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Enthalpy—entropy compensation upon metal ion coordination with porphyrins: generalization for the free bases and doubly deprotonated macrocycles*

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Enthalpy—entropy compensation upon the coordination of zinc ions by porphyrins with various structural organizations of peripheral substitution in solutions at 298 K was studied. The same compensation temperature T_c was found for both free bases and doubly deprotonated porphyrin macrocycles. The data obtained indicate that the coordination of the metal ion in the tetrapyrrole macrocycle core by the free bases and doubly coordinated forms of porphyrins is characterized by the same promoting vibrational modes.

Key words: enthalpy—entropy compensation, porphyrin macrocycles.

The molecular structure of tetrapyrrole macrocycles makes it possible to finely tune their physicochemical properties by changing the architecture of peripheral substituents, the formation of metal complexes and axial liganding of the latter, shifting acid—base equilibria in the macrocycle core.[1—5] The tetrapyrrolic compounds are involved in performing numerous vitally important functions, and the possible candidates for practical use in diverse areas among the existing and newly synthesized tetrapyrrole compounds were searched up to now.[6] Changes in the molecular structure favor often both direct and structurally mediated electronic effects, and it seems necessary to consider in detail these two cases in order to determine specific relations between structural changes in the tetrapyrrolic macrocycles and new properties gained due to these transformations.[7—8] We studied the electronic effects appeared upon macrocycle substitution to explain the observed changes in the rate constant of metal ion coordination with the purpose to use unique physicochemical properties of the deprotonated tetrapyrrole macrocycles in the development of new efficient approaches to the synthesis of metal complexes and production of new sensors for positively charged substrates.

Enthalpy—entropy compensation was shown for the complex formation of zinc ions with 10 free bases of various structures.[9] It was assumed that a relationship between the activation enthalpy $\Delta H^{\neq}$ and activation entropy $\Delta S^{\neq}$ was due to the additivity of electronic substitution effects. The enthalpy—entropy compensation is assumed to be an essential property of complicated systems having numerous soft vibrational modes.[10] The slope of the linear dependence of $\Delta H^{\neq}$ on $\Delta S^{\neq}$ makes it possible to determine the so-called compensation temperature T_c, which should contain, as expected, an extrathermodynamic information about metal ion coordination. This information can concern the shape of the potential energy surface, distribution of energy levels, some specific features of intramolecular interaction in the system, *etc*. The purpose of this work is to examine the data on the coordination of zinc ions with a series of porphyrins existing as the free bases and the doubly deprotonated form and to propose a physical explanation of the enthalpy—entropy compensation upon the coordination of metal ions by porphyrins.

Calculation Methods

The equation $\log K_a = \log(\text{Ind}) + n\log c_{\text{aH}}$, where K_a is the total acidity constant, c_{an} is the analytical concentration of the deprotonating agent in solution, Ind is the indicator ratio P^{2-}/H_2P, and n is the number of dissociated protons ($n = 2$), was used for the calculation of the acidity constants of the studied compounds.[3—5,9]

The formation of metalloporphyrins (MP) from the free porphyrins (H_2P) and divalent metal salts (MX_2) in organic solvents is described by the kinetic equation of the second order

$$dc_{H_2P}/dt = -k_v c_{H_2P} c_{MX_2}.$$

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According to described procedures,[3—5] the activation energy (E_a) for the studied temperature range was calculated using the Arrhenius equation

$$k_v = Ae[-E_a/(RT)]$$

or

$$E_a = 19.1 \cdot [(T_1T_2)/(T_2 - T_1)]\log(k_2/k_1).$$

The activation entropy ($\Delta S^{\neq}$) was calculated from the equation of the absolute reaction rate theory

$$k_v = \chi(kT/h) \cdot e[(T\Delta S^{\neq} - \Delta H^{\neq})/(RT)],$$

where χ is the transmission coefficient, k is the Boltzmann constant, h is Planck′s constant, T is temperature, $\Delta S^{\neq}$ is the entropy of activation, and $\Delta H^{\neq}$ is the enthalpy of reaction activation. Assuming that the transmission coefficient is $\chi = 1$ and taking into account that the activation enthalpy is $\Delta H^{\neq} = E_a - RT$, we have $\Delta S^{\neq} = 19.1 \cdot \log k_v + E_a/T - 253$.

Results and Discussion

A group of 21 porphyrins differing in the number and type of peripheral substituents and structural organization of the latter was chosen as objects of the study. These compounds were synthesized and characterized according to previously described procedures.[3—5,9] The molecular structure of the studied porphyrins is presented in Scheme 1. Both the free bases, which were synthesized by the addition of the "proton sponge" (1,8-diazabicyclo[5.4.0]undec-7-ene) to a solution of porphyrin in acetonitrile (MeCN).[3] Zinc diacetate $Zn(OAc)_2$ was used as the chelating agent. The experimental procedure was described in more detail.[5,9]

The dependence of the activation enthalpy $\Delta H^{\neq}$ on the corresponding activation entropy $\Delta S^{\neq}$ for the coordination of zinc ions by the studied compounds being free bases and doubly deprotonated forms is presented in Fig. 1.

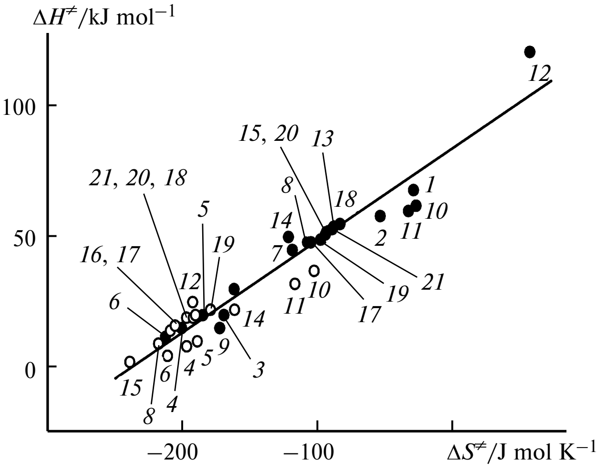
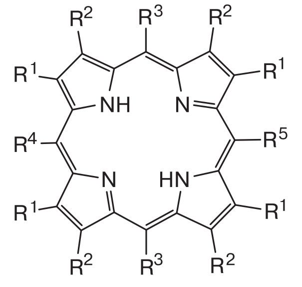


Fig. 1. Activation enthalpy $\Delta H^{\neq}$ as a function of the activation entropy $\Delta S^{\neq}$ upon the coordination by zinc ions with a series of the free bases (dark circles) and doubly deprotonated (light circles) porphyrins in MeCN at 298 K.

The examination of the obtained plot allowed us to make two important conclusions. First, the plot shows that the dependence is linear for both the free bases and doubly deprotonated forms, which is consistent with the earlier observed tendency for the free bases porphyrins.[9] Note that these results are new for the doubly deprotonated forms of porphyrins. Second, the slope of the dependence of $\Delta H^{\neq}$ on $\Delta S^{\neq}$ is the same for both the free bases and doubly deprotonated forms. Taking into account that these two groups of compounds have different electronic structures and the mechanisms of metal ion coordination for

Scheme 1



1—21

Compound	R^1	R^2	R^3	R^4	R^5
1	H	H	Ph	Ph	Ph
2	H	H	C_6H_4OH	C_6H_4OH	C_6H_4OH
3	H	H	$C_6H_4NH_2$	$C_6H_4NH_2$	$C_6H_4NH_2$
4	Me	Et	Ph	C_6H_4(*p*-OMe)	C_6H_4(*p*-OMe)
5	Et	Et	C_6H_4(*p*-OMe)	C_6H_4(*p*-OMe)	C_6H_4(*p*-OMe)
6	Me	Et	C_6H_4(*p*-OMe)	C_6H_4(*p*-NO_2)	C_6H_4(*p*-NO_2)
7	Et	Et	H	H	H
8	Et	Et	NO_2	NO_2	H
9	Me	Me	Ph	Ph	Ph
10	Me	Me	4-Me_3C-C_6H_4	4-Me_3C-C_6H_4	4-Me_3C-C_6H_4
11	Me	Me	3,5-Me_3C-C_6H_4	3,5-Me_3C-C_6H_4	3,5-Me_3C-C_6H_4
12	Br	Br	CF_3	CF_3	CF_3
13	Br	Br	Et	Et	Et
14	H	H	CF_3	CF_3	CF_3
15	Et	Et	NO_2	NO_2	NO_2
16	Me	Me	NO_2	Ph	H
17	Me	Me	NO_2	Ph	NO_2
18	Me	Me	NO_2	C_6H_4(*p*-NO_2)	NO_2
19	Me	Et	NO_2	Ph	NO_2
20	Me	Me	NO_2	C_6H_4(*p*-NO_2)	Ph
21	Me	Et	NO_2	C_6H_4(*p*-NO_2)	C_6H_4(*p*-NO_2)

them involve different number of steps, the data obtained seem to be unexpected.

The dependence of $\Delta H^{\neq}$ on $\Delta S^{\neq}$ made it possible to determine the compensation temperature (T_c) equal to 342±16 K. The pair correlation coefficient for the linear regression was found to be 0.966. We found that the calculation of the compensation temperature separately for the free bases and doubly deprotonated porphyrins showed the value in the same range but with higher root-mean-square deviations. This indicates that the common analysis of two sets of data improves the correlation parameters.

There were attempts to ascribe some physical meaning to the T_c value.[10—12] We used the simple statistical Sharp model for processing the data on T_c.[10] The model describes a conservative polyatomic system with a complex potential function including various types of interactions between the atoms. This choice of the potential funciton results in the quasi-continuous distribution of energy levels. An important feature of this model is that the model requires no knowledge of the explicit shape of the energy level distribution when the number of disturbed states is not too high and the perturbation is significant. The developed model makes it possible to obtain the estimation of the compensation temperature

$$T_c = T/(1 - kT/\delta E), \qquad (1)$$

where k is the Boltzmann constant, and δE is some characteristic energy for the disturbed transition state (difference in energies between the disturbed and initial states). According to the description presented above, δE should be considered as some average or most probable value related to the group of disturbed energy levels rather than the single value. After substitution of the T_c values, temperature $T = 298$ K (at which the experiments were carried out), and the Boltzmann constant into Eq. (1), we have that $\delta E = 19.2$ kJ mol^{-1} (about 1600 cm^{-1}). We believe that T_c correlates with the energy of promoting vibrational modes of the reaction, which provide/facilitate the coordination of the metal ion. Thus, the δE value about 1600 cm^{-1} can be interpreted as the energy of the corresponding vibrational modes of the tetrapyrrole macrocycle.

It is known that the vibrational modes of the porphyrin macrocycle are not localized[12] and all atoms of the macrocycle are involved more or less in all vibrational modes. The role of the molecular fragment (atom, bond, group of atoms) is described by its contribution to the potential energy distribution of this vibrational mode, and the same fragment can contribute substantially to several vibrational modes. The C_a—C_b, C_a—N, C_b—C_b, and C_a—C_m bonds contribute predominantly to the potential energy distribution of vibrational modes in a frequency range of 1300—1600 cm^{-1}. The modes with the contribution of the C_a—C_b, C_a—N, and C_a—C_m bonds, which are necessary for the arrangement of the metal ion, directly affect the size (and shape) of the macrocycle core. Among these modes, those whose main contribution is made by the C_a—N bond are of special attention, since they remain almost invariant in both the free bases of porphyrins and their metal complexes and are barely sensitive to the peripheral substitution of the macrocycle. It should be emphasized that we are far from intention to assign the measured energy value to any certain vibrational mode, but the role of vibrational modes involving the C_a—N bond should be distinguished. If this mode (or modes) is promoting, the coordination of metal ions can be considered as the isoenergetic (adiabatic) motion along the reaction coordinate. From the thermodynamic point of view, this promoting mode will be the most efficient regardless of the symmetry of this mode (there are modes of various symmetry involving the C_a—N bond).[13] It is important that the same character of compensation for both the free base and doubly deprotonated porphyrins excludes all modes involving the N—H bond, because the latter has no hydrogen atoms bound to the pyrrole rings in the macrocycle core.

It has been assumed previously[14] that the linear character of the enthalpy—entropy compensation can be considered as the manifestation of the additivity source in the studied systems; *i.e.*, in the considered case, all porphyrins in the series should have the same source of additivity. This source can be the effect of electronic substitution, which was recently discussed in detail.[9] The electron energy redistribution between the macrocycle and periphery by both resonance and inductive effects should be considered as the main reason for the observed tendencies in changing the complex formation rate with metal ions.

It can be mentioned that the solvent or, more exactly, vibrational modes of the solvate shell should also be considered as a source of promoting modes, since the changes in the solvate shell upon the coordination of the metal ion in the macrocycle core can also be proposed as a source of compensatory processes for chemical reactions in solution.[15] However, these effects should be omitted for the discussed set of data, because the plot reflects the additive effects in the system and they are due to the differences in the porphyrin structure rather than in the solvate shell.

This specific feature (structural distinctions) should be considered as the main one, since in the same solvent with the same coordinating metal ion in the studied series of porphyrins the structural diversity of the latter seems to be the only possible source of the observed effect. By contrast, only one porphyrin and one metal salt can be taken but a series of solvents will be used, which would result in the dependence appeared only as a result of changing the structure of the solvate shell. Thus, when the choice of the data set is valid, the single contribution can be remained and all other possible contributions can be excluded (or at least suppressed). Such an analysis of possible contributions will be the subject of our further research.

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References

1. M. O. Senge, *Photochem. Photobiol.*, 1992, **16**, 3.
2. M. O. Senge, S. A. MacGovan, J. O´Brien, *Chem. Commun.*, 2015, **51**, 17031.
3. D. T. Nam, Yu. B. Ivanova, S. G. Puhovskaya, M. M. Kruk, A. S. Syrbu, *RSC Adv.*, 2015, **5**, 26125.
4. S. G. Pukhovskaya, Yu. B. Ivanova, A. S. Semeikin, O. A. Golubchikov, *Macroheterocycles*, 2018, **11**, 73.
5. S. G. Pukhovskaya, D. T. Nam, Yu. B. Ivanova, L. S. Liulkovich, A. S. Semeikin, A. S. Syrbu, M. M. Kruk, *J. Incl. Phenom. Macrocycl. Chem.*, 2017, **89**, 325.
6. I. I. Stoikov, P. L. Padnya, O. A. Mostovaya, A. A. Vavilova, V. V. Gorbachuk, D. N. Shurpik, G. A. Evtiugin, *Russ. Chem. Bull.*, 2019, **68**, 1962.
7. B. D. Berezin, T. N. Lomova, *Reaktsii dissotsiatsii kompleksnykh soedinenii* [*Dissociation Reactions of Complex Compounds*], Nauka, Moscow, 2006, 380 pp. (in Russian).
8. D. B. Berezin, I. Yu. Bazlova, O. V. Malkova, V. G. Andrianov, *Russ. J. Coord. Chem.*, 2000, **26**, 295.
9. Yu. B. Ivanova, S. G. Pukhovskaya, N. Zh. Mamardashvili, O. I. Koifman, M. M. Kruk, *J. Molec. Liquids*, 2019, **275**, 491.
10. K. Sharp, *Protein Sci.*, 2001, **10**, 661.
11. U. Ryde, *Med. Chem. Comm.*, 2014, **5**, 1324.
12. A. Pan, T. Biswas, A. K. Rakshit, S. P. Moulik, *J. Phys. Chem. B.*, 2015, **119**, 15876.
13. K. N. Solovyev, L. L. Gladkov, A. S. Starukhin, S. F. Shkirman, *Spektroskopiya porfirinov: kolebatel´nye sostoyaniya* [*Spectroscopy of Porphyrins: Vibrational States*], Nauka i Tekhnika, Minsk, 1985, 415 pp. (in Russian).
14. R. Lumry, *Meth. Enzymol.*, 1995, **259**, 628.
15. A. I. Dragan, C. M. Read, C. Crane-Robinson, *Eur. Biophys. J.*, 2017, **46**, 301.

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