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A.A. GUSLISTY,[1] O.D. STOLIARYK,[2] O.V. KHOROLSKYI[3]
[1] Family Medicine Center Amedika LLC
(103b, Semena Paliya Str., Odesa 65123, Ukraine; e-mail: aguslisty@gmail.com)
[2] Odesa I.I. Mechnikov National University
(2, Dvoryanska Str., Odesa 65026, Ukraine; e-mail: adiabata384@gmail.com)
[3] Poltava V.G. Korolenko National Pedagogical University
(2, Ostrograds'kogo Str., Poltava 36003, Ukraine; e-mail: khorolskiy.alexey@gmail.com)

SIMILARITY BETWEEN THE ELECTROPHYSICAL PROPERTIES OF ALBUMIN MACROMOLECULES AND THE MAGNETIC PROPERTIES OF PARAMAGNETS

A similarity has been identified between the electrophysical phenomena in the aqueous-salt solutions of an albumin macromolecule and the magnetic properties of paramagnets. The character of the dependence of the zeta potential of albumin macromolecules on the pH *indicator of acid-base balance in their aqueous-salt solutions is found on the basis of the paramagnet magnetization equation. It is also found that the asymmetry in the dependence of the zeta potential of albumin macromolecules on the difference* $\mathrm{pH} - \mathrm{pH}_0$*, where* pH_0 *is the pH value at the isoelectric point, does not exceed 30%. It has been proved that the region of physicochemical parameters of the aqueous-salt solutions of proteins in living organisms coincides with the applicability region of the Landau theory of second-order phase transitions.*

Keywords: albumin macromolecule, zeta potential, acid-base balance indicator, zeta-potential critical point.

1. Introduction

This work is devoted to the study of the properties of the albumin zeta potential ζ_{alb}. This electrostatic characteristic of the albumin macromolecule is determined by the distribution of charges inside the albumin macromolecule and around it. To calculate the zeta potential of albumin, a certain model is usually applied, where the potential is determined by the distribution of charges and described by electrostatic equations and boundary conditions. In the framework of this approach, the zeta potential is found to be a function of the radius r_{alb} of albumin macromolecules, the thickness r_D of the diffuse layer, and the cell radius r_c in the case where the diffuse electric layers of neighboring albumin macromolecules overlap. The details of this approach can be found in works [1–6]. As was shown in work [7], in the framework of this approach, the zeta potential equals

$$\zeta_{\mathrm{alb}} \approx \frac{4\pi\sigma}{\varepsilon} r_D \left[\mathrm{th}\left(\frac{r_c - r_{\mathrm{alb}}}{r_D}\right) - \right.$$
$$\left. - \frac{r_D}{r_{\mathrm{alb}}} \mathrm{th}^2\left(\frac{r_c - r_{\mathrm{alb}}}{r_D}\right) + \ldots \right], \tag{1}$$

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where σ is the surface charge density of the albumin macromolecule, and ε is the dielectric constant of water.

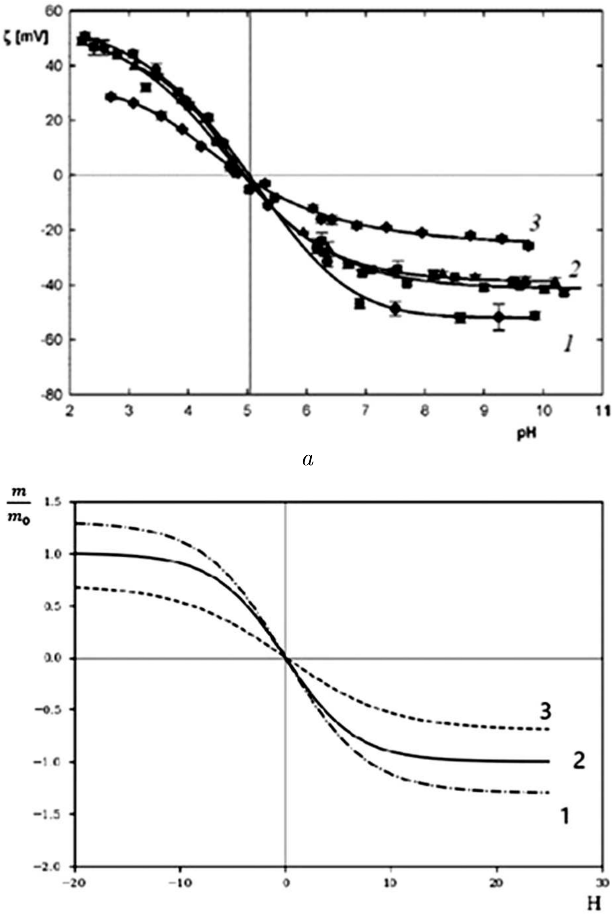
Experimental studies of the zeta potential of the albumin macromolecules in aqueous solutions and its dependence on the solution pH were carried out in works [8–10]. It was a different formulation of the problem, because the zeta potential was not associated with the parameters of charge distribution inside and outside the albumin macromolecule, but with the parameter of the solution in whole, which is the pH indicator.

In the experimental work [9], the zeta potential of the bovine and human albumins, as well as its dependence on the pH of their aqueous-salt solutions, was studied. The numerical value of pH in the aqueous solutions was varied by adding NaCl-, HCl-, and NaOH-based electrolytes (see Fig. 1). In Fig. 1, *a*, the pH-dependence of the albumin zeta potential at various concentrations of indicated electrolytes are shown. It is not difficult to recall that a similar behavior is inherent to the dependence of paramagnet magnetization on the external magnetic field strength in a vicinity of the critical point. Figure 1, *b* demonstrates the dependence of the dimensionless magnetization m/m_0 on the external magnetic field strength H, where m_0 is the maximum value of the paramagnet magnetization. As one can see, the curves describing the zeta potential dependence on the pH of the aqueous albumin solution (Fig. 1, *a*) resemble the curves describing the dependence of paramagnet magnetization on the external magnetic field strength. The curves in Fig. 1, *b* correspond to various temperature values, whereas the zeta-potential curves in Fig. 1, *a* correspond to various concentrations of the sodium-chloride based electrolyte.

It should also be noted that the magnetization curves in Fig. 1, *b* are symmetric with respect to the coordinate origin. At the same time, we see that the curves in Fig. 1, *a* are asymmetric; therefore, we must pay some attention to this issue in the future. The existence of similarity between the curves in Figs. 1, *a* and 1, *b* raises another important issue. The curves in Fig. 1, *b* are described by the hyperbolic tangent function,

$$m = m_0 \tanh\left(\frac{\gamma H}{T}\right), \tag{2}$$

where γ is the proportionality coefficient, and H is the external magnetic field strength. Due to the similarity of the curves in Figs. 1, *a* and 1, *b*, we may assume that



a

b

Fig. 1. Experimental dependences of the zeta potential of albumin ($\zeta_{\rm alb}$) on the pH indicator for various concentrations of sodium chloride salt $n_s^{(1)} = 0.6 \times 10^{18}$ cm^{-3} (*1*), $n_s^{(2)} = 1.8\times10^{18}$ cm^{-3} (*2*), and $n_s^{(3)} = 6\times10^{18}$ cm^{-3} (*3*) [9] (*a*) and schematic dependences of the relative magnetization of various paramagnets, m/m_0, on the external magnetic field strength H for various paramagnet temperatures $T_1 < T_2 < T_3$ (*b*)

$$\zeta = \zeta_0 \tanh\left[\kappa(\mathrm{pH} - \mathrm{pH}_0)\right], \tag{3}$$

where κ is a proportionality coefficient, which is reciprocal to the salt concentration. In this case, an increase in the salt concentration will lead to a decrease of the zeta-potential magnitude.

Let us pay attention to the zeta potential sign on the left and right branches of every curve in Figs. 1, *a*. The zeta potential of the aqueous-salt solution of albumin is positive on the left side, and neg-

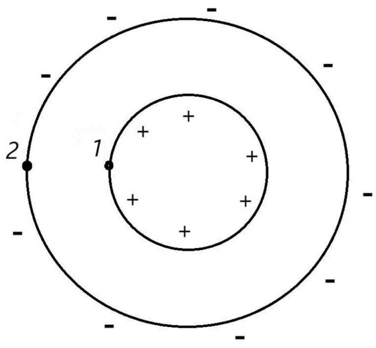


Fig. 2. Schematic diagram of the arrangement of point charges over the surface of albumin macromolecule (*1*) and at the level of the diffuse layer of the double electric layer around the macromolecule (*2*)

ative on the right side. The positive and negative values of zeta potential are determined by the polarity of a double electric layer arising around an albumin macromolecule. The left branch corresponds to the positive charge values of the Stern layer, and the right branch to its negative charge values.

The presence of H^+ ions in the aqueous environment of albumin macromolecules has two origins. First, it is the self-dissociation of water molecules,

$$H_2O \rightleftharpoons H^+ + OH^-. \quad (4)$$

Second, it is the addition of HCl and NaOH electrolytes; the latter dissociate and increase the concentration of H^+ ions on the left branches and OH^- ions on the right ones of the dependences in Fig. 1, *a*.

On the left branch of the $\zeta_{\rm alb}$(pH)-dependence curve, the variation of the numerical pH value decreases, and the concentration of H^+ ions increases. This occurs due to the addition of HCl to the aqueous-salt solution of albumin macromolecules. In this case, the H^+ ions attach to the albumin surface, and the Cl^- ions enter the diffuse electric layer. Indeed, the polarization component of the free energy is determined by the equation

$$F_{el} = \frac{1}{2}\frac{q^2}{r_{\rm alb}}\left(\frac{1}{\varepsilon} - \frac{1}{\varepsilon_{\rm alb}}\right), \quad (5)$$

where ε and $\varepsilon_{\rm alb}$ denote the dielectric constants of water and albumin material, respectively. As one can see, the free energy becomes negative, if ε is larger than $\varepsilon_{\rm alb}$ (this circumstance was established in works [11, 12]). Whence it follows that the charge tries to get into the albumin macromolecule.

The change of the numerical pH value on the right branch of the $\zeta_{\rm alb}$(pH)-dependence curve is caused by the binding of H^+ ions with OH^- ones in the aqueous environment of albumin macromolecules and the formation of water molecules. In turn, the Na^+ ions, which were formed as a result of the dissociation of NaOH, form a diffuse layer around the macromolecules. As for the position of the hydroxyl ions OH^-, the situation remains unchanged.

Let us add some clarifications to the determination of the zeta potential of albumin macromolecules. By definition, the zeta potential is determined by the equation

$$\zeta_{\rm alb} = \langle\varphi(1)\rangle - \langle\varphi(2)\rangle, \quad (6)$$

where $\varphi(1)$ is the potential at the surface of the albumin macromolecule at point (1), i.e., in the Stern layer, and $\varphi(2)$ is the potential at the boundary of a cell that covers the diffuse part of the electric layer of the albumin macromolecule (see Fig. 2). The angle brackets in Eq. (6) denote the averaging over the positions of the charges that form the electric field. As a result of the averaging, the dependence of the potential $\varphi(1)$ on the polar (θ) and azimuthal (α) angles becomes lost,

$$\langle\varphi(1)\rangle = \langle\varphi(r_1,\theta,\alpha)\rangle \to \varphi_1(r_1). \quad (7)$$

The averaged value of the potential $\varphi(2)$ is considered to equal zero: $\langle\varphi_2(r_2)\rangle = 0$.

An important circumstance that has to be taken into account hereafter is the rotation of albumin macromolecules. In the general case, an albumin macromolecule rotates around some axis with the angular velocity

$$\omega = \sqrt{\frac{k_{\rm B}T}{I}}, \quad (8)$$

where

$$I = \frac{8\pi}{3}\rho\int\limits_0^{r_{\rm alb}} r^4 dr = \frac{2}{5}m_{\rm alb}r_{\rm alb} \quad (9)$$

is the moment of inertia of the albumin macromolecule, which is modeled by a sphere. We assume that the mass of the albumin macromolecule is $m_{\rm alb} = 6.5 \times 10^4$ amu [13], and its radius equals $r_{\rm alb} = 4 \times 10^{-7}$ cm [14]. In such a way, we find that $\omega \approx 10^8$ s^{-1}.

As a result of the rotation of the albumin macromolecules, the potentials $\varphi(1)$ and $\varphi(2)$ become self-averaged over the spherical angles. Rather large values of the rotation frequency lead to the fact that even in the case of a field created by a single charge H^+, the self-averaging occurs over the angles θ and α. The same happens with the surface charge density of the albumin macromolecules. Its value can be found in a simpler way by dividing the charge value by the surface area,

$$\sigma(r_{\text{alb}}, \theta, \alpha) \to \sigma(r_{\text{alb}}) = \frac{q_{\text{alb}}}{4\pi r_{\text{alb}}}. \tag{10}$$

It is assumed that the charge distribution in the diffuse atmosphere of the albumin macromolecule corresponds to the atmosphere that remains stationary.

A consistent study of the dependence of the zeta potential of albumin macromolecules on the indicator of acid-base balance in their aqueous-salt solutions brought us to the formulation of the following tasks:

- to demonstrate a similarity between the electrophysical phenomena in the aqueous-salt solutions of albumin macromolecules in vicinities of their critical points and the magnetic phenomena of paramagnets in a vicinity of the Weiss critical point of their spin subsystem;
- to determine the possibility of applying the Landau theory to describe the similarity of the electrophysical properties of albumin macromolecules and the magnetic properties of paramagnets;
- based on the equation for the behavior of paramagnets and the similarity between the magnetic and electrophysical phenomena, to determine the character of the zeta potential dependence on the pH of aqueous-salt solutions of albumin.

2. Temperature Dependences of Zeta Potential for the Aqueous-Salt Solutions of Albumin and Fibrinogen

The temperature dependence of zeta potential plays an important role in the analysis of the electrophysical properties of albumin. The temperature dependence of the zeta potential in a temperature interval of 25–70 °C was studied in works [15, 16]. It was shown that the zeta potential of human serum albumin and fibrinogen vanishes at the temperature $T_{\text{H}} = 42$ °C (see Fig. 3). When approaching T_{H}, the zeta potential of albumin and fibrinogen rapidly increases from a value of -27 mV, which corresponds to the lower boundary ($T = 30$ °C) of the temperature interval of mammalian life.

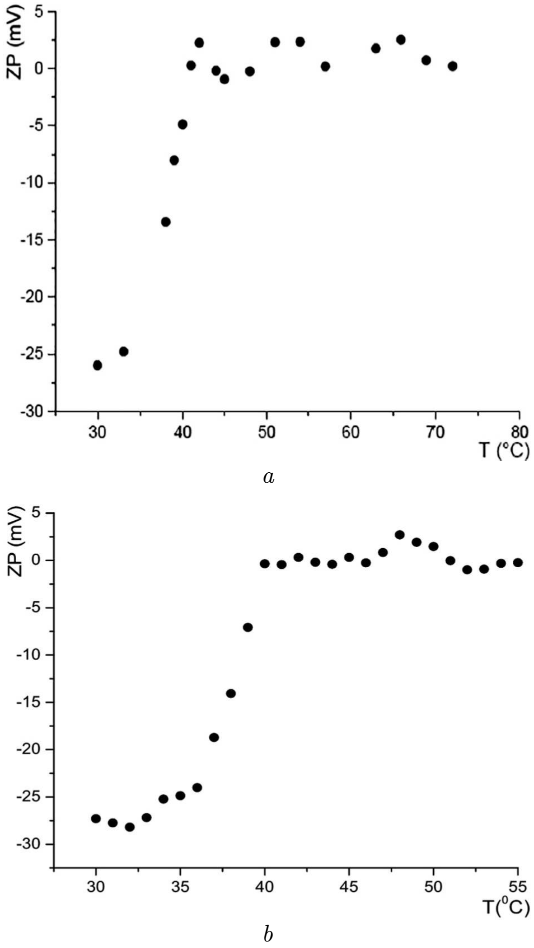
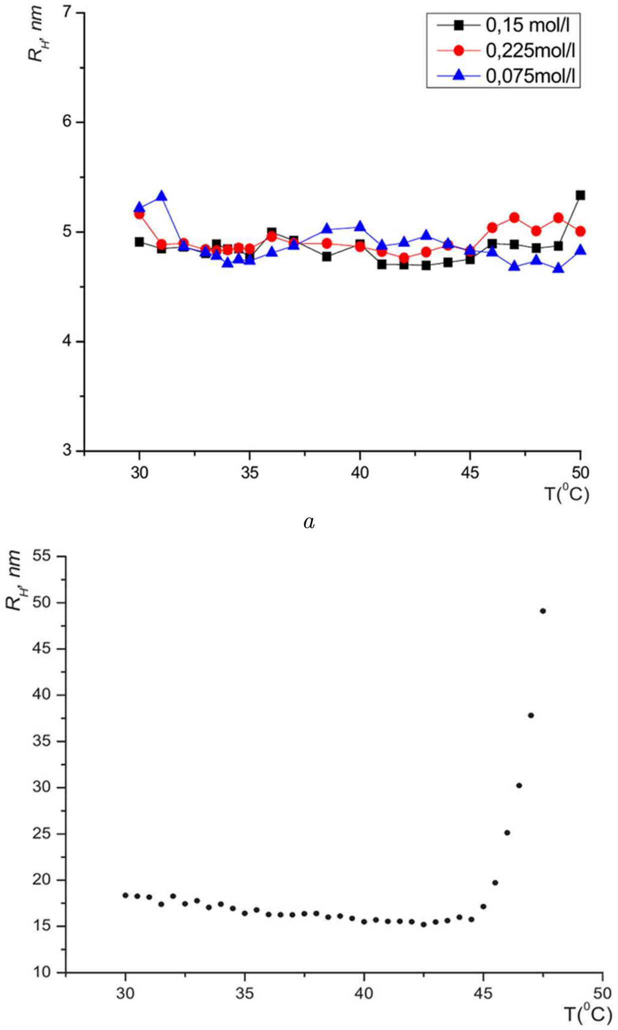


Fig. 3. Temperature dependences of the zeta potential for the aqueous-salt solutions of albumin (*a*) and fibrinogen (*b*) at pH = 7.4 and a sodium chloride concentration of 0.075 mol/l [15]

It should be noted that the hydrodynamic radius R_g is constant within the specified temperature interval, which testifies to the change of only electrophysical properties of the proteins under consideration (Fig. 3).

An important supplement to Fig. 3 is Fig. 4, where the temperature dependences of the hydrodynamic radii of albumin and fibrinogen macromolecules are shown. Note that the temperature $T_{\text{H}} = 42$ °C is not accidental. In works [17–19], it was found that the so-called dynamic phase transition occurs at $T_{\text{H}} = 42$ °C, when the thermal motion of water



a

b

Fig. 4. Temperature dependences of the hydrodynamic radius of albumin (*a*) and fibrinogen (*b*) [15, 16]

molecules changes from crystal-like to argon-like. In other words, the temperature behavior of the settled lifetime τ_0 of water molecules changes substantially at this temperature:

$$\tau_0 \gg \tau_1, \quad \text{if } T < T_\mathrm{H}, \tag{11}$$

$$\tau_0 \sim \tau_1, \quad \text{if } T \geqslant T_\mathrm{H}, \tag{12}$$

where $\tau_1 = a/v$ is the time of molecule transition from one position of temporal vibrations to another, a is the average distance between the molecules, and v is the speed of thermal motion of water molecules. Inequality (11) corresponds to the crystal-like character of the thermal motion of water molecules. Condition (12) means that the rotational motion of water molecules becomes possible, and the character of thermal motion in water resembles that in argon.

Thus, the temperature T_H splits the temperature values into two intervals: $T_\mathrm{tr} < T < T_\mathrm{tr} + 42$ °C and $T_\mathrm{tr} + 42$ °C $< T < T_c$. The thermal motion of water molecules has a crystal-like character, $\tau_0 \gg \tau_1$, in the former interval, and the argon-like behavior in the latter one. So, the temperature T_H, which is identified with 42 °C, can be called a critical point of electrophysical transformations in the aqueous solutions of albumin.

According to the above, the behavior of the zeta potential is determined by the relationship

$$\zeta \approx \begin{cases} \zeta(T) & \text{if } T < T_\mathrm{H}, \\ 0 & \text{if } T > T_\mathrm{H}. \end{cases} \tag{13}$$

It is analogous to the behavior of magnetization near the critical point T_c of a magnet [20]. Indeed,

$$m \approx \begin{cases} m(T) & \text{if } T < T_c, \\ 0 & \text{if } T > T_c. \end{cases} \tag{14}$$

Such a behavior of the zeta potential and the magnetization allows us to introduce a so-called order parameter of the system, $\varphi(T)$, which exhibits a similar behavior type. Together with this parameter, we can introduce the Landau free energy, which has the form

$$f_L(\tau, h, \varphi) \approx f_0 - h\varphi + \frac{1}{2}\tau\varphi^2 + \frac{b}{4}\varphi^4, \tag{15}$$

where f_0 is the free energy of the system at the critical or singular point, $\tau = (T - T_p)/T_p$ is the dimensionless temperature, T_p is the temperature of the system at the critical or singular point ($T_p = T_c$ in the case of paramagnet, and $T_p = T_\mathrm{H}$ in the case of aqueous albumin solution), and h is equal to the magnetic field strength H for the paramagnet and to pH for the aqueous albumin solution.

In the framework of Landau theory, the temperature dependence of the order parameter is determined from the condition of free energy minimum, $\partial f_L/\partial\varphi = 0$, which leads to the expression

$$\varphi \approx \begin{cases} -\sqrt{-\tau/b} & \text{if } \tau < 0, \\ 0 & \text{if } \tau > 0. \end{cases} \tag{16}$$

This formula rather correctly describes the change of the paramagnet magnetization when approaching the critical point, but in the zeta-potential case, its temperature dependence is described only approximately (see Fig. 5).

According to Eq. (15), the behavior of the order parameter as a function of the external field strength near the critical point looks like

$$\varphi = h/\tau. \tag{17}$$

This formula was repeatedly tested and confirmed for magnets, but it has not been checked for an aqueous solution of albumin. Beyond the scope of Landau theory, the dependence of the order parameter on the magnetic field strength is described by the formula

$$\varphi = \tanh\left(\kappa h + \frac{\varphi}{\tau}\right), \tag{18}$$

where h is the external magnetic field strength. It is not difficult to verify that, for low external magnetic fields, formula (18) transforms into formula (17) (see Fig. 6).

Owing to the similarity between the electrophysical properties of albumin macromolecules and the magnetic properties of paramagnets, formula (18) can be used to describe the zeta potential of aqueous albumin solutions. That is, formula (18) actually justifies our assumption about the dependence of the zeta potential on the hyperbolic tangent to the argument $(\mathrm{pH} - \mathrm{pH}_0)$.

3. Asymmetry of the Zeta Potential of Albumin Macromolecules

An analysis of Fig. 1 shows that the curves describing the behavior of zeta potential are not only similar to the curves describing the paramagnet magnetization, but also differ from them by a certain asymmetry. This fact means that the values ζ_1 and ζ_2 of the zeta potential at two conjugate points x_1 and $x_2 = -x_1$ are not identical, i.e., $|\zeta_1(x_1)| \neq |\zeta_2(x_2)|$ (see Fig. 7).

In the case where the curves are exactly symmetric, i.e., $\zeta = \zeta_0 \tanh(\kappa x)$, the combination

$$f(x) = \frac{1}{2}\left(\zeta(x_1) + \zeta(x_2)\right) \Rightarrow 0. \tag{19}$$

The same combination can serve as a measure of the curve asymmetry,

$$\Delta\zeta_{\mathrm{alb}}(x) = \left(\zeta_0^{(r)} \tanh(\kappa_r x) - \zeta_0^{(l)} \tanh(\kappa_l x)\right), \tag{20}$$

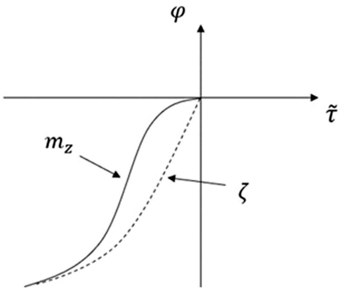


Fig. 5. Dependences of the ordering degree φ of paramagnetic molecules (m_z) and the zeta potential of albumin macromolecules (ζ) on the dimensionless temperature $\tilde{\tau}$. The curves intersect at the critical point where the paramagnet magnetization m_z and the zeta potential of albumin ζ vanish

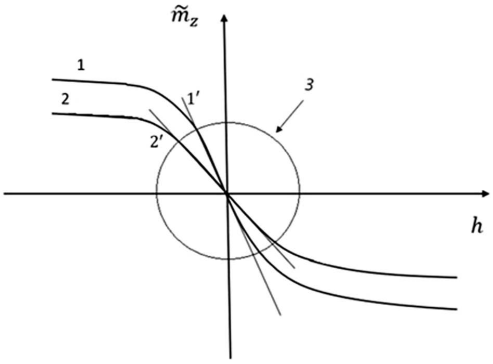


Fig. 6. Dependences of the paramagnet magnetization m_z on the external magnetic field strength h. Curves *1* and *2* correspond to different temperatures. Lines *1′* and *2′* are tangents to the corresponding curves in the vicinity of critical point. The scope of the Landau theory validity is marked by circle *3*

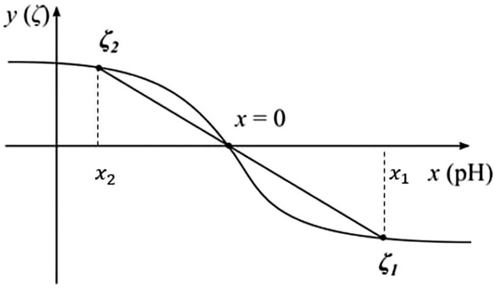


Fig. 7. Schematic illustration of the asymmetry of ζ_{alb} as a function of $x = \mathrm{pH} - \mathrm{pH}_0$

where $\zeta_0^{(r)}$, κ_r, $\zeta_0^{(l)}$, and κ_l are coefficients corresponding to the right and left branches of the dependence $\zeta(x)$. The values of these coefficients are presented in Table.

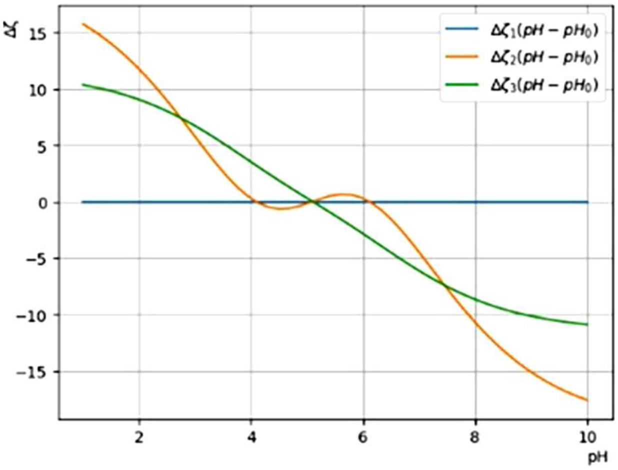


Fig. 8. $\Delta\zeta_{\text{alb}}(x)$-values corresponding to the curves in Fig. 1

Parameters of the zeta-potential dependences of albumin on the pH of its aqueous-salt solutions

Curve No.	Left branch, κ_l	Left branch, ζ_0^l	Right branch, κ_r	Right branch, ζ_0^r
1	0.54	53.3	0.54	53.3
2	0.39	60	0.63	40
3	0.45	35	0.54	23.5

As one can see from Fig. 7,

- at the lowest salt density $n_s^{(1)} = 0.6 \times 10^{18}$ cm^{-3}, the deviation of zeta potential from the dependence $\zeta = \zeta_0 \tanh(\kappa x)$ is practically absent,
- the largest deviation from this dependence occurs at $n_s^{(2)} = 1.8 \times 10^{18}$ cm^{-3}.

Hence, an increase in the salt density leads to a non-monotonic increase of the deviation from the symmetric curve corresponding to $\zeta = \zeta_0 \tanh(\kappa x)$. The relative deviation from theoretical dependence (20) is described by the formula

$$\Delta\widetilde{\zeta}_{\text{alb}} = \frac{\Delta\zeta_{\text{alb}}(x)}{\zeta_0}, \tag{21}$$

where $\zeta_0 = \max(|\zeta_0^{(r)}|, |\zeta_0^{(l)}|)$.

It should be noted that deviations from the tangential character of the dependence $\zeta_{\text{alb}}(x)$ are observed at the salt densities that exceed the value $n_s^{(1)} = 0.6 \times 10^{18}$ cm^{-3}. This value is less than the concentration of sodium chloride in blood plasma, 15.12×10^{19} cm^{-3}. The concentration of all dissolved salts in blood plasma reaches a value of about 17.38×10^{19} cm^{-3}. This fact testifies that the asymmetry effects corresponding to the pH-dependence of the zeta potential in blood plasma have to be pronounced.

An analysis of the data in Table demonstrates that the relative deviation $\Delta\widetilde{\zeta}_{\text{alb}}$ at the three indicated above values of salt concentration does not exceed 30% of the ζ_0- value. The deviation $\Delta\widetilde{\zeta}_{\text{alb}}$ lies within the experimental error interval. Therefore, the applicability of the formula $\zeta = \zeta_0 \tanh(\kappa x)$ for describing the zeta potential as a function of the difference $\text{pH} - \text{pH}_0$ is justified.

4. Physical Interpretation of Isoelectric Point pH$_0$

The dependence of the zeta potential ζ_{alb} on the acid-base balance indicator testifies to the availability of such a numerical value pH$_0$ at which ζ_{alb} vanishes (see Fig. 1, *a*). The pH value at which the zeta potential becomes equal to zero is called the isoelectric point of the albumin macromolecule, IEP$_{\text{alb}}$. The IEP$_{\text{alb}}$-value lies within the interval pH = 4.7÷5.1. In the absence of buffer substances, the zeta potential value tends to zero at pH$_0$ = 5.1. If the buffer substance 2-(N-morpholino)ethanesulfonic acid (MES) with the concentration $n_{\text{MES}} \approx 6.0 \times 10^{18}$ cm^{-3} is added, then the acid-base equilibrium indicator shifts, with $\Delta\text{pH} = -0.2$. This shift of pH occurs owing to the dissociation of the MES molecule and the appearance of free H$^+$ ions. As a result, the pH value decreases and becomes equal to 4.9. As the buffer substance concentration increases, ΔpH also increases.

Another buffer substance, tris(hydroxymethyl)aminomethane (TRIS), when being added to an aqueous-salt solution of albumin with pH values within an interval of 4.9÷5.1, acts as an alkali. Therefore, the TRIS molecule does not dissociate, and its NH$_2$-group attaches H$^+$ ions. The formation of the protonated form of this molecule (TRIS-H$^+$) gives rise to an increase of the pH of the aqueous solution of albumin macromolecules to 5.1. All experiments in work [9] with the addition of buffer substances were carried out at a temperature of 25 °C.

At the same time, in work [15], the numerical value of zeta potential vanishes at $T_H = 42$ °C. This temperature corresponds to a critical point at which substantial electrophysical transformations occur in the aqueous solutions of albumin. These transformations take place as a result of a dynamic phase transition in water.

Due to the rotation of an albumin macromolecule, the electric field around it can be assumed symmetric even in the case $z_{\text{alb}} \approx 1$. Let us estimate the charge of albumin at the isoelectric point, where pH = 5.1. The average value of the molar fraction of albumin in blood plasma equals $c_{\text{alb}} = 1.5 \times 10^{-5}$, which corresponds to its concentration $n_{\text{alb}} = 0.5 \times 10^{18}$ cm^{-3}. The concentration of water is $n_w \approx 3 \times 10^{22}$ cm^{-3}. Whence it follows that the molar concentration of albumin equals

$$c_{\text{alb}} = n_{\text{alb}}/n_w \approx 1.67 \times 10^{-5}. \qquad (22)$$

Since $c_{\text{H}+} = c_{\text{alb}} z_{\text{H}+}$, we obtain

$$\text{pH} = -\lg\,[c_{\text{alb}}\, z_{\text{H}+}]. \qquad (23)$$

If only one H^+ ion is attached to the albumin molecule, we obtain the following pH value:

$$\text{pH}_1 = -\lg[c_{\text{alb}}] = 5 - \lg(1.67) = 4.78. \qquad (24)$$

This result is close to the value $\text{pH}_0 = 5.1$ at the isoelectric point of the aqueous solution of albumin. Then, from the expression

$$\text{pH}_0 = -\lg[z_{\text{H}+}] - \lg[c_{\text{alb}}] = 5.1, \qquad (25)$$

we find the average value $z_{\text{H}+}$ for the H^+ ions attached to the albumin molecule, $z_{\text{H}+} \approx 0.73$. The obtained numerical value of the H^+ ions corresponds to $\text{pH}_0 = 5.1$. Thus, at the indicated value of pH_0, seven hydrogen ions fall on ten albumin macromolecules whose zeta potential equals zero. This is possible, because the positive charge of albumin is compensated by the negative charge of ions from the solution surrounding the albumin molecule.

5. Discussion of Results

Our study of the dependence of the zeta potential of albumin macromolecules on the pH indicator of the acid-base balance in their aqueous solution revealed its similarity to the behavior of the paramagnet magnetization. This similarity in a vicinity of the critical point provides grounds for applying the theory of phase transitions of the second kind to the electrophysical properties of aqueous albumin solutions. We attract attention to the existence of a critical point T_{H}, where the numerical value of the zeta potential tends to zero. This behavior is identical to the character of the magnetization change of a paramagnet at its critical point. Near the critical point T_{H}, the behavior of the zeta-potential dependence as a function of pH has a linear character. This region of the linear dependence $\zeta_{\text{alb}}(\text{pH})$ coincides with the applicability region of the Landau theory. Moreover, the existence interval of the majority of living organisms coincides with the region where the dependence of zeta potential on pH is linear. In this case, all vital processes are at the boundary separating the region of the Landau theory applicability and the electrophysical properties of albumin.

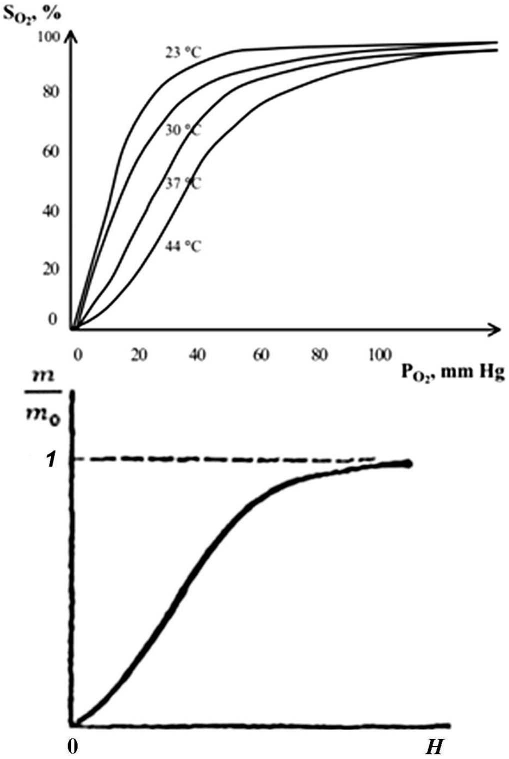


Fig. 9. Dependences of the oxygen saturation degree of hemoglobin in the blood, S_{O_2}, as a function of the partial pressure of oxygen in the alveoli, P_{O_2} at various temperatures [21] (*a*), and schematic dependence of the paramagnet magnetization m/m_0 on the external magnetic field strength H (*b*)

In particular, the process of hemoglobin saturation with oxygen is remarkably similar to the process of paramagnet magnetization in an external magnetic field. The curves in Fig. 9, *a* correspond to temperatures of 44 °C, 37 °C, 30 °C, and 23°C [21]. The notation m_0 corresponds to the maximum value of paramagnet magnetization [22]. It should be noted that the curves of hemoglobin saturation with oxygen and paramagnet magnetization have a similar behavior. Such a physiological characteristic as the S_{O_2} index is also described by the hyperbolic tangent law.

6. Conclusions

To summarize, a similarity between the electrophysical phenomena in aqueous-salt solutions of albumin macromolecules and the magnetic properties of paramagnets has been found. The character of the dependence of the zeta potential of albumin macromolecules on the pH indicator of acid-base balance in their aqueous-salt solutions is determined on the basis of equation for paramagnet magnetization. It is found that the asymmetry in the dependence of the zeta potential of albumin macromolecules on the difference $\mathrm{pH} - \mathrm{pH}_0$ does not exceed 30%, where pH_0 is the pH value at the isoelectric point. It has been proved that all life processes occur in the region of parameters where the Landau theory is applicable.

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А.А. Гуслістий, О.Д. Столярик, О.В. Хорольський

ПОДІБНІСТЬ ЕЛЕКТРОФІЗИЧНИХ ВЛАСТИВОСТЕЙ МАКРОМОЛЕКУЛ АЛЬБУМІНУ ТА МАГНІТНИХ ВЛАСТИВОСТЕЙ ПАРАМАГНЕТИКІВ

У роботі встановлена подібність електрофізичних явищ у водно-сольових розчинах макромолекул альбуміну та магнітних властивостей парамагнетиків. Визначено характер залежності дзета-потенціалу макромолекул альбуміну від показника кислотно-лужного балансу pH їх водно-сольових розчинів, спираючись на рівняння намагніченості парамагнетиків. Встановлено, що асиметрія залежності дзета-потенціалу макромолекул альбуміну від різниці pH-pH$_0$ не перевищує 30%, де pH$_0$ – це значення показника в ізоелектричній точці. Доведено, що фізико-хімічні властивості водно-сольових розчинів протеїнів в області ключових параметрів життєдіяльності організмів співпадають з областю застосування теорії фазових переходів другого порядку Ландау.

Ключові слова: макромолекула альбуміну, дзета-потенціал, показник кислотно-лужного балансу, особлива точка дзета-потенціалу.