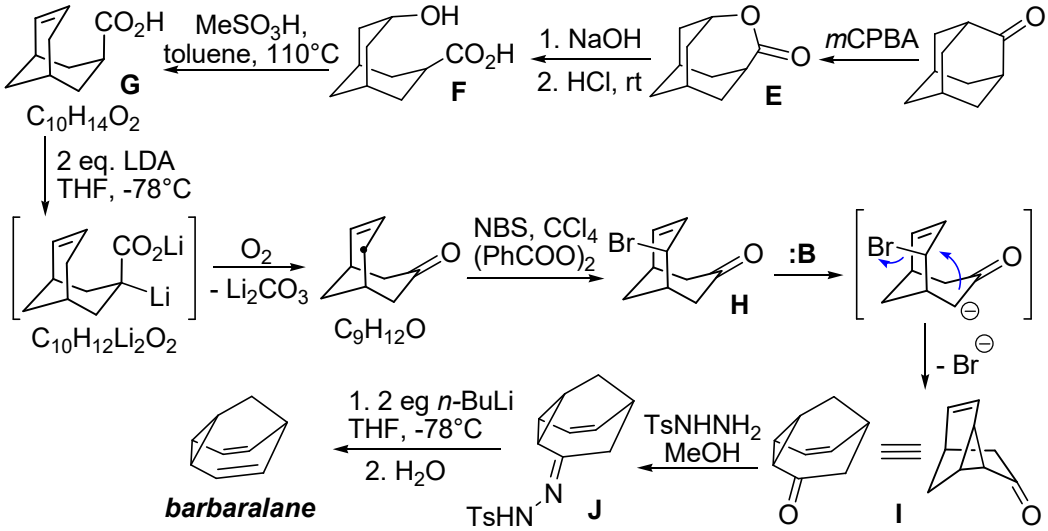


Fig. 1. Structures of bicyclo[5.1.0]octadiene and ***barbaralane***.



Scheme 4. Synthesis of ***barbaralane*.**

After solving of the ***barbarelane*** structure we can start to decode the synthetic scheme. The analysis of the structure of the starting adamantanone and unsaturated byciclic ketone showed that the reaction sequence leads to loosing of one carbon atom from carbonyl group of adamantanone. Taking into account the reagent used we can conclude that the oxidation of adamantanone by *m*-CPBA is Bayer-Villiger rearrangement affording polycyclic ester. The next steps are ester hydrolysis and acid induced water elimination which leads to unsaturated acid **G** ($C_{10}H_{14}O_2$). It is clear, that treatment of the this carboxylic acid by 2 eq. of strong base like LDA leads to di-lithium salt (see Scheme 2, problem), which has the formula $C_{10}H_{12}Li_2O_2$. Analysis of the intermediate and unsaturated ketone formulas showed that this step is oxidative decarboxylation ($C_{10}H_{12}Li_2O_2 + O_2 = C_9H_{12}O + Li_2CO_3$). The ketone has two bromination positions, allylic and CH-acidic α-position of keto-group. The given conditions clearly indicate radical bromination, which leads to bromoketone **F**. Basic treatment of the bromoketone **F** could lead to generation of carbanion, which undergoes intramolecular cyclization to tricyclic ketone **G**. This ketone **G** has the tricyclo[3.3.1.$0^{2,8}$]nonane skeleton equal to ***barbaralane***. Ketone **G** with

tosyl hydrasine gives corresponding hydrazone **H**. The last step of the synthesis is Bamford-Stevens elimination, a special case of Shapiro reaction (Scheme 2)[5] (each correct structure **E** – **H** – 0.5 points, total 3 points)

4. At –110°C the rearrangement is stopped and the ***barbaralane*** has 6 signals in ^{13}C NMR spectra. But at room temperature the molecule rapidly changes back and forth between the two structures. Therefore the C(1) and C(5), C(2) and C(4) becomes equal in NMR spectra (see Fig. 2) and at room temperature ***barbaralane*** has only 4 signals in ^{13}C NMR spectra. This is called *valence tautomerism* and is quite distinct from resonance, even though only electrons shift. (0.5 points for each correct number, total 1 point)

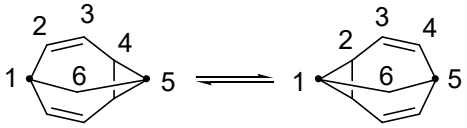


Fig. 2. Valence tautomerism of ***barbaralane***

Literature:

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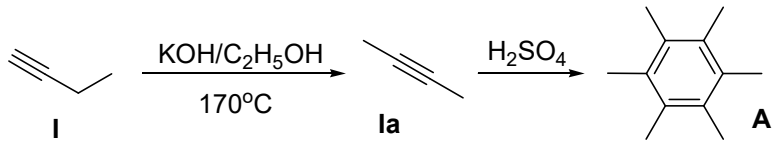
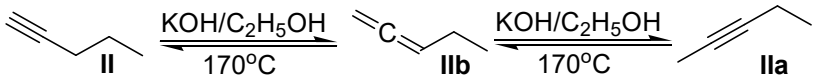
Problem 5 (author Bahtin S.G.)

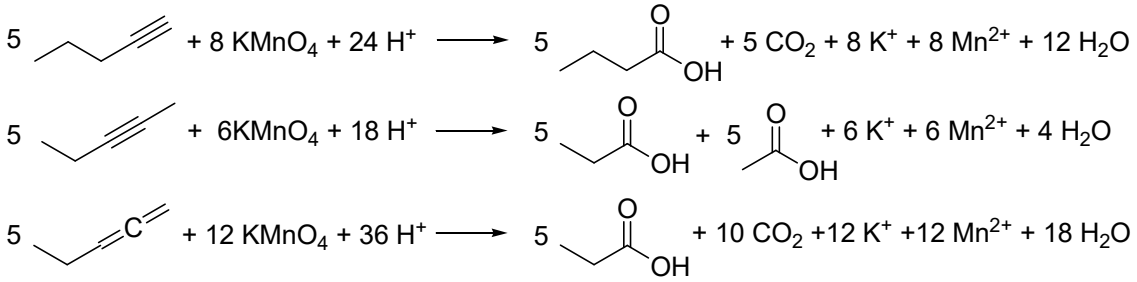
1. In compound **I** $n_C : n_H = (88.89/12) : (11.11/1) = 7.41 : 11.11 = 1 : 1.5 = 2 : 3 – (C_2H_3)_x$. The hydrocarbon $C_{12}H_{18}$ has the general formula $C_nH_{2n–6}$, i.e. is an arene. Only one singlet in the aliphatic region in ^1H NMR spectra of compound **A**, which corresponds to (18/3) = 6 CH_3-groups showed that **A** – hexamethylbenzene. The value $x = 1$ for **I** is impossible due to valency (C_2H_3 is a radical). When $x = 2$ the formula of **I** is C_4H_6. Given that fact that there is an isomer of **I** with different position of the multiple bond - compound **Ia**, able to converts to hexamethylbenzene in one step (only one organic product according to the task, e.g its trimerization reaction), we could conclude that **Ia** is butyn-2, and **I** is butyn-1 [1-3] (0.5 points for each correct structure **I**, **Ia** and **A**, 1.5 points in total).



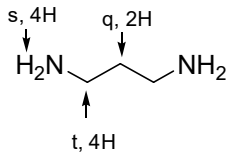
2. According to the results from above mentioned sections, the discussed isomerization is a rearrangement of terminal alkyne (R–C≡C–H) to alkyne with a non-terminal triple bond (R'–C≡C–R''). It is obvious that in a course of the oxidation of R–C≡C–H with the cleavage of multiple carbon bonds, CO_2 and the highest carboxylic acid (RCOOH) will formed (in our case it is butanoic acid). Therefore, the initial terminal alkyne **II** is pentyne-1, and the product of the shifting of the triple bond **IIa** is pentyne-2. Molecules **II** and **IIa** both contain 2 C(sp) atoms. In accordance with the problem data the isomer **IIb**, which is intermediate of pentyne-1 rearrangement into pentyne-2, should have only one sp-carbon, which is possible only for the cumulated diene – pentadiene-1,2 [4] (0.5 points for each correct structure **II**, **IIa** and **IIb**, 1.5 points in total):



3. When writing the corresponding equations, it is necessary to take into account that by the oxidizing of terminal alkyne to acid and CO_2 is an 8-electron process; oxidation of nonterminal alkyne to two carboxylic acids is a 6-electron process; oxidation of terminal allene to acid and two CO_2 molecules is a 12-electron process [5] (each correctly balanced equation is 0.5 points, 1.5 points in total).



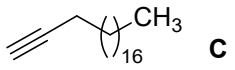
4. Taking into account ^{1}H NMR data, the structure of $C_3H_{10}N_2$ is 1,3-diaminopropane:



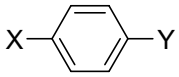
Upon treatment of the 1,3-diaminopropane by equivalent amount of KH the corresponding amide $KNHCH_2CH_2NH_2$ (**X**) formed, which is a strong base, called in the literature KAPA (Potassium 3-Aminopropylamide). The disubstituted alkyne **IIa** bearing non-terminal triple bond is thermodynamically more stable than the monosubstituted terminal alkyn **II**. Thus, in rearrangement **II** to **IIa** KOH acts as a catalyst, which accelerates achievement of thermodynamic equilibrium through a series of transfer of protons *via* the allene type intermediate. In a case of "reverse" rearrangement **IIa** into **II** the strong base (like KAPA) shifted equilibrium into **II** due to the deprotonation of acetylenic C≡C–H proton affording pure soluble potassium salt (in accordance with Le Chatelier's principle). Thus, unlike the KOH catalyst, the KAPA base acts as a reagent and therefore it is used in stoichiometric amount [6] (the structure of $C_3H_{10}N_2$ –

0.25 points, the structure of **X** – 0.25 points; the role of bases KOH and **X** – 0.25 points each, 1 point in total).

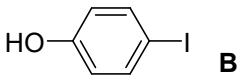
5. According to the task the compound **C**, is the unbranched homologue of terminal alkine **I**, i.e. has the general formula C_nH_{2n-2}; $w_C = 12n / (12n + 2n - 2) = 0.8633$; $n = 20$:



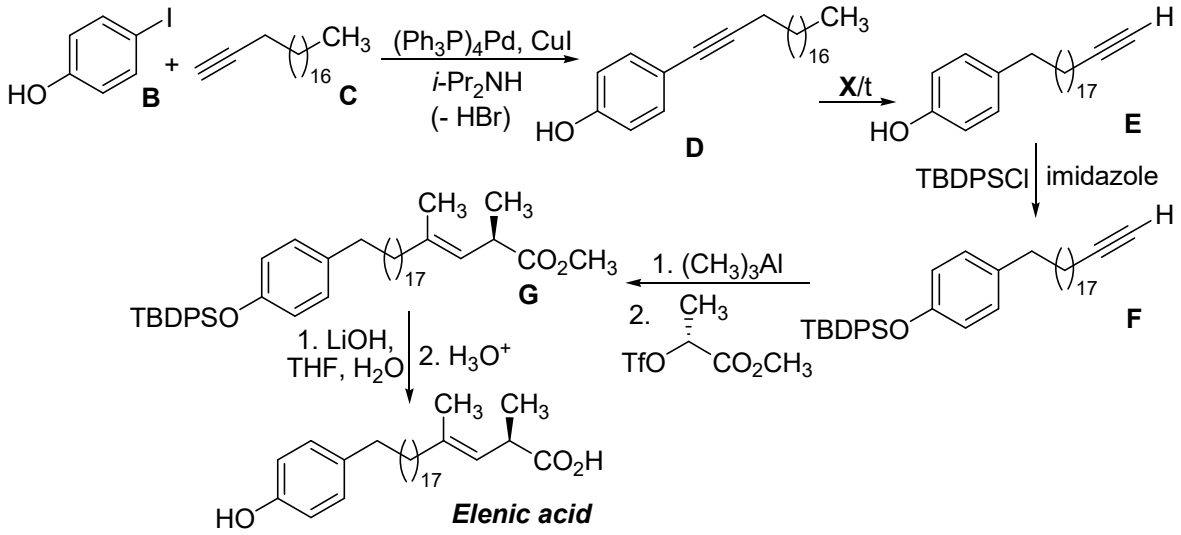
According to ^{1}H NMR data, the second starting material **B** contains 1 + 2 + 2 = 5 atoms of H. Then $M_B = 5 / 0.0227 = 220$ and the number of carbon atoms in **B** is $222 \cdot 0.3273 / 12 = 6$. In this case, the two doublets (2H integral intensity) in the aromatic region (δ = 6.6 and 7.5 ppm) indicate the presence in **B** of a *para*-substituted benzene ring. This is in agreement with the presence of 6 C atoms in it. So **B** contains a fragment:



In this case, the last fifth proton (from 1H NMR) must be present in one of the substituents. On the other hand, according to the synthesis scheme, the coupling of **B** and **C** is the Sonogashira reaction with hydrogen halide elimination. Since **C** is alkyne, it means that halogen was present in compound **B**. Finally (except carbon and hydrogen) in **B** is 220 – 12·6 – 5 = 143 Da. If Hal is fluorine, the 143 – 19 = 124 Da – still remains – too much for a substituent containing one H atom; the same goes for Cl and Br. In the case Hal – iodine, then in the remainder 143 – 127 = 16 Da, which corresponds to the oxygen atom in the substituent. So **X** and **Y** are I and OH. The structure of **B** is:



According to the problem the coupling of **B** and **C** leads to the formation of internal alkyn **D** via HI elimination. The fact allows us to unambiguously solve the structure of **D**.



Due to results obtained in questions 1 – 4, the transformation **D** under the treatment of **X** is multiple shifting of the C≡C bond to the end of the carbon chain (zipper reaction), affording the terminal alkyne **E**. Than the phenol group in **D** is protected forming **F** with subsequent treatment by trimethyl-

aluminum. In this case, an organometallic derivative should be intermediate formed, which is then alkylated by triflate derivative into product **G.** The two final stages of the synthesis of helenic acid include hydrolysis of the ester and the deprotection of the TBDPS group [7] (structures **B**, **C** and **E** – 0.5 points for each; structures **D**, **F** and **G** – 0.5 points for each, 4.5 points in total).

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Problem 6 (authors Kandaskalov D.V., Borschevsky A.Ya.)

1. –Pb, $PbSO_4$ | H_2SO_4 | PbO_2, Pb+ (0.5 points)

2. а) $Pb + PbO_2 + 2H_2SO_4 = 2PbSO_4 + 2H_2O$ (0.25 points)

б) $E° = E_2^0 - E_1^0 = 1.682 - (-0.359) = \underline{2.041\ V}$ (0.25 points)

в) $\Delta_r G^0 = -nFE^0 = -2 \cdot 96485 \cdot 2.041 = -393.9\ kJ \cdot mol^{-1}$ (1 point)

г) $K = \exp(-\Delta_r G^0/RT) = \exp(-393851.77/8.314/298.15) = \underline{1.01 \cdot 10^{69}}$ (0.5 points, 2 points in total)

3. $Pb + H_2SO_4 = PbSO_4\downarrow + H_2\uparrow$ (0.5 points)

4. а) $PbO_2 + 2H_2SO_4 = Pb(SO_4)_2\downarrow + 2H_2O$ (0.5 points)

б) $PbO_2 + Pb(SO_4)_2 = 2PbSO_4 + O_2\uparrow$ (0.5 points, 1 point in total)

5. On the Pb electrode we have Pb oxydation which corresponds to the half-reaction: $Pb^{2+} + 2e^- = Pb$. The Nernst equation for this process is (1.5 points)

$$E_{Pb} = E_{Pb}^0 + \frac{RT}{2F} \ln a(Pb^{2+})$$

As the concentration of Pb^{2+} is very low, the activity is assimilated to the concentration and we have (1.5 points, 3 points in total)

$$E_{Pb} = E_{Pb}^{\ 0} + \frac{RT}{2F}\ln[Pb^{2+}] = -0.126 + \frac{0.059}{2}\lg(0.93\cdot10^{-6}) = -0.126 - 0.178 = \underline{-0.304\ V}$$

6. Knowing the molar weight of the acid $M(H_2SO_4) = 98.08\ g\cdot mol^{-1}$, we find the molality of the acid $m(H_2SO_4) = 3.835\ mol\cdot kg^{-1}$ (0.5 points), and its activity $a(H_2SO_4) = \gamma m = 0.165 \cdot 3.835 = 0.633$ (1 point).

The Nernst equation for the total reaction in the cell (1.5 points, 3 points in total):

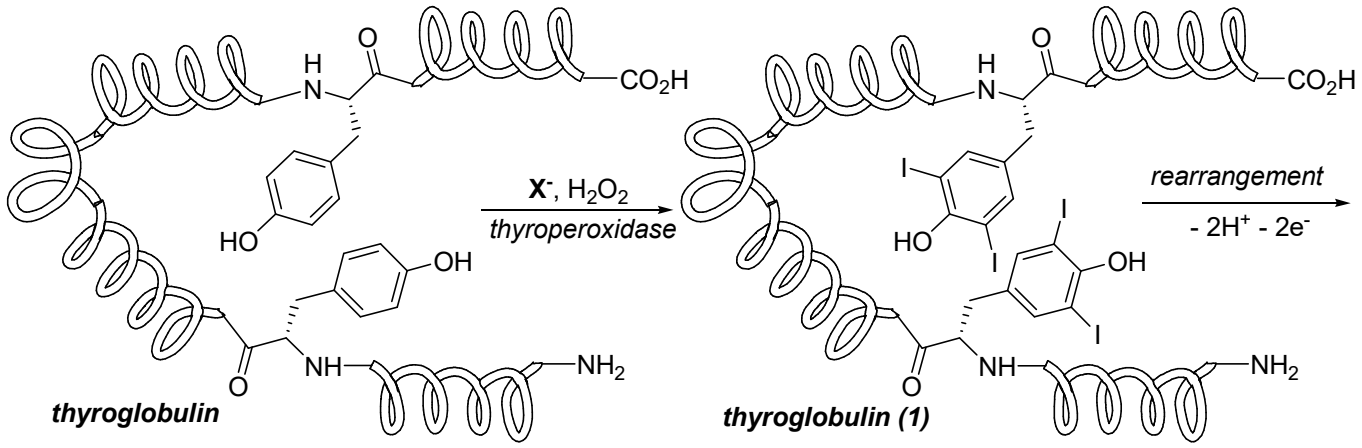
$$E = E^0 + \frac{RT}{2F}\ln\frac{a(H_2SO_4)^2}{a(H_2O)^2} = 2.041 + 0.059\lg\frac{0.633}{0.7} = \underline{2.038\ V}$$

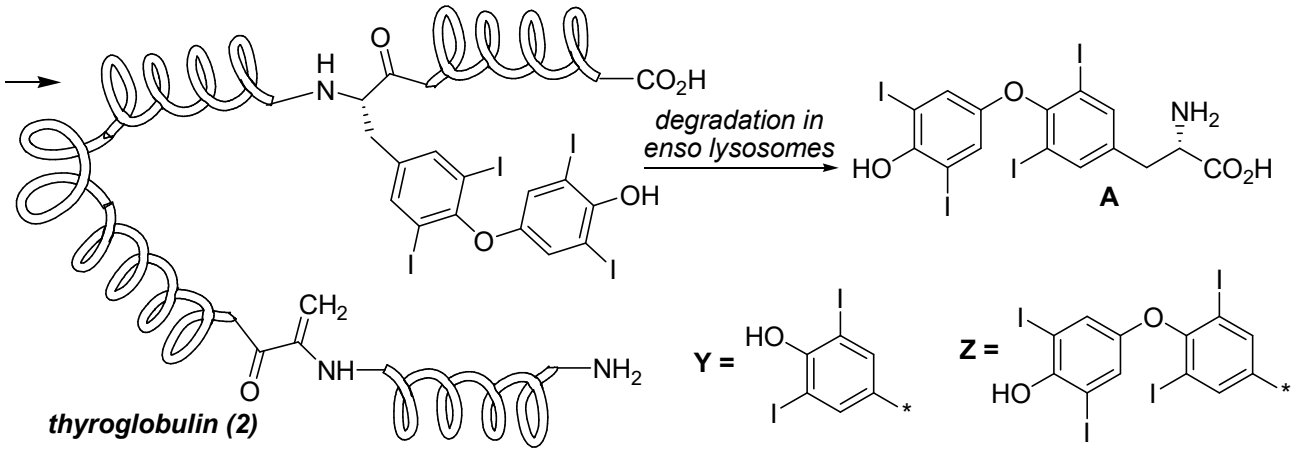
Problem 7 (authors Volochnyuk D.M., Gorlova A.A.)

1. High content of **W** in the organic compounds **A**, **B**, and **F** (58.48 to 67.88%!) suggests that it is iodine. This is further confirmed by the process localization in the thyroid body. Then, $\mathbf{X}^-$ is iodine anion and the **A** → **B -** transformation is deiodination. Let us consider the below set of equations denoting **A** as RI_n, and **B** as RHI_{n-1}.

$$n\cdot AW(I) / [MW(R) + n\cdot AW(I)] = 0.6534$$
$$(n-1)\cdot AW(I) / [MW(RH) + (n-1)\cdot AW(I)] = 0.5848$$

which gives $n = 4$ and MW(R) = 269. The molecular weight of R is by 4 a.m.u. less than that of **C**. Then, **C** is a fully deiodinated compound with the same carbon scaffold as in **A** and **B**. The molecule of **A** contains 4 iodine atoms, hence, the first stage consists in double iodination of the tyrosine units via the electrophilic mechanism at the ortho-positions with respect to the phenolic group, whereas **Y** is diiodophenol. Further transfer of the diiodophenol fragment to the bisiodated thyrosine unit, followed by hydrolysis, affords **A**, the thyroid hormone T4.

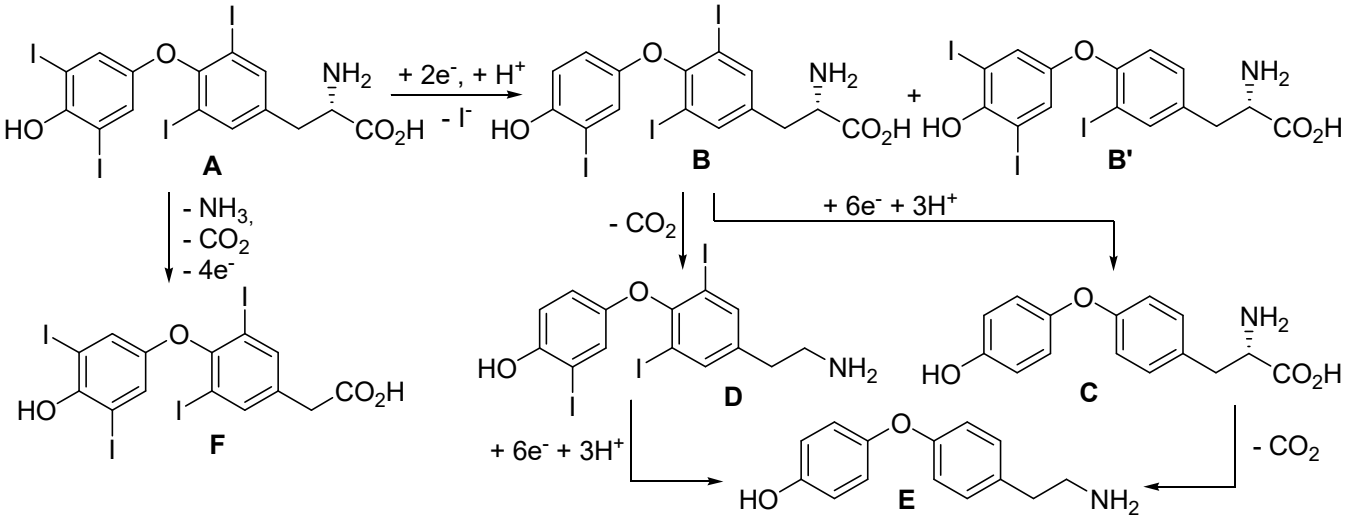




Scheme 1. Biosynthesis of the thyroid hormone **T4**.

Further transformations are shown in Scheme 2. The choice between structures **B** and **B'** is unambiguous due to steric availability of the iodine atom; **B** is the thyroid hormone (**T3**), **B'** is an inactive compound (**rT3**), **C** is tyrosine (amino acid), **D** and **E** are threonamines, potentially psychoactive compounds. **F** is an acid known as **Tetrac** exhibiting anticancer activity towards certain affections of thyroid body (0.5 point for the anion **X**, 0.5 point for the calculations; 1 point for each of the compounds **A** – **F**, fragments **Y** and **Z**; 10 points in total).

The problem can be solved starting from deciphering **E**. The gross formula of **E** = gross formula of **C** ($C_{15}H_{15}NO_4$) – CO_2 = $C_{14}H_{15}NO_2$. Analysis of the number of signals in the NMR spectra unambiguously gives the structure of **E**.



Scheme 2. Biosynthesis of **B** – **F**.

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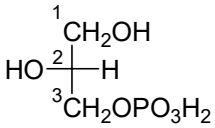
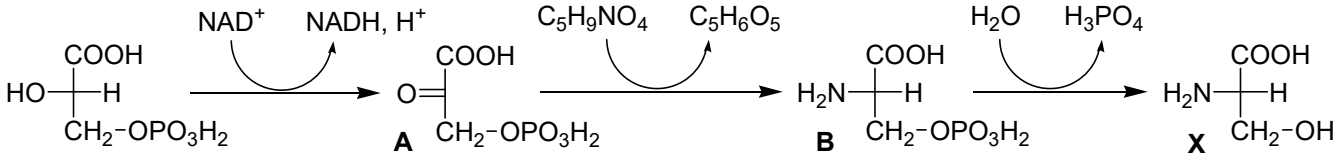
Problem 8 (author Kutsenok E.O.)

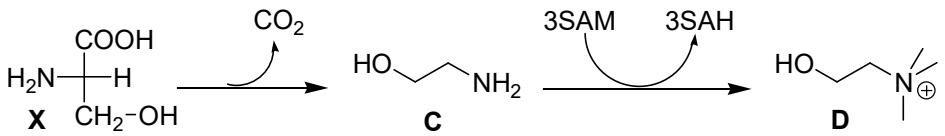
1. In the glycerol 3-phosphate molecule, the C-2 atom has four different substituents. The Fischer projection of the *R*-isomer is given below. Its relative configuration is *L*, since the OH-group is left-directed (0.5 point for the structure, 0.5 points for the relative configuration, 1 point in total)



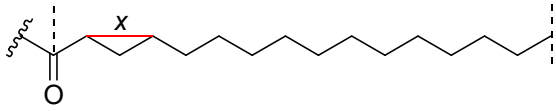
2. Of all groups present in glycerol 3-phosphate, only hydroxyl group can be oxidized (to the carbonyl one). The material balance of further transformation suggests loss of one O atom and attachment of NH_3 group. Only a compound with the formula of $C_5H_9NO_4$ can be the canonical α-amino acid (glutamic acid), therefore transamination is the second step at the scheme. Hence the structures of **A**, **B** and **X** (serine) are determined unambiguously:



The last steps are decarboxylation of serine, followed by triplicate methylation of the amino group (0.5 point for each structure, charged forms of ionogenic groups accepted, 2.5 points in total):



3. The figure below shows the hydrophobic part of the phospholipid (inside the dashed lines). The length of this part equals 7.5 segments denoted ***x***.



Utilizing geometric calculations and the C–C bond length:

$$\boldsymbol{x} = \text{tg}(109°/2) \cdot 0.154 \cdot 2 = 0.4 \text{ nm}.$$

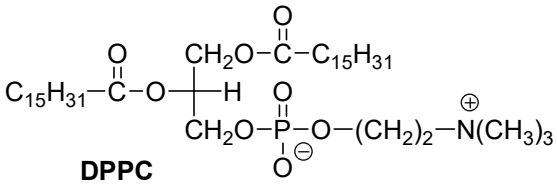
Then the length of the hydrophobic part of the molecule is $0.4 \cdot 7.5 = 3$ nm. Since the liposomal radius is of 50 nm, the internal cavity radius is:

$$r_{\text{internal}} = 50 - 3 \cdot 2 = 44 \text{ nm}.$$

The volume of the internal cavity is found using the formula of a ball volume (1 point for the length of hydrophobic part, 0.5 point for the volume of the internal cavity, 1.5 points in total):

$$\boldsymbol{V_{internal}} = \frac{4}{3}\pi \cdot 44^3 = 3.6 \cdot 10^5 \text{ nm}^3$$

4. a) m (lipids) $= 25 \cdot 0.02 = 0.5$ mg $= 5 \cdot 10^{-4}$ g



DPPC

M(DPPC) = $M(C_{40}H_{80}NO_8P)$ = 734 g/mol
N(lipids) = $5 \cdot 10^{-4} / 734 \cdot 6.02 \cdot 10^{23} = 4 \cdot 10^{17}$ molecules.
$S_{\text{external}} = 4\pi \cdot 50^2 = 3 \cdot 10^4$ nm^2.
N(external lipids in the liposome) = $3 \cdot 10^4 / 0.44 = 6.8 \cdot 10^4$ lipids.
$S_{\text{internal}} = 4\pi \cdot 44^2 = 2.4 \cdot 10^4$ nm^2.
N(internal lipids in the liposome) = $2.4 \cdot 10^4 / 0.44 = 5.5 \cdot 10^4$ lipids.
N(lipids in the liposome) = $1.2 \cdot 10^5$ lipids.
N(liposomes) = $4 \cdot 10^{17} / 1.2 \cdot 10^5 = 3.3 \cdot 10^{12}$ particles.
Concentration of the liposomes: $3.3 \cdot 10^{12} / 5 = 6.6 \cdot 10^{11}$ part/mL
(0.5 points for the molecular weight of DPPC, 1 point for the number of the liposomes, 0.5 points for the concentration of the liposomes, 2 points in total)

b) $V_{\text{internal, total}} = 3.6 \cdot 10^5 \cdot 3.3 \cdot 10^{12} = 1.2 \cdot 10^{18}$ nm^3 = 1.2 mm^3 = $1.2 \cdot 10^{-3}$ mL (0.5 points).

5. $\ln(c_0/c)/t = \ln 2/t_{½}$; $t_{½}(Dox)$ = 24 h; $t_{½}$(liposomes) = 26 h. As you can see from the data obtained, the difference in the use of liposomal and free form of doxorubicin is not significant. In practice, liposomes are further modified with polyethylene glycol to achieve a more pronounced effect, which helps to increase $t_{½}$ up to 46 h (0.5 point for using the first order kinetics equation, 0.5 point for each $t_{½}$, 1.5 points in total).

6. The mass of *Dox* inside the liposomes: $25 \cdot 1.24 \cdot 10^{-3} = 0.031$ mg.

$\ln(m_0/m)/t = \ln 2/t_{½}$ (for the same volume, the concentration can be replaced by mass); $m(Dox) = 7.77 \cdot 10^{-11}$ mg; m(*Dox* inside the liposomes) = 0.02 mg (0.5 point for each mass, 1 point in total).