Ministry of Health of the Republic of Belarus
Educational institution
"Gomel State Medical University"

Department of General and Bioorganic Chemistry

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**METHODOLOGICAL MANUAL**
for conducting the laboratory class with the first-year students
of the Faculty of International Students
studying in the specialty 7-07-0911-01 "Medical business" (FIS)
English-speaking students
in the discipline "Medical chemistry"

**Topic 9: Colligative properties of solutions**

Time: 2 hours

2023

## THE TRAINING AND EDUCATIONAL GOALS, MOTIVATION TO STUDY THE TOPIC

**The purpose of the class:**

To form ideas about the colligative properties of solutions of electrolytes and non-electrolytes.

**The tasks of the class:**

As a result of the class, the student *must know:*

the laws describing the colligative properties of solutions of electrolytes and nonelectrolytes.

The student *must be able to:*

1) solve computational problems to determine the colligative properties of solutions of various substances;

2) determine the molar masses of nonelectrolytes by cryoscopic method.

**Motivation to study the topic:**

The study of the colligative properties of solutions of substances allows us to form an idea about the processes of mass transfer in the human body, as well as about the properties of solutions used in medicine.

Osmosis regulates the inflow of water into the cells and intercellular structures. Osmotic pressure is important in biological systems because cell walls are semipermeable membranes. In particular, when a person is receiving intravenous fluids, the osmotic pressure of the fluid needs to be approximately the same as blood serum; otherwise bad things can happen.

## NECESSARY EQUIPMENT

1. Methodological manual for students on the topic "Colligative properties of solutions".

2. Reference materials of physico-chemical constants for the 1$^{st}$ year education international students.

3. Chemical reagents and equipment necessary for laboratory work.

## CONTROL QUESTIONS ON THE TOPIC OF THE CLASS

1. Colligative properties of solutions of electrolytes and nonelectrolytes.
2. Vapor pressure lowering is the First Raoult's Law.
3. Ebullioscopic Raoult's Law.
4. Cryoscopic Raoult's Law.
5. Osmosis and osmotic pressure.

## COURSE OF THE CLASS

**The theoretical part**

**1. COLLIGATIVE PROPERTIES OF SOLUTIONS OF ELECTROLYTES AND NONELECTROLYTES**

Solutes affect some properties of solutions that depend only on the concentration of the dissolved particles. Properties that depend upon the number of solute's particles, and not on their nature are called *colligative properties*. Four important colligative properties that we will examine here are follows:

- *vapor pressure lowering;*
- *boiling point elevation;*
- *freezing point depression;*
- *osmotic pressure.*

Molecular compounds (nonelectrolytes) separate into individual molecules when they are dissolved, so for every 1 mol of dissolved molecules, we get 1 mol of particles. On the contrary, ionic compounds (electrolytes) separate into their constituent ions when they dissolve, so 1 mol of an ionic compound will produce more than 1 mol of dissolved particles. For example, each mole of NaCl that dissolves give 1 mol of $Na^+$ ions and 1 mol of $Cl^-$ ions, for a total of 2 mol of particles in solution. Thus, the effect of the dissolution of NaCl on the properties of the solution can be twice as large as the effect of the dissolution of the same number of moles of glucose ($C_6H_{12}O_6$) [1-3].

## 2. VAPOR PRESSURE LOWERING – THE FIRST RAOULT'S LAW

Vapor pressure is what you get when the liquid is in a closed container at a certain temperature. At this temperature, an equilibrium is established between the number of particles leaving the surface and the number of particles returning to the surface again. In the 1980s, Raoul discovered that when a non-volatile solute (such as salt or sugar) is dissolved in a solvent, the vapor pressure decreases. The lowering of vapor pressure depends on the mole fraction of the solute and the vapor pressure of the pure solvent.

*The First Raoult's Law* may be formulated as:

▪ **the vapor pressure of solutions containing non-volatile solute(s) is always lower than the vapor pressure of pure solvents.**

Processes of evaporation and condensation are smaller in solution because nonvolatile solute bind solvents' molecules thus retarding evaporation process (decreasing a fraction of solvent molecules with energy sufficient to enter the vapor phase).
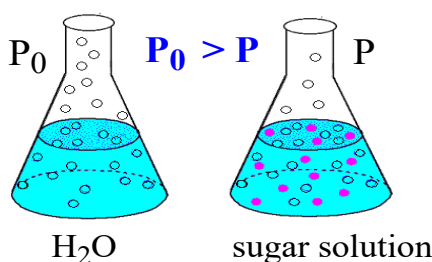


H₂O          sugar solution

Figure 1 – The presence of solute particles blocks some of the ability for liquid particles to evaporate. Thus, solutions of non-volatile solutes typically have a lower vapor pressure than the pure solvent.

Mathematical description of First Raoul's Law for a binary system:

*For nonelectrolytes:*

$$\frac{P_0 - P}{P_0} = \frac{n(X)}{n(X) + n(solvent)} = \chi(X)$$

▪ **The relative lowering of vapor pressure of a dilute solution containing non-volatile solute is equal to the mole fraction of this solute − χ(X).**

$P_o$ − vapor pressure of a pure solvent;

3

P − vapor pressure of a solution;

$\dfrac{P_0 - P}{P_0}$ —— relative lowering of vapor pressure;

n(X) − number of moles of solute, mol;
n(solvent) − number of moles of solvent, mol.

*For electrolytes:*

$$\frac{P_0 - P}{P_0} = \frac{i \times n(X)}{i \times n(X) + n(solvent)}$$

$i$ − isotonic coefficient (Van't Hoff's factor), which characterizes the ionization of the electrolyte;

$$\alpha = \frac{i - 1}{n - 1}$$

α − ionization percent;
n − number of ions contained in the molecule:

| | |
|---|---|
| NaCl | n = 2 |
| $Na_2SO_4$ | n = 3 |
| $Na_3PO_4$ | n = 4 |

## 3. EBULLIOSCOPIC RAOULT'S LAW

*Ebullioscopic Law ("ebullio" − boiling)* is a consequence of the First Raoult's Law:

▪ ***boiling point of solution containing non-volatile solute(s) is always higher than boiling point of pure solvent.***

*The boiling point of a liquid* is a temperature under which its vapor pressure equals the external atmospheric pressure.

*For nonelectrolytes:*

$$\Delta T_b = K_b \times C_m(X) = \frac{K_b \times m(X) \times 1000}{M(X) \times m(solvent)}$$

*For electrolytes:*

$$\Delta T_b = i \times K_b \times C_m(X)$$

$\Delta T_b = T_{b\,(Sln)} - T_{b\,(Solvent)}$ − boiling point elevation;
$C_m(X)$ − molality, mol/kg;
$K_b$ − the molar boiling point elevation constant of a solvent (0.52°×kg/mol for water).

## 4. CRYOSCOPIC RAOULT'S LAW

▪ *Freezing point of solution containing non-volatile solute(s) is always lower than freezing point of pure solvents.*

*The freezing point of a liquid* is a temperature under which its vapor pressure equals the vapor pressure of solid solvents.

*For nonelectrolytes:*

$$\Delta T_f = K_f \times C_m(X) = \frac{K_f \times m(X) \times 1000}{M(X) \times m(solvent)}$$

For electrolytes:

$$\Delta T_f = i \times K_f \times C_m(X)$$

$\Delta T_f = T_{f(Solvent)} - T_{f(Sln)}$ − freezing point depression;

$C_m(X)$ − molality, mol/kg;

$K_f$ − the molar freezing point depression constant of a solvent ($1.86° \times$ kg/mol for $H_2O$).

For blood plasma of people $\Delta T_f$ equals to $0.56°$, for blood plasma of mammals $\Delta T_f$ is a bit higher ($0.58°$).

**Problem 1.** Which solution's freezing point deviates more from that of pure water − a 1 M solution of NaCl or a 1 M solution of $CaCl_2$?

*Solution:*

*Colligative properties depend on the number of dissolved particles, so the solution with the greater number of particles in solution will show the greatest deviation. When NaCl dissolves, it dissociates into two ions, $Na^+$ and $Cl^-$. But when $CaCl_2$ dissolves, it dissociates into three ions − one $Ca^{2+}$ ion and two $Cl^-$ ions. Thus, $CaCl_2$ will have 50 % more impact on freezing point depression than NaCl.*

**Problem 2.** Calculate the freezing point depression and boiling point elevation for a solution containing 1.49 g of KCl in 360 ml of water.

*Solution:*

$$\Delta T_f = i \times K_f \times C_m(KCl); \qquad \Delta T_b = i \times K_b \times C_m(KCl)$$

$$C_m(KCl) = \frac{moles\ of\ solute:\ n(KCl)}{mass\ of\ solvent(kg):\ m(H_2O)}$$

*n* (KCl) = m / M = 1.49 / 74.5 = 0.02 mol; *m* ($H_2O$) = 0.360 kg

$$C_m(KCl) = \frac{0.02}{0.360} = 0.055\ mol/kg$$

*KCl is a strong electrolyte, hence, α(KCl) = 100 % or 1;* $KCl \rightarrow K^+ + Cl^-$

$$\alpha = \frac{i-1}{n-1} \quad (n - number\ ions\ contained\ in\ a\ molecule),\ hence,$$

*i* = α × (n − 1) + 1 = 1 × (2 − 1) + 1 = 2

$\Delta T_f = 1.86 \times 2 \times 0.055 = 0.2046°;$ \qquad $\Delta T_b = 0.52 \times 2 \times 0.055 = 0.0570°$

***Answer:*** *$\Delta T_f = 0.2046°$; $\Delta T_b = 0.0570°$*

## 5. OSMOSIS AND OSMOTIC PRESSURE

**Osmosis** is a reversible thermodynamic process of water diffusion through the semi-permeable membrane from pure water to a solution, or from a dilute solution into a more concentrated one.
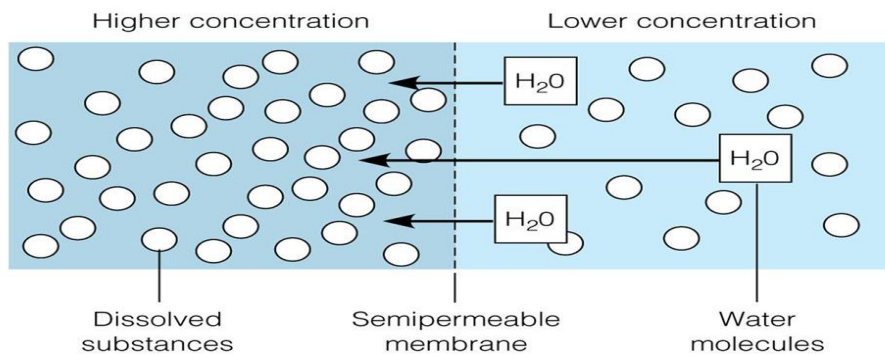
Figure 2 – Scheme of the osmosis

Osmosis is driven by a difference in a solute concentration on the two sides of the membrane. Diffusion of water across a membrane generates a pressure called **osmotic pressure ($\pi$, kPa).**

Osmotic pressure is a colligative property of solutions that is observed using a semipermeable membrane, a barrier with pores small enough to allow solvent molecules to pass through but not solute molecules or ions. The net flow of solvent through a semipermeable membrane is called osmosis (from the Greek *osmós*, meaning "push"). The direction of net solvent flow is always from the side with the lower concentration of solute to the side with the higher concentration.

Osmotic pressure is calculated by the *Van't Hoff's equations:*
*For nonelectrolytes: $\pi = R \times T \times C_M(X)$,*
*For electrolytes*: *$\pi = i \times R \times T \times C_M(X)$*

T − temperature, K;

R − gas constant (8.31 J/mol×K);

$C_M(X)$ − molar concentration of the solute, mol/l.

Cell membranes of plants and animals are permeable for water molecules and some small ions. Normal osmotic pressure of blood plasma is 740-780 kPa (37 ºC) or 7.3-7.7 atm. It should be remembered that 1 atm = 101.3 kPa

Solutions according to the value of osmotic pressure of blood plasma may be classified:

Solutions

isotonic
$\pi = 740 - 780$ kPa

hypertonic
$\pi > 780$ kPa

hypotonic
$\pi < 740$ kPa
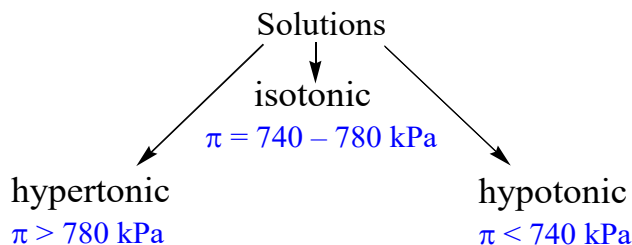
Most solutions used in medicine for intravenous injections are *isotonic (with the same osmotic pressure as blood).* Their injection into the blood vessel doesn't disturb osmotic homeostasis of a body. They are:
a) 0.9 % by mass NaCl solution;
b) 4.5 % by mass glucose solution.

When a red blood cell is placed in a *hypertonic solution ($\pi > 780$ kPa),* intracellular water tends to be removed from the cell by osmosis into a more concentrated surrounding

solution. This process, known as plasmolysis, causes the cell to shrink and eventually stop functioning.

When an erythrocyte is placed in a *hypotonic solution (π < 740 kPa),* water tends to move into the cell. The cell swells and eventually bursts, releasing hemoglobin and other protein molecules. This phenomenon is known as hemolysis – the destruction of blood. Its initial stage occurs when the osmotic pressure becomes ~ 360-400 kPa, complete hemolysis occurs at 260-300 kPa.
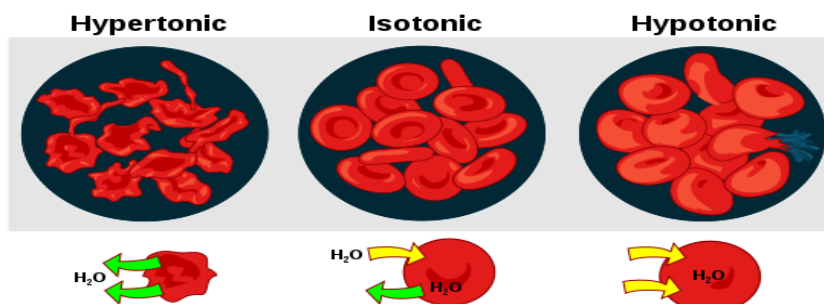


Figure 3 – Diagram of erythrocytes in hypertonic solution (cell shrinks),
isotonic solution (cell remains unchanged) and hypotonic solution (cell swells and bursts)

Nevertheless, some hypertonic solutions are applied in medicine. They are:
• 10 % by mass of NaCl solution used for healing purulent wounds;
• 25 % by mass of $MgSO_4$ solution for the treatment of hypertensive crises.

Mainly electrolytes are responsible for high osmotic pressure of blood plasma and other biological fluids.

Colloidal particles of proteins not able to pass through cell membranes also contribute into osmotic pressure of blood plasma, but their oncotic pressure is rather low: 3-4 kPa.

Osmosis plays a key role in biological processes:
▪ absorption of nutrients;
▪ elimination of waste products of metabolism;
▪ active transport of water [1-3].

***Problem 3.*** 0.63 M solution of $HNO_3$ is used in laboratory as an oxidizing agent. What is its osmotic pressure at t = 20 °C?

***Solution:***

$\pi = i \times R \times T \times C_M$

*$HNO_3$ is a strong electrolyte, hence, α($HNO_3$) = 100 % or 1.*

$\alpha = \dfrac{i-1}{n-1}$ *(where n is a number of ions contained in a molecule);*

$HNO_3 \rightarrow H^+ + NO_3^-$

*$i = \alpha \times (n-1) + 1 = 1 \times (2-1) + 1 = 2$*

*Hence, $\pi = 2 \times 8.31 \times (273 + 20) \times 0.63 = 3067.8$ kPa*

***Answer: π = 3067.8 kPa***

**The practical part**
Safety instructions before laboratory work.

LABORATORY WORK

*Determination of the molar mass of a medicinal substance (nonelectrolyte) by cryoscopic method*

*Equipment of the experiment:* a crystallizer, a glass with a volume of 50-100 ml, measuring cylinders for 25 ml, a thermometer with scale divisions of 0.1-0.2 °C, a stirrer, a metal stand, a cooling mixture, a glucose solution.

*The method of performing the experiment:* the determination of the molar mass of a substance by lowering the freezing point of its solution in comparison with a pure solvent is performed using a cryoscope.

**1.** The scheme of a simplified cryoscope is shown in Figure 4.



**1** - a thermometer
**2** - a stirrer
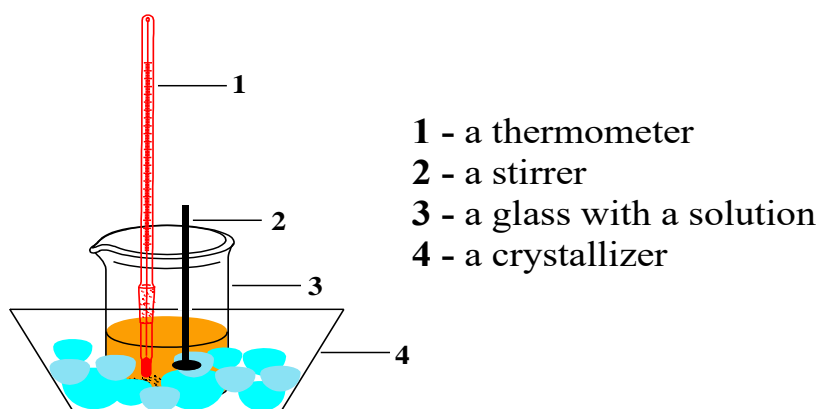**3** - a glass with a solution
**4** - a crystallizer

Figure 4 − Simplified cryoscope

Prepare a cooling mixture consisting of small pieces of ice and some crystals of table salt, and place it in a crystallizer. The temperature of the cooling mixture should be approximately −6 °C.

Pour 25 ml of a glucose solution with known mass percent of glucose (the density of the solution is considered equal to 1 g/ml) into a chemical glass and place the glass in the cooling mixture. Dip the thermometer into the solution and look after the temperature decreasing. Don't forget to mix the solution to avoid its local overcooling. Mark a temperature when the first ice crystals appear in the glass.

**2.** Write down the experimental data:

| | |
|---|---|
| Volume of a glucose solution | $V_{sln} = 25$ ml |
| Percent by mass of glucose | $\omega_{gl} = 5$ % |
| Mass of glucose | $m_{gl} = V_{sln} \times \rho_{sln} \times \omega_{gl} =$ |
| Mass of water | $m_{water} = m_{sln} - m_{gl} =$ |
| Freezing point of water | $t_{f\,(water)} = 0$ °C |
| Freezing point of a solution | $t_{f\,(sln)} =$ |
| Freezing point depression | $\Delta t_f = t_{f\,(water)} - t_{f\,(sln)} =$ |

**3.** Using cryoscopic Raoult's Law calculate glucose molar mass:

$$\Delta t_f = K_f \times \frac{m\,(C_6H_{12}O_6)\times 1000}{M\,(C_6H_{12}O_6)\times m\,(H_2O)} \; ;$$

$$M(C_6H_{12}O_6) = K_f \times \frac{m\,(C_6H_{12}O_6)\times 1000}{\Delta t_f \times m\,(H_2O)} =$$

The molar freezing point depression constant of water is 1.86 °·kg/mol.

**4.** Calculate the absolute and relative errors of the experiment, taking in account that the true molar mass of glucose is 180 g/mol.

$$D = |M_{gl}{}^{true} - M_{gl}{}^{exp}| =$$

$$D_0 = \frac{D}{M_{gl}^{true}} \times 100\% =$$

**Control over the assimilation of the topic**
It is conducted in the form of an oral conversation with students.

### QUESTIONS FOR SELF-CONTROL OF KNOWLEDGE
1. Colligative properties of solutions of electrolytes and nonelectrolytes.
2. Vapor pressure lowering is the First Raoult's Law.
3. Ebullioscopic Raoult's Law.
4. Cryoscopic Raoult's Law.
5. Osmosis and osmotic pressure.

*Exercises for the self – control*

**1.** Vapor pressure of a water is 25 kPa (65 ºC). Calculate the vapor pressure of the solution at the same temperature, which contains 13.62 g of sugar in 90 g of water.
*Answer: 24.8 kPa*

**2**. How many grams of glucose should be dissolved in 270 g of water for:
a) reducing the freezing point of the solution by one degree;
b) increasing the boiling point of the solution by one degree?
*Answer: 26.15 g; 93.54 g*

**3**. How many degrees will the boiling point of the solution increase compared to the boiling point of water if 9 g of glucose $C_6H_{12}O_6$ is dissolved in 100 g of water?
*Answer: at 0.26°*

**4.** The isotonic coefficient of an aqueous solution of hydrochloric acid is 1.66 (ω = 6.8 %). Calculate the freezing point of this solution.
*Answer: –6.15°C*

**5.** At 25 °C, the osmotic pressure of a solution containing 2.8 g of high molecular compound in 200 ml of the solution is 0.70 kPa. Calculate the molar mass of the solute.

*Answer: 49530 g/mol*

**6.** Calculate the osmotic pressure of a solution containing 16 g of sucrose ($C_{12}H_{22}O_{11}$) and 350 g of water at 293 K (the density of the solution should be taken equal to 1 g/cm$^3$).

*Answer: 311 kPa*

## QUESTIONS FOR INDEPENDENT WORK OF STUDENTS (IWS)

1. Osmolarity and osmolality of solutions.

2. Cryoscopy and ebullioscopy, their application in medical and biological research.

## LIST OF SOURCES USED

1. Medical chemistry : textbook for students of higher education establishments – med. univ., inst. and acad. / V.O. Kalibabchuk, V.I. Halynska, L.I. Hryshchenko et al. ; ed. by V.O. Kalibabchuk. – 6th ed., corr. – Kyiv : AUS Medicine Publishing, 2018. – P. 62-70.

2. Основы химии для иностранных студентов = Essential chemistry for foreign students : учебно-методическое пособие / С. В. Ткачёв [и др.]. – 5-е изд. – Минск : БГМУ, 2018. – С. 83-88. – Режим доступа: http://rep.bsmu.by:8080/handle/BSMU/21054.

3. Филиппова, В. А. Общая химия : учеб. пособие для студентов лечеб. факта, обуч. на англ. яз. : в 2 ч. = General Chemistry : Educational guaidance for students medical department in English medium / В. А. Филиппова, А. В. Лысенкова, Л. В. Чернышева. – Гомель : ГомГМУ, 2009. – Ч. 1. – 192 с. URI: https://elib.gsmu.by/handle/GomSMU/2679.