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Thermodynamics of complex formation of natural iron(III)porphyrins with neutral ligands

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Abstract

Calorimetric titrations in benzene and chloroform at 298.15 K have been performed to give the complexes stability constants and the thermodynamic parameters for the complex formation of nature iron(III)porphyrins with pyridine. Stoichimetry of the complexes formed has been determined. It has been found that the thermodynamic parameters obtained depend on nature of peripheral substituents of the porphyrins. The estimation of the influence of Cl^- and Ac^- ions on the processes studied has been carried out. Using thermodynamic analysis method, the crystallsolvates of nature iron(III)porphyrins with benzene have been studied. Stoichiometry, thermal and energetic stability of the π–π-complexes formed have been determined. The data obtained have been used to the estimate solvent effect on the thermodynamic parameters of axial coordination of pyridine on the iron(III)porphyrins in benzene.

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Keywords: Iron(III)porphyrins; Molecular complexformation; Titration; Calorimetry

1. Introduction

Iron porphyrins are known to be prosthetic group of hemoproteins which are of vital importance [1]. These porphyrins serve as the binding sites for molecular oxygen in the oxygen carrying proteins at its transport (hemoglobin) or accommodation (myoglobin). The iron porphyrins catalyze decomposition of peroxides (catalaza and peroxidaza) as well as oxidation of alkanes, mimicking the function of cytochrome P_{450}. The basis of these biologically significant processes is donor–acceptor interactions of iron porphyrins with different molecular ligands and amino acid residues of proteins. It is known that a selectivity of complex formation (volume of heme pocket) [1,2] and stability of complexes of the iron porphyrins are determined by the nature of the porphyrin macrocycle as well as their specific interactions with fragments of pseudosolvate environment [2]. The correlation between structure parameters of metalloporphyrins and their coordination properties has been studied extensively in present time. Several parameters of the metalloporphyrin molecules such as chromophor system, metal atom, aromatic character of the porphyrin macrocycle allow to investigate coordination properties of the iron porphyrins by UV-Vis absorption spectroscopy, NMR, IR, EPR spectroscopy as well as diamagnetic susceptibility measurements [3].

As pointed out by the authors of the review [4] on thermodynamic and kinetic characteristics of intermolecular specific interactions of the metalloporphyrins, there are several problems associated with

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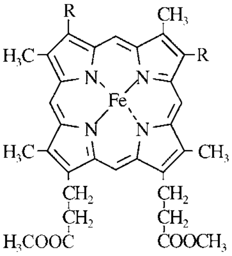
the studies of coordination properties of the porphyrins. They are the following: (1) discrepancy in the stability constant values of metalloporphyrin–ligand complexes reported by different authors; (2) the thermodynamic parameters obtained under condition of electronic excitation (electronic spectroscopy) are considered as those of the ground state; (3) it is difficult to separate the spectral changer caused by coordination, solvatochromic effects and changes of solvent properties (dielectric permitivity). Moreover, coordination of ligands by the metalloporphyrins, especially in aqueous solutions [5,6], is often complicated by association metalloporphyrins and ligand exchange. As rule, this leads to formation of mixture of complexes with different stoichiometry and structure and doesn't allow to establish the correlation between structure parameters and properties of the porphyrins studied. For example, the iron(III)porphyrin forms a few complexes of different composition at different pH and addition of another solvents [6].



I (X)FeHP$_{t.m.e}$: R= $CH(OCH_3)CH_3$, X= Cl^-

II (X)FeDP$_{d.m.e}$: R= H, X= Cl^-

III (X)FePP$_{d.m.e:}$ R= $CH{=}CH_2$, X= Cl^-, Ac^-

Therefore in the present work the ethers of natural iron(III)porphyrins with different substituents in the 2 and 4 positions of macrocycle have been studied. The studies were carried out in benzene and chloroform which form with iron(III)porphyrins the axial complexes [3,7]. It should be noted that in this case the nonaqueous solutions can be considered as physiological systems because heme residues of hemoproteins are preferentially surrounded by amino acids residues but not by water [1,2]. The thermodynamic parameters of interactions (K_s, ΔH^0, ΔS^0) of the iron(III)porphyrins with pyridine and the stoichiometry of the complexes formed have been determined using the method of calorimetric titrations. The specific interactions of the iron(III)porphyrins with the solvents used have been studied on the basis of the data of thermogravimetric analysis of crystallosolvates of the iron(III)porphyrins with the solvents.

2. Experimental

2.1. Materials

Iron(III)hematoporphyrin IX (ClFeHP$_{t.m.e.}$), iron(III)deuteroporphyrin IX (ClFeDP$_{d.m.e.}$), iron(III)protoporphyrin IX (ClFePP$_{d.m.e.}$, AcFePP$_{d.m.e.}$) were synthesized by the method described in detail elsewhere [3]. The samples were purified by chromatography on Al_2O_3 of the second degree of activity according to Brockman. The samples of iron(III)porphyrins were recrystallized from hexane and evaporated to dryness under vacuum at 330–350 K. The purity of the samples was controlled by spectroscopic method. The absorption spectral data agree well with that published [3].

Benzene (C_6H_6), pyridine (C_5H_5N), chloroform ($CHCl_3$) were commercial high purity products. The solvent were dried by molecular sieves of 4 Å size and distilled. The middle fractions were collected. The purity of the solvent was controlled by chromatography. It was 99.98% for C_5H_5N and C_6H_6; 99.95% for $CHCl_3$. The water content of the solvents was determined by Karl Fischer titration. It was not greater than 0.02% for all the solvent used. Chloroform was stabilized by 2-methyl-2-butene (volume ratio 1:1000) because traditional stabilizator ethanol is not inert regards to metalloporphyrins [4] and can compete with pyridine in axial coordination process.

2.2. Apparatus and procedure

Calorimetric titrations were performed at 298.15 K by using precision differential calorimeter, which was connected to computer for the automated titration and data processing [8]. In a typical run, a solution of pyridine in C_6H_6 or $CHCl_3$ (0.02–0.5 $mol\,kg^{-1}$) was continuously introduced into solution of iron(III)porphyrin in C_6H_6 or $CHCl_3$ (10^{-6} to 10^{-4} mol kg^{-1}) placed in calorimetric cell. All solutions were made up by weight. Densities of the solutions were measured using bicapillar picnometers and used to calculate the molar concentrations. The heats of dilution of the ligand were measured separately, for which appropriate correction were made. The stability constants (K_s) and enthalpy changes (ΔH) of complexes formation were calculated by computer simulation with continuously changing K_s to minimize U value: $U(K_s\,\Delta H)=\sum(Qn(\exp)-Qn(\mathrm{cal}))^2$; using the program type "CALORY" [9]. No concentration dependencies of the thermodynamic parameters were observed over the concentration range mentioned above.

Thermogravimetric analysis was performed on a derivatograph 1000D (MOM, Hungry). The samples of crystallosolvates of metalloporphyrins were prepared according to the method described elsewhere [10,11]. The detailed experiment and calculation procedure has been reported previously [10].

3. Discussion

Specific solvation of the metalloporphyrins by aromatic molecules has a great influence on axial coordination of molecular ligands. The results obtained from thermogravimetric analysis show that iron(III)porphyrins form thermally stable complexes with benzene (Table 1). For example, the derivatogram of the crystallosolvate of the ClFePP with benzene is presented in Fig. 1.

Table 1
Decomposition temperature of the iron(III)porphyrin complexes with benzene and enthalpy of evaporation of benzene from the complexes

System	Stoichiometry[a]	T_{decomp} (K)	ΔH_{evp}[b] (kJ mol^{-1})
ClFeDP–C_6H_6	1:2	356	13.0
	1:1	373	49.9
ClFePP–C_6H_6	1:2	377	90.1
	1:1	391	108.4
ClFeHP–C_6H_6	1:2	385	95.3
	1:1	402	124.7

[a] Metalloporphyrin/benzene ratio.

[b] The uncertainly in the experimental ΔH_{evp} values is $\pm(0.8–1.5)$ kJ mol^{-1}.

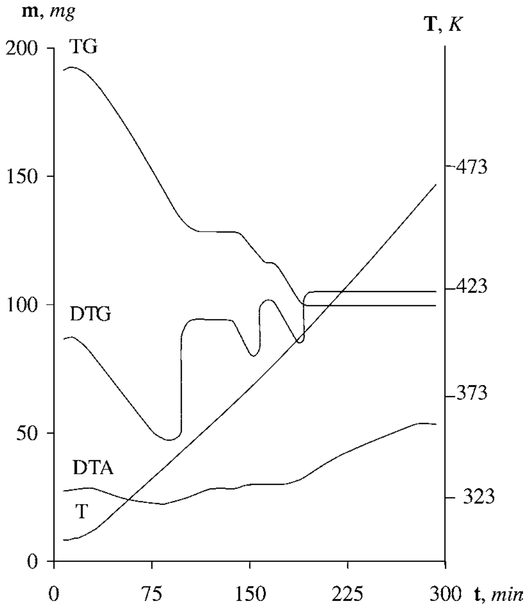


Fig. 1. TG, DTG, DTA and T curves for the thermal decomposition of crystallosolvates of iron(III)porphyrins with benzene.

The process of removing of benzene from the crystallosolvate is stepwise. The ΔH_{evp} value at the first step is very close to those for pure solvent [12]. This may be attributed to breakdown of the solvent structure formed due to universal interaction. On the contrary, the peaks observed at higher temperatures on the DTG curves are characterized by the ΔH_{evp} values which differ significantly from ΔH_{evp} for pure benzene. This fact may be explained by breakdown of the molecular complexes due to specific interactions. It should be noted that the ΔH_{evp} consists of two contribution: (1) the enthalpy changes due to breaking of the iron(III)porphyrin–benzene bonds and (2) the enthalpy changes arising from the expansion at solid–gas transition. The latter is about 2/3 kJ mol^{-1} and this contribution may be neglected.

Thus, the enthalpy changes of evaporation of the benzene molecules from the crystallsolvates reflect the strength of the iron(III)porphyrin–benzene bond.

Clear stoichiometry, high thermal and energetic stability show that the complexes formed are not inclusion complexes. As can be seen from the presented data, the energy of intermolecular interactions of the iron(III)porphyrins with benzene increases in the order: ClFePP $<$ ClFeDP $<$ ClFeHP. It is known that in π–π-complexes of the metalloporphyrins the molecules of aromatic solvents are mainly oriented above and under the porphyrin macrocycle plane. But in some cases the displacement of these axial ligands can lead to blocking up the reactive center of the metalloporphyrins [13,14]. Moreover, the strength of the π–π-complexes formed is results of σ–π-attachment and π–π-repulsion between aromatic molecules. The iron(III)porphyrins studied differ only in the nature of the substituents in the 2 and 4 positions. Therefore the decrease of energy of specific interactions of the iron(III)porphyrins with π-donor benzene molecules may be linked to electronic effects of the peripheral substituents. So, introduction of the oxygen containing $CH(OCH_3)CH_3$ substituent leads to decrease of σ-electron density of the porphyrin macrocycle and promotes the complex formation the porphyrins with π-donor benzene molecules. This fact may be explained by the ability of the $CH(OCH_3)CH_3$ substituents to −I-electron effect of substitution in relation to the porphyrin macrocycle because of the presence of CH-group as isolator of conjugation. The data reported previously [16] indicated that the introduction of vinyl substituents in the H_2PP and ZnPP leads to the +I an –C-effects of substitution, respectively. The positive inductive effect will prevent from π–π-complex formation with benzene unlike –C-effect. Taking into account the position of the ClFePP in the order mentioned above it can be concluded that the effect of conjugation decreases the aromatic character of the ClFePP macrocycle in comparison with ClFeDP. As a result, π–π-repulsion between aromatic systems of the porphyrin and benzene decreases. It is interesting to note that synthetic symmetrically substituted chloride of iron(III)tetraphenylporphyrin specifically interacts with benzene to form 1:1 complexes ($\Delta H_{\mathrm{evp}} = 43.4 \pm 2.8\,\mathrm{kJ\,mol^{-1}}$; $T_{\mathrm{decomp}} = 335\,\mathrm{K}$) while the natural iron(III)porphyrins form 1:2 complexes with benzene. Probably this is due to +I-electron effect of phenyl group of the iron(III)tetraphenylporphyrin [15]. Moreover, the synthetic and natural porphyrins differ in the distribution of electron densities located on the atoms of the macrocycles [16]. This fact can play a certain role in the formation of the complexes of different stoichiometry.

The results of the calorimetric study are presented in Table 2. It is known that the energies of donor–acceptor interactions of the metalloporphyrins with electron donor ligands depends on effective charges on central metal atoms. The effective charge depends on electron donor capability of the porphyrin ligand. According to the own [14] and literature data [3,17], in gas state and in solvent of low solvating abilities a basicity of the porphyrin ligands decreases in the order: $H_2DP > H_2PP > H_2PP(I)$.

Table 2
Thermodynamic parameters of complex formation of Fe(III)porphyrins with pyridine in benzene and chloroform at 298.15 K

Fe(III)-porphyrin	Stoichiometry[a]	C_6H_6			$CHCl_3$		
		K_s	$-\Delta H^0$ ($\mathrm{kJ\,mol^{-1}}$)	ΔS^0 ($\mathrm{J\,mol^{-1}\,K^{-1}}$)	K_s	$-\Delta H^0$ ($\mathrm{kJ\,mol^{-1}}$)	ΔS^0 ($\mathrm{J\,mol^{-1}\,K^{-1}}$)
ClFeDP	1:1	86 ± 9	2.78 ± 0.45	28 ± 7	769 ± 14	2.36 ± 0.09	47 ± 11
	1:2	14 ± 4	6.35 ± 0.21	1 ± 2	200 ± 11	3.20 ± 0.12	33 ± 7
ClFeHP	1:1	357 ± 15	2.01 ± 0.06	42 ± 9	1982 ± 418	0.94 ± 0.05	60 ± 9
	1:2	165 ± 7	2.70 ± 0.07	33 ± 6	294 ± 67	2.37 ± 0.05	39 ± 7
ClFePP	1:1	235 ± 20	1.93 ± 0.03	39 ± 8	709 ± 145	1.87 ± 0.03	48 ± 7
	1:2	67 ± 13	2.52 ± 0.04	27 ± 6	31 ± 7	3.86 ± 0.28	16 ± 5
AcFePP	1:1	86 ± 27	2.57 ± 0.07	29 ± 8	670 ± 31	6.64 ± 0.34	32 ± 7
	1:2	24 ± 6	2.31 ± 0.05	19 ± 6	107 ± 26	9.46 ± 0.70	7 ± 4
ClFeTFP[b]	1:1	40 ± 6	4.52 ± 0.51	16 ± 2	255 ± 20	1.96 ± 0.09	39 ± 7
AcFePFP[b]	1:1	33 ± 6	5.90 ± 0.87	9 ± 3	164 ± 17	3.35 ± 0.28	31 ± 2

[a] Metalloporphyrin/pyridine ratio.

[b] [22].

It should be noted that effects of the substituents determine this order in the 2 and 4 positions of the porphyrin macrocycle. There is a reversible relationship between capability of metal atom to porphyrin binding and capability of metal atom to binding of electron donor ligands [1]. However the present study indicates that the interactions of the metalloporphyrins with the solvents should be taken into account. For example, it should be supposed from the order (I) that the strength of the pyridine–iron(III)porphyrin bond should increase in the order: ClFeDP $<$ ClFePP $<$ ClFeHP.

However in proton donor and aromatic solvents the order has found to be the following: ClFeHP $<$ ClFePP $\leq$ ClFeDP in chloroform and ClFePP $\leq$ ClFeHP $<$ ClFeDP in benzene. It should be noted that the nature of interactions of the porphyrins with the solvent studied is different. So the decrease of ΔH^0 values of interaction of ClFeHP with pyridine in chloroform in comparison with benzene is result of specific solvation of $CHCl_3$ molecules. Obviously the hydrogen bonding formed prevents from negative induction effect of $CH(OCH_3)CH_3$ group. The benzene molecules are not capable of specific interactions with the substituents. However, as indicated above, benzene forms π–π-complexes with the metalloporphyrins (Table 1). Probably the increase of π-electron density of the porphyrin macrocycle induced by the interaction with π-donor molecules of benzene leads to an increase of macrocycle effect of screening. This is the reason of less exothermic effect of coordination process of pyridine by ClFePP and ClFeHP in comparison with ClFeDP. The latter is less capable of specific interaction with benzene (Table 1).

Thus, the present study has indicated an important role of the solute–solvent interactions and influence of the nature of the porphyrin macrocycle on ability of natural iron porphyrins for complex formation. The influence of steric effects of the peripheral substituents on the complex formation has not been found even for ClFeHP containing voluminous peripheral substituents.

The coordination of pyridine by iron(III)porphyrins in benzene is accompanied by more exothermic effect than that in chloroform. The less stable Fe(III)P·nPy complex is formed in benzene. It can be concluded that the coordination of pyridine molecules by the porphyrins in benzene is not accompanied by destruction of the corresponding π–π-complexes $Fe(III)P\cdot 2C_6H_6$. As a result, the mixed $Fe(III)P\cdot 2C_6H_6\cdot 2Py$ complexes are formed.

The presence of ions in the iron(III)porphyrin molecules has a strong influence on the thermodynamic parameters of pyridine coordination (Table 2). It becomes obvious if we compare the results given in Table 2 with the data obtained previously for coordination of pyridine by synthetic zinc(II)porphyrins [18]. The process of coordination of the first pyridine molecule by zinc(II)porphyrins is more exothermic as compared with the second pyridine molecule. For the iron(III)porphyrins there is the metal out-of-plane displacement affects towards the ion. The out-of-plane distance of the metal in these complexes is about 0.45 Å. Obviously the coordination of the first pyridine molecule by iron(III)porphyrins is accompanied by energy consumptions due to draw the metal atom in plane of the macrocycle. However such explanation of the ΔH^0 values of coordination of the fist ligand molecule by iron(III)porphyrins is not sufficient.

One must keep in mind that the iron porphyrins can exist in high-spin and low-spin states. The spin state can change due to coordination of electron donor ligands [19,20]. The calculated enthalpy changes of the equilibrium transition of the iron(III)porphyrins from low-spin to high-spin state have been reported to be from 18.8 to 25 kJ mol^{-1}.

According to the magnetic susceptibility measurements [21] and spectroscopic data [3], the nature iron(III)porphyrins are in high-spin state while in the pyridine complexes these porphyrins are in low-spin state [3].

The data present in Table 2 indicate that the nature of the ions (Cl^- or Ac^-) has essential influence on the axial coordination process of the natural iron(III)porphyrins. Comparison of the data obtained for iron(III)protoporphyrin with those for iron(III)tetraphenylporphyrin indicate that the influence of the nature of the ions on the coordination process of pyridine is the same for both the porphyrins.

4. Conclusions

Thus the efficiency of the binding of electron donor ligands by natural iron porphyrins depends on the nature of the porphyrin macrocycle as well as the interactions of peripheral substituents and π-system of the porphyrin macrocycle with the solvents.

The data obtained may be applied to estimate the influence of nonpolar and polar environment of hemes on their coordinative properties and efficiency of binding of heme with protein.

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