Problem 1

Organic derivatives of inorganic acids usually become known much later than the corresponding inorganic salts, but there are some exceptions. Thus, in 1956, Huisgen and Ugi obtained the compound PhX (**A**), the structure of which was unambiguously proven 27 years later by single crystal X-ray diffraction analysis. On the contrary, the studies of the acid HX and its inorganic derivatives were carried out only by quantum chemical methods until the beginning of the 21st century. Thus, in 2001, the existence of the FeX_2 molecule (**B**) was predicted with the binding energy of the Fe^{2+} and $2X^-$ ions forming it only slightly lower than that of the ions in the isoelectronic molecule FeY_2 (**C**), discovered already in 1951. The light-orange compound **C** with the melting point of 173°C and the boiling point of 249°C is stable when heated to about 450°C, soluble in organic solvents, including benzene, and insoluble in water. It laid the foundation of a new field of chemistry, which was further included in both inorganic and organic chemistry textbooks.

A derivative of **A** was later obtained according to the Huisgen and Ugi procedure from 4-methoxyaniline using NaQ salt. When this new compound was oxidized with ceric(IV) ammonium nitrate (CAN) at −40°C in the presence of zinc nitrate, the formation of a mixed salt $Zn(X)NO_3$ (**D**) was observed. When kept at −20°C, this salt decomposes releasing a gas and forming another salt, $Zn(Q)NO_3$ (**E**), containing the same elements as **D**, including 38.59% zinc.

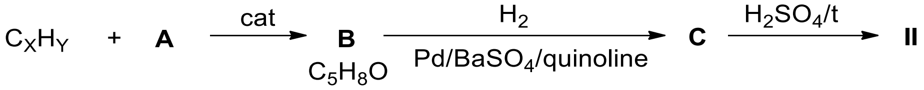
The compound **F**, an isomer of **B**, was obtained in 1999. **F** is isoelectronic to another known iron compound **G**, a light-yellow liquid immiscible with cold water. **F** dissolves in ethanol, benzene, acetic acid and is used mainly to obtain high-purity iron powder. According to calculations, **F** is by 260 kcal/mol more stable than **B**, still the binding energy of the components in it does not exceed 33.7 kcal/mol.

In 2017, a stable salt **H** was obtained by oxidation of another aryl-X type compound with *meta*-chloroperbenzoic acid in the presence of iron bis(glycinate). After purification by column chromatography, **H** was characterized by single crystal X-ray diffraction analysis. It turned out that this salt has a complex composition: it contains X anions, chloride ion, ammonium and hydronium (H_3O^+) cations, whereas the content of hydrogen, nitrogen and chlorine in **H** is 4.31%, 81.42% and 6.06%, respectively. Starting from this salt, other salts of the acid HX with a variety of cations are obtained by a cation metathesis reaction.

1. Write down molecular formulas of HX, **D**, and **E**; draw the structures of **A**–**C**.
2. Write down equations of the reactions used by Huisgen and Ugi to synthesize PhX.
3. Draw the structures of **F** and **G**.
4. Calculate the molecular formula of **H**.

Problem 2

Crystals of an optically active terpene hydrocarbon further referred to as “cembrene” (**I**) were isolated from *Pinus albicaulis* (Whitebark Pine) in 1951. This hydrocarbon was the first natural compound, the molecule of which was found to contain a carbocycle of an unusual size. All terpenes are usually considered as polymerization products of the hydrocarbon **II**. Terpenes are subdivided into monoterpenes ($n = 2$), sesquiterpenes ($n = 3$), diterpenes ($n = 4$), triterpenes ($n = 6$) and polyterpenes depending on the number of units (n) of **II**. One of the industrial syntheses of **II** is given below:



$$C_XH_Y + \mathbf{A} \xrightarrow{cat} \underset{C_5H_8O}{\mathbf{B}} \xrightarrow[Pd/BaSO_4/quinoline]{H_2} \mathbf{C} \xrightarrow{H_2SO_4/t} \mathbf{II}$$

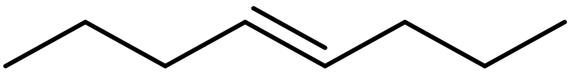
1. Determine the structures of C_XH_Y, **A**–**C,** and **II**, if C_XH_Y gives a precipitate with an ammonia solution of silver oxide, while the carbonyl compound **A** does not react with it.
2. Choose the catalyst for the first step from the list: a) Al_2O_3; b) H_2SO_4; c) $(C_2H_5)_3N$; d) $[(i\text{-}C_3H_7)_2N]Li$; e) KOH.

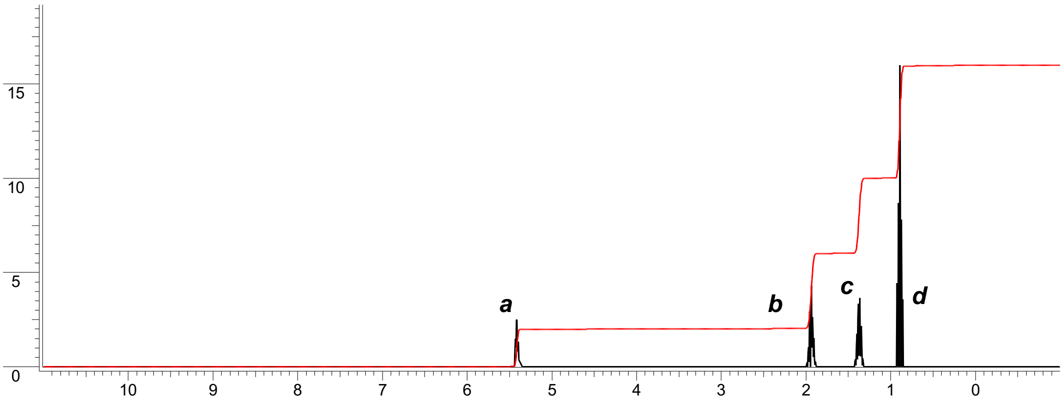
The structure of cembrene was elucidated in 1962. According to the mass spectrum data, the molecular weight of **I** is 272 a.m.u. 16.32 g of **I** can completely add 2764 mL of H_2 (50°C, 2.3 atm) in the presence of Pd/C.

3. Determine the molecular formula of **I.** Which class of terpenes (monoterpene, sesquiterpene, diterpene, triterpene, polyterpene) does it belong to?
4. Calculate the number of rings (n_{ring}) and double bonds ($n_{\text{C=C}}$) in the molecule of **I**.

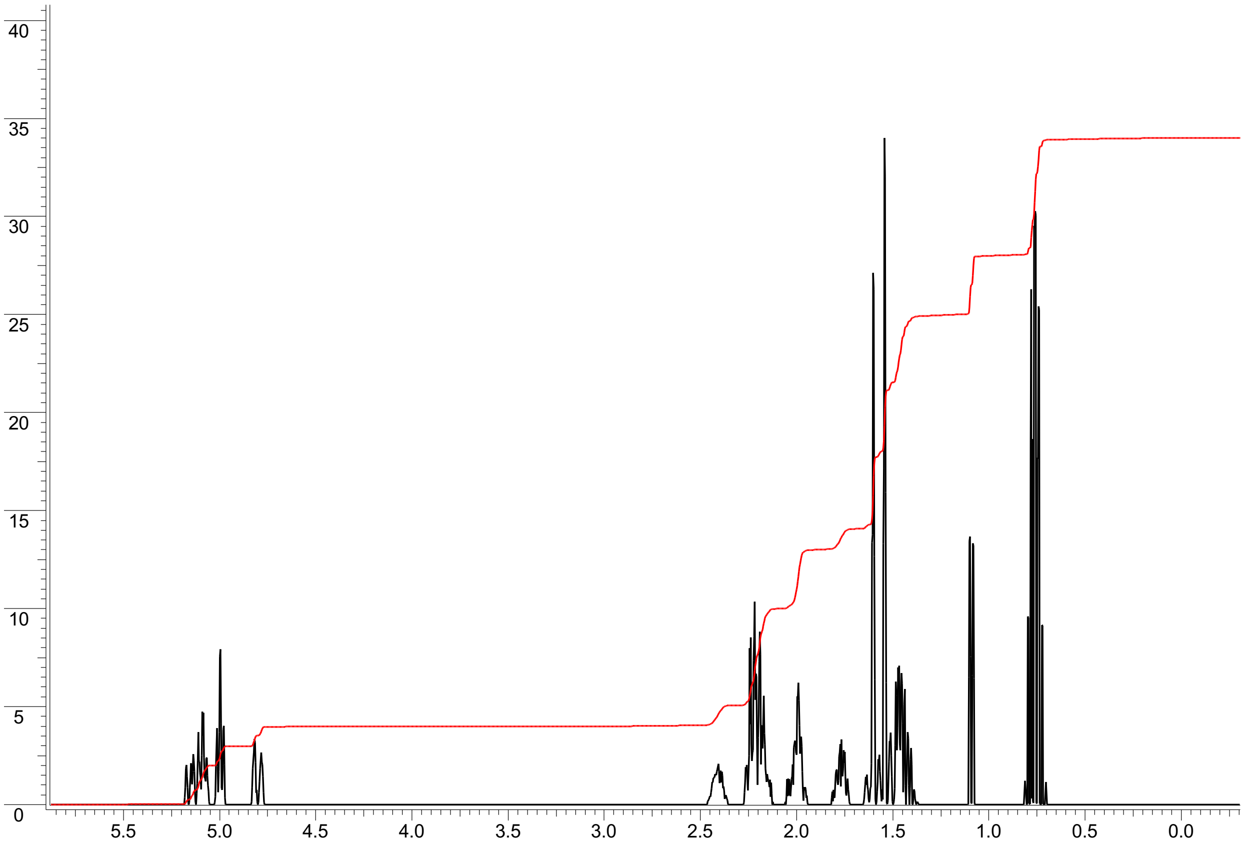
The reduction of **I** under the action of Li/NH_3 leads to the formation of dihydrocembrene (**III**). The ^{1}H NMR spectra of *trans*-4-octene and **III** are shown below.

5. In the *trans*-4-octene structure, label the groups ***a*** – ***d*** that give the corresponding signals in the spectrum. Calculate the total number of hydrogen atoms at the double (n_H-sp^2) and single (n_H-sp^3) C-C bonds in the molecule of **III**.





^{1}H NMR spectrum of *trans*-4-octene.



^{1}H NMR spectrum of **III**.

Ozonolysis of **III** with subsequent treatment with H_2O_2 gave an equimolar mixture of 2-isopropyl-5-oxohexanoic acid, 2-methylpentanedioic acid and a thermally stable bifunctional compound **X**; no other carbon-containing products were found.

6. Calculate the molecular formula of **X** and determine its structure.
7. Determine the ring size in cembrene.

Problem 3

> Don't worry about your problems with math. Believe me, mine are much more serious.
> Albert Einstein

The inhabitants of the border regions of the biosphere ought to adapt evolutionarily to extremely strict living conditions. This fact explains that they are usually referred to as extremophiles. In particular, barophiles (for example, some species of fish) are adapted to life under conditions of huge hydrostatic pressure of the ocean depths, which typically causes a disruption in the structure of proteins. In order to minimize the effect of such a press, barophiles produce special low-molecular organic oxygen-containing substances – osmolytes (for example, glycerol or glycine), which stabilize the structure of proteins due to the formation of hydrogen bonds.
The compound **X**, a major osmolyte in deep-sea organisms, has the carbon to nitrogen mass ratio of 2.57:1. The number of atoms of any of the four elements in the molecule **X** can be represented as a power of three (3^m, where m is an integer).

1. Prove by giving an appropriate mathematical expression (equation) that the molecular weight of any **X** with the formula matching the condition given above is always an odd number (provided that A_r are rounded to the nearest integer).

X is degraded enzymatically according to the reaction equation:

$$\mathbf{X} \rightarrow \mathbf{X1} + \mathbf{X2}.$$

X1 and **X2** are gaseous substances under standard conditions (25°C, 1 atm), toxic to humans. The densities of the substances strictly relate as 3:2, when using the atomic masses of the elements rounded to the nearest integer.

2. Determine the molecular formulas of **X**, **X1** and **X2**, keeping in mind that the integrality of the molecular weights is the key idea behind the solution. Show your calculations.
3. Determine the structure of **X** if all the carbon atoms in it are equivalent.

Available as a laboratory reagent, white crystalline substance **Y** (M = 111 g/mol), also has osmolyte properties and is used primarily in the study of protein folding to reduce the denaturing effect of urea. **X** and **Y** are identical according to the following: elemental composition (1), mass ratio of carbon and nitrogen (2), equivalence of carbon atoms (3).

4. Draw the structure of **Y**, paying attention to the angles between the bonds.

The compound **Z** is another osmolyte in marine organisms. The functioning of **X** and **Z** is due to a similar structural motif. It is known that the number of hydrogen atoms ($N_H \le 10$) in the molecule of **Z** is the product of the numbers (different from each other) of all other atoms (for example, for an arbitrary substance $C_aH_bO_cN_d$: $b = a \cdot c \cdot d$ with $a \neq c \neq d$).
Z is degraded enzymatically according to the reaction equation:

$$\mathbf{Z} \rightarrow \mathbf{Z1} + CH_2{=}CH{-}COOH.$$

5. For a theoretical structural formula of **Z**, devoid of formal intramolecular charges on the atoms, prove by giving the corresponding molecular formula that of the four elements forming it, only one exhibits an odd valence (denote the unknown element **E**). Indicate which coefficients in the formula support the proof.

Z1 is non-enzymatically oxidized by molecular oxygen dissolved in sea water to a single product, **Z2** (M = 78 g/mol). The molecule of **Z2** contains one type of atom of each element.

6. Determine the molecular and structural formulas of **Z**, **Z1** и **Z2**. Prove by calculations.

Problem 4

Metabolism is a paradoxical concept of sustaining life. Although enzymes are incredibly complex in their structure and function, most of substrates, intermediates and products are deceptively simple.
Some species can still grow and develop despite the lack of carbohydrates produced due to photosynthesis or obtained as nutrients. Such organisms can utilize C-2 compounds (molecules containing 2 carbon atoms) as growth substrates. In 1957, Krebs and Kronberg made seminal discovery of a pathway based on glyoxylate (Fig. 1) that solves this problem in plants, prokaryotes, and archaea.

In aqueous solutions, glyoxylic acid exists as a monohydrate (Fig. 2). Spectral analysis suggests an equilibrium with the symmetrical hemiacetal **X**, formed when the monohydrate reacts with a non-hydrated glyoxylate in a 1:1 molar ratio.

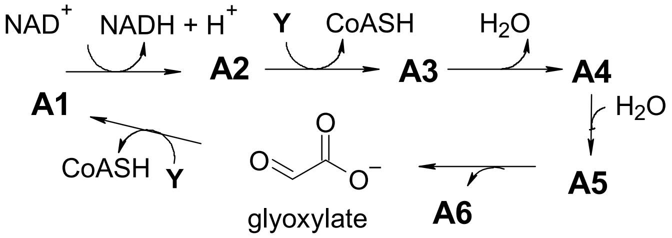


Fig. 1. Glyoxylate cycle.

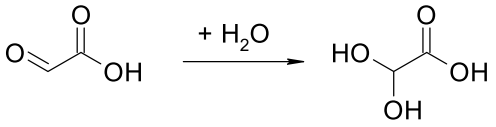


Fig. 2. Monohydrate formation.

1. Draw the structure of **X**.

2. Decipher the scheme in Fig. 1 if it is known that all metabolites within the cycle are composed of the same three elements and that the elemental composition in the table refers to the species found under physiological conditions at pH 7.4. Note that all the metabolites are acyclic products, whereas **A4** has *E*-*Z* isomers.

3. Write down the balanced net equation of the glyoxylate cycle. If needed, show the coenzyme A residue as –SCoA.

Metabolite	Overall charge (absolute value)	ω(C) (%)
A1	2	36.37
A2	2	36.94
A3	3	38.11
A4	3	42.12
A5	3	38.11
A6	2	41.39

In 1959, Harold Kronberg, Kreb's student, discovered that glyoxylate is biosynthesized from C-2 precursors **X1, X2** and **X3**.

4. Draw the structures of **X1, X2** and **X3**, considering the information in the table below.

M of the form prevailing at pH 7.4 (g/mol)	$n(CO_2)/n(H_2O)$ from complete combustion of solid X(N)	Overall charge in an aqueous solution (absolute value)
X3 = **X1** (rounded to the integer)	1 (**X1**)	1 (**X1**)
X2 – **X1** = 13	2 (**X2**)	2 (**X2**)
	4/5 (**X3**)	0 (**X3**)

The following reaction sequence is found in some plants: **X1** → glyoxylate → **X3**.

5. From the list (amidase, oxidase, reductase, transamidase), choose the correct enzymes that are responsible for the **X1** → glyoxylate and glyoxylate → **X3** transformations.

Mammalian cells can also produce glyoxylate and pyruvate in mitochondria from the non-canonical amino acid 4-hydroxyproline, found as a residue in collagen (Fig. 3).

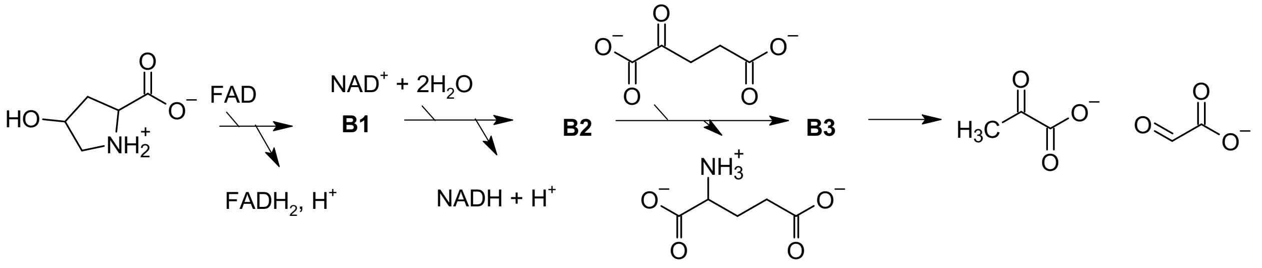


Fig. 3. Biosynthesis of glyoxylate from 4-hydroxyproline.

6. Draw the structures of **B1**, **B2**, and **B3**. Note that the last step is catalyzed by aldolase.
7. Propose the scheme of a pathway leading from pyruvate to glyoxylate in organism.

Problem 5

The dependence of solubility of a solid substance *c* on its particle size *r* obeys the Gibbs–Freundlich–Ostwald equation:

$$c(r) = c_0 e^{\frac{2\sigma V_m}{rRT}}$$

(c_0, σ, and V_m are the solubility of the macroscopic phase, specific surface energy, and molar volume of the substance, respectively; *R* is the universal gas constant; *T* is the absolute temperature). For a poorly soluble halide **X**, the solubility of the nanoparticles with $r = 100$ nm is by 9.3% higher compared to the macrophase at the temperature of 25°C, $\sigma = 450$ mJ/m^2, and density $d = 3.18$ g/cm^3.

1. Calculate the molar volume of the halide **X**. *If you failed to determine* V_m*,, use* $V_m = 2.95\cdot10^{-5}$ *m*^{3}*/mol in further calculations.*
2. Calculate the molar mass and determine the formula of the halide **X**.

The dependence of solubility on the particle size is behind the Ostwald ripening of precipitates. Since the solubility is increased with the decrease in the particle size, a solution saturated with respect to smaller particles is supersaturated with respect to the larger ones. This leads to gradual transfer of the matter from the smaller particles to the larger ones and, hence, overall increase in the particle size of the precipitate.

3. A specimen of the precipitate of **X** contains particles with the size of 40, 60, and 80 nm (10 g of each fraction). Calculate the average size of the particles in the specimen. Hereafter consider that the particles are cubic, their size *r* corresponding to the edge length of the cube.
4. Calculate the solubility of each fraction if the solubility product of the macrophase is $K_{sp} = 3\cdot10^{-11}$.
5. Calculate the average particle size in the precipitate once its Ostwald ripening is complete. Consider that ripening is possible if the solubility of the smaller (dissolving) particles exceeds 10^{-5} mol/L, and the difference in the solubilities of the dissolving and growing particles exceeds 5%. Take that the rate of the particles growth is proportional to their initial surface area throughout the entire ripening process.

Problem 6

At 0°C, the salt **X** exists as colorless crystals readily soluble in water. Heating the mixture of **X** with either an excess of **A** (solid at 0°C, w(O) = 43% by mass) or an excess of **B** (solid at 0°C, w(O) = 65% by mass) can be used as laboratory methods for obtaining small quantities of gaseous (at 0°C and 100 kPa) binary substances **C** and **D**, respectively. **C** and **D** are readily soluble in water.

If an equimolar amount of **D** is introduced into a sealed reactor filled with **C** at 0°C and 100 kPa, then the pressure in the reactor decreases to almost zero. The osmotic pressure of the solution prepared from 677 mg **B** and 15.3 cm^3 of water at 25°C is approximately equal to 1075 kPa.

A saturated (at 20°C) aqueous solution of **D** remains practically colorless when stored in air. To determine the concentration of **D** in such a solution, an aliquot of 1.00 cm^3 was titrated with a pre-standardized NaOH solution. 26.13 cm^3 of the alkali solution was consumed. To standardize the alkali solution, the hydrochloric acid was prepared as follows. A 10.00 cm^3 aliquot of the HCl solution saturated at 20°C (41.8% by mass, density 1.202 g/cm^3) was placed in a 250 cm^3 volumetric flask and brought to the mark with water. 10.00 cm^3 of the prepared hydrochloric acid was consumed to standardize a 10.00 cm^3 aliquot of the alkali solution.

1. Determine the composition and give the formulas of **A**, **B**, **C**, **D**, and **X**. Support by calculations.
2. Write the equations of all the reactions described.
3. Propose a laboratory method for obtaining **D** different from that described in the task.
4. A heated concentrated aqueous solution of **X** reacts with magnesium. Write the equation of this reaction.

Problem 7

Interactions between molecules, atoms and ions are referred to as intermolecular. These are much weaker than the forces of covalent and ionic interactions, but their play a very important role. The energy (E_1) of the interaction of two atoms at the distance between the centers of which equals R can be calculated using the equation:

$$E_1 = b\exp(-aR) - \frac{d}{R^6}.$$

The first term in this equation is responsible for repulsion which leads to an increase in the energy of the system, whereas the second one is responsible for the attraction between instantly induced dipoles which leads to a decrease in the energy of the system. Repulsion predominates at short distances, while attraction prevails at larger ones. Constants a, b and d depend on the electronic structure of the particles. The values of these constants (in atomic units, a.u.) for some pairs of atoms obtained from experimental data are given below.

	He–He	He–Ne	He–Ar	He–Kr	He–Xe
a	2.10	2.27	2.01	1.85	1.83
b	6.55	33.0	47.9	26.1	42.4
d	2.39	4.65	15.5	21.85	33.95

When doing calculations, you should use the value of R in atomic units (a.u.). Potential energy is also obtained in a.u. A negative value of E_1 means that the energy of the system at this distance is by the value equal to the absolute value of E_1 less than the energy at an infinite distance between particles.

1. Calculate E_1 for the system of two He atoms for the distances R equal to 5.00 a.u. and 7.00 a.u.
2. Using the method of successive approximations, estimate the maximum value by which the energy of the system of two He atoms can decrease due to intermolecular interaction.

If the interacting particles are charged, then the Coulomb interaction additionally arises between them, the potential energy of which (E_2, in a.u.) can be calculated using the formula:

$$E_2 = \frac{q_1 q_2}{R},$$

where q_1 and q_2 are the charges of particles in a.u. (1 a.u. of charge is equal to the absolute value of the electron charge), R is the distance in a.u.

3. Let us consider the LiF molecule with a 100% ionic bond. The distance between the centers of the nuclei is 152 pm. Calculate the energy of dissociation of the LiF molecule into ions:

$$\mathrm{LiF(g) = Li^{+}(g) + F^{-}(g)}.$$

Note: Isoelectronic particles have the same constants in the equation for E_1.
(If you failed to calculate the dissociation energy of LiF, then take it as $20.0 \cdot 10^{-19}$ *J in further calculations).*

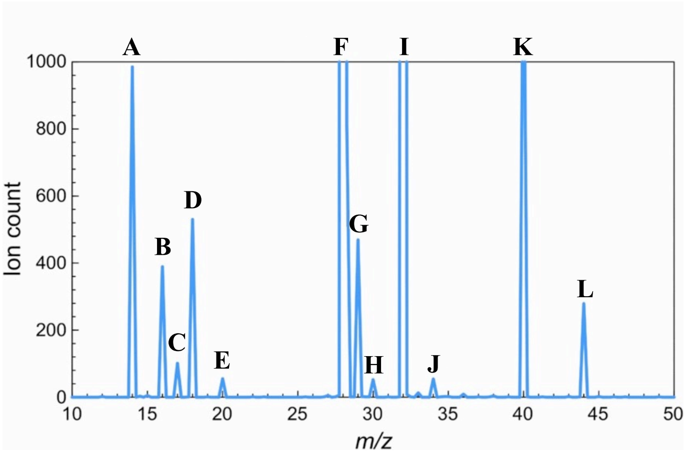
4. The ionization energy of the lithium atom is 5.39 eV, and the electron affinity energy of the fluorine atom is 3.45 eV. Calculate the molar bond energy of LiF.

Additional reference materials: 1 a.u. of length = 52.9 pm; 1 a.u. of energy = 27.21 eV.

Problem 8

Mass spectrometry is one of the most important methods of analytical chemistry, which allows us to determine the composition and structure of unknown substances. In this problem, you will analyze the results of two independent experiments.

Experiment 1. The mass spectrum of dried air with encoded signals **A**–**L** is given below. The mass spectrum shows the dependence of the signal intensity (Ion count) on the m/z value (m is the molecular mass of the particle, z is the charge of the particle, the cation in this problem). All signals **A**–**L** are formed by five main components of air: N_2, O_2, Ar, CO_2, H_2O.



1. For each signal **A**–**L**, give the corresponding particle(s) with the particle charge and mass numbers of the elements.

Experiment 2. The composition of a sample can be estimated from the ratio of signal intensities (I) in a mass spectrum. In the experiment, five tests were performed in air in a closed system: 1) 4 human inhalations–exhalations; 2) photosynthesis of a plant (1 day); 3) rusting of iron (30 min); 4) combustion of octane (5 min); 5) decomposition of hydrogen peroxide under the action of *baker's* yeast (5 min).

2. Give the reaction equations occurring in the described tests.

The air at the end of each test was then analyzed by mass spectrometry. The results of the experiment are summarized in the table:

Sample	$I(O_2)/I(N_2)$	$I(O_2)/I(Ar)$	$I(CO_2)/I(Ar)$	$I(H_2O)/I(Ar)$
Air (initial)	0.214	14.4	0.23	3.2
Sample **I**	0.179	12.1	0.35	3.6
Sample **II**	1.97	130	2.9	5.1
Sample **III**	0.181	11.6	12.2	3.7
Sample **IV**	0.226	16.1	0	3.7
Sample **V**	0.054	3.3	35	5.35

3. Calculate the content (mol.%) of all components in the initial air.
4. Assign the samples **I**–**V** to the five tests performed. Confirm your answer with calculations or by comparing the numerical values you used.
5. Provide a reaction equation that can explain the increased CO_2 content in the sample **II**.