

Effect of Halogenation of *ortho*-Positions of Tetraphenylporphyrin and Its Cd(II) Complex on Their Complexing Ability towards *d*-Metal Salts in Dimethylformamide

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The complex formation reactions of 5,10,15,20-tetra(2,6-dichlorophenyl)- and 5,10,15,20-tetra(2,6-difluorophenyl) porphyrins, as well as metal exchange reactions of their Cd(II) complexes with Zn(II) and Co(II) cations in dimethylformamide were investigated by the spectrophotometric method. Effect of the substituent nature in the macrocycle and the salt solvate complex on the coordination and metal exchange reactions was revealed. The kinetic parameters of metal exchange Cd(II)-(2,6-dihalogenophenyl)porphyrins with Zn(II) and Co(II) salts in dimethylformamide were calculated. The mechanism of the metal exchange reaction is proposed, which suggests the formation of a binuclear intermediate. The synthesized compounds were identified using UV-Vis, ¹H NMR spectroscopy and mass-spectrometry.

Keywords: Halogenophenylporphyrins, metalloporphyrins, intermediate, complexation, metal-exchange reaction.

Влияние галогенирования *орто*-положений тетрафенилпорфирина и его Cd(II) комплекса на их комплексообразующую способность по отношению к солям *d*-металлов в диметилформамиде

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Спектрофотометрическим методом исследованы реакции комплексообразования 5,10,15,20-тетра(2,6-дихлорфенил)-, 5,10,15,20-тетра(2,6-дифторфенил)порфирина и металлообмена их Cd(II) комплексов с катионами Zn(II) и Co(II) в диметилформамиде. Выявлено влияние природы заместителей в макроцикле и сольватном комплексе соли на реакции координации и металлообмена. Рассчитаны кинетические параметры металлообмена Cd(II) (2,6-дигалогенфенил)порфиринов с солями Zn(II) и Co(II) в диметилформамиде. Предложен механизм реакции металлообмена, предполагающий образование биядерного интермедиата. Синтезированные соединения идентифицировали методами электронной абсорбционной, ЯМР ¹H спектроскопии и масс-спектрометрии.

Ключевые слова: Галогенфенилпорфирины, металлопорфирины, интермедиат, комплексообразование, реакция металлообмена.

Introduction

The variety of porphyrins and their metal complexes structures opens up the broad prospects for their application in various fields of science and technology.^[1-7] Porphyrins

and their complexes with metals are used as components of solar cells, catalysts, agents for photodynamic therapy of cancer, sensors for detecting ions and gaseous substrates of various natures.^[8-10] By selective introduction of electron-withdrawing substituents into the porphyrin molecule, it is

possible to create the systems with an uneven distribution of electron density within the tetrapyrrole macrocycle, which is of interest to create the materials with nonlinear optical properties or increased n-conductivity.^[11,12]

In recent years, there is an increasing interest in the study of fluorine-containing porphyrins.^[13-15] The authors of work^[13] have shown that fluorine-containing substituents in metalloporphyrins contribute to increase the quantum yield of singlet oxygen in comparison with non-fluorinated analogs. The introduction of polyfluoroaliphatic substituents to a greater degree than aliphatic ones contributes to an increase in the molecule lipophilicity. This is used in drugs development to improve their penetration through the cell membrane.^[14] Moreover, bulky perfluoroaliphatic substituents are used to prevent the aggregates formation in solution, because they reduce the intermolecular interactions and promote the better solvation. In addition to their main function, the photosensitizers containing fluorine atoms in the structure can also be used to diagnose the tumors and inflammation foci by 19F-MRI. In the work^[15] the spectral-luminescence and electrochemical properties of perfluorinated Zn(II) octaphenylporphyrazines are studied.

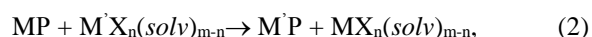
The formation processes of the metalloporphyrins (see reaction (1)) determining their ability to exist in living systems and function as catalysts, dyes, polymers, photo- and thermal stabilizers have been studied for many decades.^[16-18]



where H_2P is a porphyrin ligand, $\text{MX}_2(\text{sol})_{n-2}$ is a solvate complex of a metal salt, sol is a solvent, MP is a metalloporphyrin.

The salts of doubly charged transition metal ions (the size of which corresponds to the size of the macrocycle cavity) interact most easily with porphyrin ligands. However, the formation process of the metalloporphyrins even with these salts is mainly characterized by extremely low rates. The porphyrin formation reaction often requires a heating or a long time to complete it. This is due to the fact that in the transition state of complex formation, the cation must be desolvated, which is an energetically unfavorable process leading to a high-energy transition state.^[16] In the transition state of the complexation, the cation must be desolvated, what is an energetically unfavorable process leading to a high-energy transition state. As a result, the rule is applied that the more rigidly the ligand is preorganized to bind the cation, the lower the rate of the process.

It should be noted that some metalloporphyrins cannot be obtained by the complexation reaction of a porphyrin ligand with a metal cation. Cd(II) and Mg(II) porphyrins are often prepared by template cyclotetramerization. In these cases, the reaction of metal exchange of labile metalloporphyrins with the corresponding metal cation (2) is feasible to use:^[19-24]



where MP and $\text{M}'\text{P}$ are metalloporphyrins, $\text{M}'\text{X}_n(\text{sol})_{m-n}$ and $\text{MX}_n(\text{sol})_{m-n}$ are solvate complexes of metal.

The metal exchange reactions are widely used in the creation of fluorescent labels and metal-containing nanoclusters, as well as in the field of medicine.^[25]

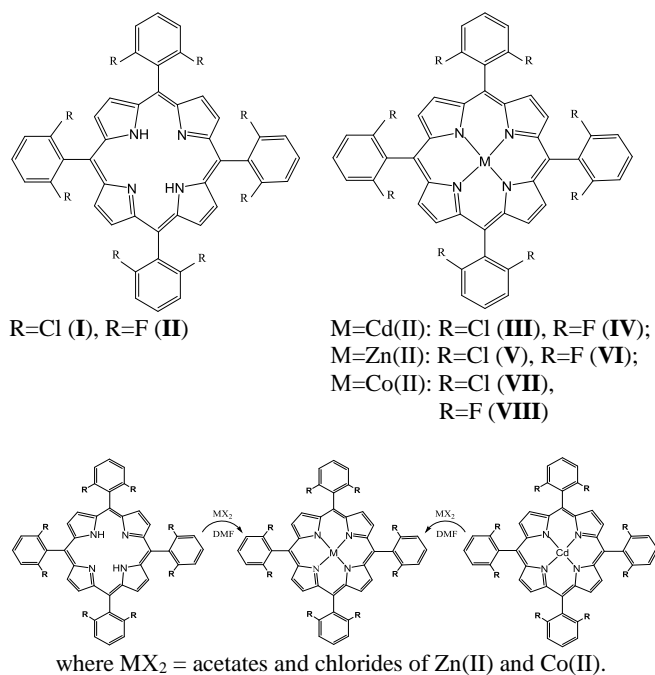
The main factors controlling the rate and mechanism of the metal exchange reaction in porphyrin complexes are the macrocycle ligand nature, the electronic structure and the solvation environment of the leaving $(\text{M})^{n+}$ and entering $(\text{M}')^{n+}$ salt cations, the anionic composition $(\text{X})^-$ of the coordination sphere solvate salts $[\text{M}'\text{X}_n(\text{sol})_{m-n}]$ and the nature of the solvent (sol).

The questions of possible mechanisms of metal exchange of the metal porphyrins and metal phthalocyanines in organic solvents were first discussed in the works.^[26,27]

The widespread use of metal exchange on the example of the labile complexes of water-soluble porphyrins of other metals is shown in the works of Hambright.^[25] The results of the work^[28] are of particular interest to obtain the well-defined metal-molecular structures on surfaces. This can open the way to a synthesis of new metalloporphyrins, which is unavailable under conditions of solution chemistry.

To study the solvation effect on the metal exchange reaction (2), Cd(II) complexes were successfully used.^[29] The metal exchange reaction in Mg complexes of chlorophyll derivatives can be widely used for the synthesis of ecologically safe and stable dyes of the chlorophyll series,^[30] as well as for the synthesis of d-metal complexes with blood group porphyrins.^[26,27,31-33] The study of the effect of various factors on the course of metal exchange in solutions of metalloporphyrins allows not only to better understand the process mechanism, but also to select the optimal conditions for the synthesis of metalloporphyrins, which are formed by reaction (2) with orders of magnitude faster than in the direct interaction of porphyrin-ligand H_2P and a metal salt.^[34]

In this article the complex formation reactions of 5,10,15,20-tetra(2,6-dichlorophenyl)- and 5,10,15,20-tetra(2,6-difluorophenyl)porphyrins and the metal exchange reactions of their Cd(II) complexes with Zn(II) and Co(II) cations in dimethylformamide (Scheme 1) were investigated by the spectrophotometric method.



Scheme 1.

Experimental

5,10,15,20-Tetra(2,6-dichlorophenyl)porphyrin (**I**) and 5,10,15,20-tetra(2,6-difluorophenyl)porphyrin (**II**) (Porphychem) were used in the experiment. Cadmium complexes with porphyrins **I** and **II** were obtained by the Adler method.^[35] Zinc acetates and chlorides (Acros), alumina (Merck), CDCl_3 , C_6D_6 (Aldrich), DMF (Panreac), solvents (chemical pure grade) were used without additional purification. The UV-Vis spectra were measured on a spectrophotometer Cary-100 (Varian). ^1H NMR spectra (500 MHz) were obtained on a Bruker AV III-500 instrument (internal standard TMS). Mass spectra were recorded on a Maldi TOF Shimadzu Biotech Axima Confidence mass spectrometer (dihydroxybenzoic acid matrix).

The investigation of the complex formation porphyrins (1) and metal exchange of their cadmium complexes (2) reactions with metal salts in DMF were carried out by sampling. At certain time intervals, samples of equal volume were taken from the reaction mixture, dissolved in an equal amount of DMF, placed in a spectrophotometer cuvette, and UV-Vis spectra were recorded at room temperature. The kinetic experiment methodology and experimental data processing are described detail in^[36].

Cd(II) 5,10,15,20-tetra(2,6-dichlorophenyl)porphyrin (III) was synthesized as described in^[37]. Porphyrin **I** (0.02 g, 0.0225 mmol), $\text{Cd}(\text{OAc})_2$ (0.052 g, 0.225 mmol), DMF (15 mL), time 3 min. Yield 0.02 g (0.02 mmol, 88 %). ^1H NMR (C_6D_6) δ ppm: 8.73 s (8H, pyrrole), 7.36 d (8H, Ph^m , $J = 7.6$ Hz), 6.97 t (4H, Ph^n , $J = 7.65$ Hz). Mass spectrum, m/z (Ie, %): 1000.2 (82) $[\text{M}]^+$ (calculated for $\text{C}_{44}\text{H}_{20}\text{N}_4\text{Cl}_8\text{Cd}$ 1000.7).

Cd(II) 5,10,15,20-tetra(2,6-difluorophenyl)porphyrin (IV). A mixture of porphyrin **II** (0.02 g, 0.0264 mmol) and $\text{Cd}(\text{OAc})_2$ (0.061 g, 0.264 mmol) in DMF (5 mL) was heated in a flask with reflux condenser to boiling point, it was refluxed within 30 s. The reaction mixture was cooled, poured into water, NaCl was added, the precipitate was filtered off, washed with water, dried, reprecipitated from hexane. Yield: 0.021 g (0.0242 mmol, 92%). ^1H NMR (C_6D_6) δ ppm: 8.96 s (8H, pyrrole), 7.09 d (8H, Ph^m , $J = 7.6$ Hz), 6.96 t (4H, Ph^n , $J = 7.65$ Hz). Mass spectrum, m/z (Ie, %): 870.88 (87) $[\text{M}+2\text{H}]^+$ (calculated for $\text{C}_{44}\text{H}_{20}\text{N}_4\text{F}_8\text{Cd}$ 869.08).

Zn(II)-5,10,15,20-tetra(2,6-dichlorophenyl)porphyrin (V). *Method A*: A mixture of porphyrin **I** (0.02 g, 0.0225 mmol) and $\text{Zn}(\text{OAc})_2$ (0.083 g, 0.450 mmol) in DMF (15 mL) was heated and refluxed within 30 min. The reaction mixture was cooled, poured into water, NaCl was added, the precipitate was filtered off, washed with water, dried and purified by alumina chromatography with dichloromethane as eluent. Yield 0.016 g (0.0168 mmol, 75%). *Method B*: A mixture of porphyrin **I** (0.02 g, 0.0225 mmol) and ZnCl_2 (0.061 g, 0.450 mmol) in DMF (15 mL) was heated and refluxed within 20 min. Processed similarly to A. Yield 0.017 g (0.0178 mmol, 80%). *Method C*: A mixture of complex **III** (0.02 g, 0.02 mmol) and ZnCl_2 (0.027 g, 0.2 mmol) in DMF (12 mL) was heated and refluxed within 2 min. Processed similarly to A. Yield: 0.018 g (0.0190 mmol, 94 %). *Method D*: A mixture of complex **III** (0.02 g, 0.02 mmol) and $\text{Zn}(\text{OAc})_2$ (0.037 g, 0.2 mmol) in DMF (12 mL) was heated and refluxed within 12 min. Processed similarly to A. Yield: 0.017 g (0.0179 mmol, 89%). ^1H NMR (CDCl_3) δ ppm: 8.75 s (8H, pyrrole), 7.79 d (8H, Ph^m , $J = 7.6$ Hz), 7.70 t (4H, Ph^n , $J = 7.65$ Hz). Mass spectrum, m/z (Ie, %): 952.9 (98) $[\text{M}+\text{H}]^+$ (calculated for $\text{C}_{44}\text{H}_{21}\text{Cl}_8\text{N}_4\text{Zn}$ 952.9) (Figure 1Sb in Supporting Information).

Zn(II) 5,10,15,20-tetra(2,6-difluorophenyl)porphyrin (VI). *Method A*: A mixture of porphyrin **II** (0.02 g, 0.0264 mmol) and $\text{Zn}(\text{OAc})_2$ (0.049 g, 0.264 mmol) in DMF (5 mL) was heated and refluxed within 2 min. The reaction mixture was cooled, poured into water, NaCl was added, the precipitate was filtered off, washed with water, dried and purified by alumina chromatography, first with dichloromethane, then with chloroform as eluent. Yield: 0.018 g (0.0219 mmol, 83 %). *Method B*: A mixture of porphyrin **II** (0.02 g, 0.0264 mmol) and ZnCl_2 (0.036 g, 0.264 mmol) in DMF (5 mL) was heated and refluxed within 10 min. Pro-

cessed similarly to A. Yield: 0.018 g (0.0219 mmol, 83 %). *Method C*: A mixture of complex **IV** (0.02 g, 0.023 mmol) and ZnCl_2 (0.031 g, 0.23 mmol) in DMF (5 mL) was heated to reflux. Processed similarly to A. Yield: 0.018 g (0.0219 mmol, 95 %). *Method D*: A mixture of complex **IV** (0.02 g, 0.023 mmol) and $\text{Zn}(\text{OAc})_2$ (0.042 g, 0.23 mmol) in DMF (5 mL) was heated and refluxed within 2 min. Processed similarly to A. Yield: 0.017 g (0.0207 mmol, 90%). ^1H NMR (CDCl_3) δ ppm: 8.99 s (8H, pyrrole), 7.82 t (4H, H^n , $J = 7.65$ Hz), 7.41 d (8H, Ph^m , $J = 7.6$ Hz). Mass spectrum, m/z (Ie, %): 821.09 (98) $[\text{M}+\text{H}]^+$ (calculated for $\text{C}_{44}\text{H}_{21}\text{F}_8\text{N}_4\text{Zn}$ 821.09) (Figure 2Sb).

Co(II) 5,10,15,20-tetra(2,6-dichlorophenyl)porphyrin (VII). *Method A*: A mixture of porphyrin **I** (0.02 g, 0.0225 mmol) and $\text{Co}(\text{OAc})_2$ (0.08 g, 0.450 mmol) in DMF (15 mL) was heated and refluxed within 2 h. The reaction mixture was cooled, poured into water, NaCl was added, the precipitate was filtered off, washed with water, dried and purified by alumina chromatography, with chloroform as eluent. Yield: 0.016 g (0.0169 mmol, 74 %). *Method B*: A mixture of porphyrin **I** (0.02 g, 0.0225 mmol) and CoCl_2 (0.058 g, 0.450 mmol) in DMF (15 mL) was heated and refluxed within 80 min. Processed similarly to A. Yield 0.016 g (0.0169 mmol, 74 %). *Method C*: A mixture of complex **III** (0.02 g, 0.02 mmol) and CoCl_2 (0.026 g, 0.2 mmol) in DMF (15 mL) was heated and refluxed within 30 s. Processed similarly to A. Yield: 0.018 g (0.0190 mmol, 94 %). *Method D*: A mixture of complex **III** (0.02 g, 0.02 mmol) and $\text{Co}(\text{OAc})_2$ (0.035 g, 0.2 mmol) in DMF (15 mL) was heated and refluxed within 20 min. Processed similarly to A. Yield: 0.017 g (0.0180 mmol, 89 %). ^1H NMR (CDCl_3) δ ppm: 14.65 br.s (8H, pyrrole), 9.45 br.s (4H, H^n), 8.90 br.s (8H, H^m). Mass spectrum, m/z (Ie, %): 948 (97) $[\text{M}+\text{H}]^+$ (calculated for $\text{C}_{44}\text{H}_{21}\text{Cl}_8\text{N}_4\text{Co}$ 947.9) (Figure 3Sb).

Co(II) 5,10,15,20-tetra(2,6-difluorophenyl)porphyrin (VIII). *Method A*: A mixture of porphyrin **II** (0.02 g, 0.0264 mmol) and $\text{Co}(\text{OAc})_2$ (0.047 g, 0.264 mmol) in DMF (7 mL) was heated and refluxed within 1.5 min. The reaction mixture was cooled, poured into water, NaCl was added, the precipitate was filtered off, washed with water, dried and purified by alumina chromatography, first with dichloromethane, then with chloroform as eluent. Yield: 0.018 g (0.0221 mmol, 85%). *Method B*: A mixture of porphyrin **II** (0.02 g, 0.0264 mmol) and CoCl_2 (0.034 g, 0.264 mmol) in DMF (7 mL) was heated and refluxed within 10 min. Processed similarly to A. Yield: 0.017 g (0.0208 mmol, 80 %). *Method C*: A mixture of $\text{Cd}(\text{II})$ porphyrin **IV** (0.02 g, 0.023 mmol) and CoCl_2 (0.03 g, 0.23 mmol) in DMF (5 mL) was heated to 100 °C. The final product was processed similarly to A. Yield: 0.018 g (0.0221 mmol, 95 %). *Method D*: A mixture of $\text{Cd}(\text{II})$ porphyrin **IV** (0.02 g, 0.023 mmol) and $\text{Co}(\text{OAc})_2$ (0.041 g, 0.23 mmol) in DMF (5 mL) was heated and refluxed within 2 min. Processed similarly to A. Yield: 0.018 g (0.0221 mmol, 95 %). ^1H NMR (CDCl_3) δ ppm: 15.36 br.s (8H, pyrrole), 9.43 br.s (4H, H^n), 9.28 br.s (8H, H^m). Mass spectrum, m/z (Ie, %): 816.1 (97) $[\text{M}+\text{H}]^+$ (calculated for $\text{C}_{44}\text{H}_{21}\text{F}_8\text{N}_4\text{Co}$ 816.1) (Figure 4Sb).

Results and Discussion

The studies have shown that $\text{Zn}(\text{II})$ 5,10,15,20-tetra(2,6-dichlorophenyl)porphyrin (**V**) is formed by the interaction of porphyrin **I** with $\text{Zn}(\text{OAc})_2$ (molar ratio 1:20) in boiling DMF within 30 min. The complexation reaction of 2,6-difluoro-substituted porphyrin **II** with zinc acetate in DMF proceeds ~ an order of magnitude faster than 2,6-dichloro-substituted porphyrin **I**. Thus, $\text{Zn}(\text{II})$ 5,10,15,20-tetra(2,6-difluorophenyl)porphyrin (**VI**) was obtained by boiling a dimethylformamide solution of porphyrin **II** with $\text{Zn}(\text{OAc})_2$ (molar ratio of reagents 1:10) within 2 min.

This fact can be explained by the steric factor and the electronic influence of the substituents.^[38] The bulk chlorine atoms in the *ortho*-positions prevent the coordination

of the metal with the macrocyclic ligand (reaction 1). The electron-acceptor fluorine atoms are more conducive to weakening the intracyclic NH-bonds of porphyrin in comparison with chlorine atoms.

The UV-Vis spectral characteristics of the obtained Zn(II) porphyrins are given in Table 1. The mass spectrum of complex **V** (Figure 1Sb in *Supporting Information*) has the signal of molecular ion with m/z 952.9 (calculated for $C_{44}H_{21}Cl_8N_4Zn - 952.9$). The 1H NMR spectrum of complex **V** in $CDCl_3$ contains signals of β -protons at 8.75 ppm, signals of *meta*- and *para*-protons at 7.79, 7.70 ppm (Figure 1).

The mass spectrum of complex **VI** (Figure 2Sb) has the signal of molecular ion with m/z 821.09 (calculated for $C_{44}H_{21}F_8N_4Zn - 821.09$). The 1H NMR spectrum of compound **VI** in $CDCl_3$ exhibits the signals of pyrrole protons at 8.99 ppm, *para*- and *meta*-protons of phenyl rings at 7.82 and 7.41 ppm.

The complexation reaction of 2,6-dichlorosubstituted porphyrin **I** with $Co(OAc)_2$ (molar ratio 1:20) in boiling DMF during only 2 h leads to the formation of a mixture of Co(II) and Co(III) tetra(2,6-dichlorophenyl)porphyrins. Co(II) 5,10,15,20-tetra(2,6-dichlorophenyl)porphyrin (**VII**) was obtained by alumina chromatography of a cobalt-porphyrins mixture. For comparison, Co(II) 5,10,15,20-tetra(4-chlorophenyl)porphyrin was obtained by the interaction of the corresponding porphyrin with $Co(OAc)_2$ (molar ratio 1:10) in boiling DMF during 30 s.^[39]

The mass spectrum of Co(II) 5,10,15,20-tetra(2,6-dichlorophenyl)porphyrin has the peak of m/z 947.98, corresponding to the molecular ion of compound **VII** (Figure 3Sb). There are the broadened signals of pyrrole and phenyl protons at 14.65, 9.45 and 8.90 ppm, respectively, in the 1H NMR spectrum of **VII** (Co(II) ground state configuration $3d^7$).

On the contrary, the coordination of 2,6-difluorosubstituted porphyrin **II** with $Co(OAc)_2$ (molar ratio 1:10) in boiling DMF already within 1.5 min leads to the formation of Co(II) 5,10,15,20-tetra(2,6-difluorophenyl)porphyrin (**VIII**). The mass spectrum of complex **VIII** has the signal of molecular ion with m/z 816.1 (calculated for $C_{44}H_{21}F_8N_4Co - 816.1$) (Figure 4Sb). The 1H NMR spectrum of paramagnetic Co(II) complex **VIII** in $CDCl_3$ contains broadened signals of pyrrole and phenyl protons at 15.36, 9.43 and 9.28 ppm, respectively (Figure 2).

Table 1. UV-Vis spectral parameters of halogen-substituted Cd(II), Zn(II) and Co(II) tetraphenylporphyrins in DMF, λ , nm, (log ϵ).

Complex	Soret bands	Q-bands
III	418 (4.77), 438 (5.53)	578 (4.34), 620 (3.98)
IV	413 (4.88), 435 (5.63)	572 (4.41), 612 (3.89)
V	405 (4.66), 426 (5.50)	559 (4.35), 594 sh.
VI	399 (4.76), 419 (5.64)	552 (4.44), 588 sh.
VII	411 (5.32)	532 (4.26)
VIII	407 (5.39)	532 (4.36)

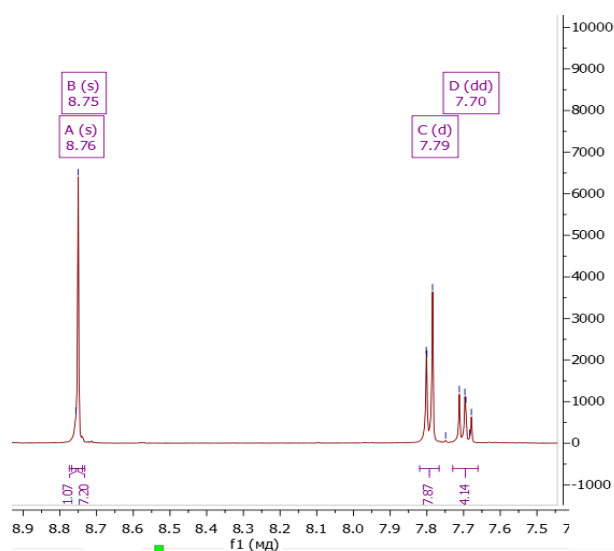


Figure 1. The informative fragment of the 1H NMR spectrum of compound **V** in $CDCl_3$.

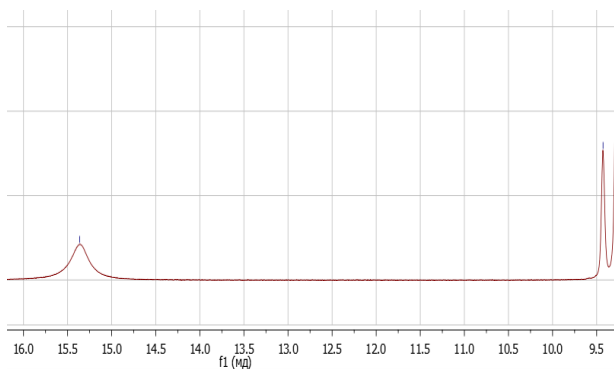


Figure 2. The informative fragment of the 1H NMR spectrum of Co(II) 5,10,15,20-tetra(2,6-difluorophenyl)porphyrin in $CDCl_3$.

Comparison of the complex formation reactions of tetraphenylporphyrin with cobalt and zinc acetates (molar ratio of reagents 1:10) in DMF^[40,41] with the reactions of *ortho*-substituted porphyrins shows that the steric factor makes a significant contribution to the processes under study. Thus, the formation time of Co(II) and Zn(II) tetraphenylporphyrins in boiling DMF is from 30 s to 2 min.^[40,41] When chlorine atoms are introduced into the *ortho*-positions of tetraphenylporphyrin, the time of formation of the corresponding zinc and cobalt complexes increases significantly (from 30 min to 2 h at a 20-fold molar excess of salts). Less bulky fluorine atoms in the *ortho*-positions of tetraphenylporphyrin do not significantly affect the course of complexation reactions.

The replacement of the $Co(OAc)_2$ by $CoCl_2$ in the coordination with porphyrin **II** contributes to increase in the reaction time. Thus, the formation time of **VIII** is 10 min and 1.5 min in the interaction of 2,6-difluoro-substituted porphyrin **II** with $CoCl_2$ and $Co(OAc)_2$, respectively. The formation time of Zn(II) 5,10,15,20-tetra(2,6-difluorophenyl)porphyrin increases ~ 5 times during the complexation of porphyrin **II** with zinc chloride in boiling DMF.

The opposite picture is observed in the formation of Zn(II) 5,10,15,20-tetra(2,6-dichlorophenyl)porphyrin and Co(II) 5,10,15,20-tetra(2,6-dichlorophenyl)porphyrin. These porphyrins are formed more easily in the coordination of 2,6-dichloro-substituted porphyrin **I** with ZnCl₂ and CoCl₂ in boiling DMF than with the corresponding acetates. The time of the reaction of porphyrin **I** with ZnCl₂ and CoCl₂ is reduced to 20 and 80 min, respectively. This is probably due to an increase in the size of the ionic radius of salts based on acetic acid compared to chlorides in coordination with sterically hindered porphyrin **I**.

The formation time of *ortho*-substituted Zn(II) and Co(II) porphyrins is reduced when using a metal exchange reaction. This fact is due to the difference in the mechanisms of porphyrins complexation^[38] and metal exchange of labile complexes^[42] with metal salts in various solvents. In^[43], the bonding energies of porphyrins and their cadmium complexes were calculated. It was shown that the energy of detachment of two protons from the porphyrin molecule is higher than the energy of the Cd-P bond.

The position of substituents in the phenyl rings of Cd(II) porphyrin has a significant effect on the metal exchange reaction (2). Thus, Zn(II) 5,10,15,20-tetra(2,6-dichlorophenyl)porphyrin **V** was obtained by the interaction of Cd(II) porphyrin **III** with ZnCl₂ (molar ratio of reagents 1:10) in boiling DMF within 2 min. Under comparable conditions, Zn(II) 5,10,15,20-tetra(4-chlorophenyl)porphyrin was formed already at room temperature within 20 min.^[44]

Metal exchange of cadmium complexes with zinc and cobalt chlorides proceeds faster than the corresponding acetates. This fact is due to the strengthening of the solvate salt, which must be destroyed during the metal exchange reaction.^[38] Co(II) 5,10,15,20-tetra(2,6-dichlorophenyl)porphyrin was formed by refluxing the cadmium complex **III** with CoCl₂ in DMF during 30 s. Under similar conditions, complexes of zinc **V** and cobalt **VII** were obtained by interaction of complex **III** with zinc acetate and cobalt acetate within 12 and 20 min, respectively.

Zn(II) 5,10,15,20-tetra(2,6-difluorophenyl)porphyrin was obtained by heating of cadmium complex **IV** with ZnCl₂ in DMF to reflux. Co(II) 5,10,15,20-tetra(2,6-difluorophenyl)porphyrin was formed by heating of Cd(II) porphyrin **IV** with CoCl₂ in DMF to 100 °C. When zinc and cobalt chlorides are replaced by the corresponding acetates, the formation time of zinc **VI** and cobalt **VIII** complexes in boiling DMF increases to 2 min and practically coincide with the time of obtaining these compounds using the coordination reaction (1).

The UV-Vis spectra of 2,6-dichlorosubstituted porphyrin **I**, their Cd(II) and Zn(II) complexes are shown in Figure 3. The UV-Vis spectra characteristics of synthesized compounds are given in Table 1.

The complexation reaction of porphyrin **II** with acetate of Co(II) in DMF has been studied by electron absorption spectroscopy. It was found that the effective rate constant (k_{eff}) of the complexation reaction of **II** with Co(OAc)₂ in DMF at T = 358 K is $5.24 \cdot 10^{-5} \text{ s}^{-1}$. In order to determine the kinetic parameters of reaction (2), we have studied the metal exchange reactions of *ortho*-halogenated Cd(II) porphyrins **III** and **IV** with CoCl₂ and ZnCl₂ in DMF. The obtained experimental data are presented in Tables 2-5. The character of changes in the UV-Vis spectra during the metal exchange reaction of **IV** with ZnCl₂ in DMF is shown in Figure 4.

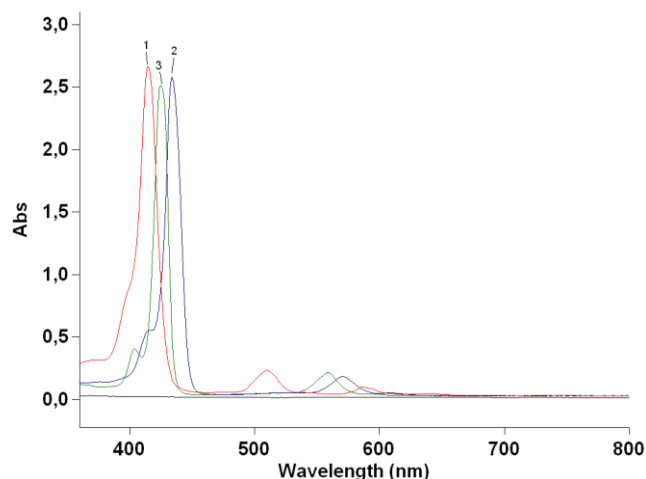


Figure 3. UV-Vis spectra of porphyrin **I** (1), cadmium complex **III** (2) and zinc complex **V** (3) in DMF.

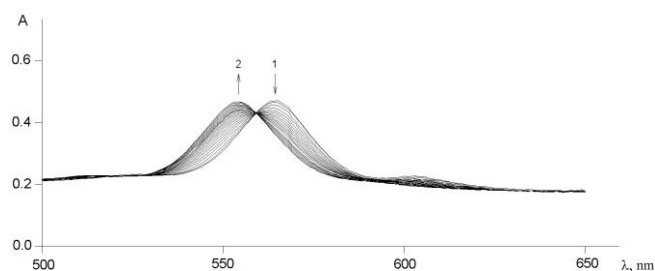


Figure 4. Changes in the UV-Vis spectra during the metal exchange reaction of **IV** with ZnCl₂ in DMF at T = 343 K in the initial moment of time (1), after 80 minutes (2) ($C_{\text{cap}} = 2.5 \cdot 10^{-5} \text{ M}$, $C_{\text{ZnCl}_2} = 2.5 \cdot 10^{-3} \text{ M}$).

Table 2. Rates of exchange of Cd²⁺ for Co²⁺ in Cd(II) 5,10,15,20-tetra(2,6-dichlorophenyl)porphyrin in DMF ($C_{\text{cap}} = 2.5 \cdot 10^{-5} \text{ M}$).

$C_{\text{CoCl}_2} \cdot 10^3, \text{ M}$	T, K	$k_{\text{eff}} \cdot 10^4, \text{ s}^{-1}$	$k_v \cdot 10^2, \text{ L} \cdot \text{mol}^{-1} \cdot \text{s}^{-1}$	$E_a, \text{ kJ} \cdot \text{mol}^{-1}$	$\Delta S^\ddagger, \text{ J} \cdot \text{mol}^{-1} \cdot \text{K}^{-1}$
2.5	298	0.38 ^a	1.52	37±15	-208±50
	338	2.20±0.07	8.80		
	343	2.88±0.10	11.52		
	348	3.22±0.14	12.88		

^a Calculated according to the Arrhenius equation.

Table 3. Rates of exchange of Cd²⁺ for Zn²⁺ in Cd(II) 5,10,15,20-tetra(2,6-dichlorophenyl)porphyrin in DMF ($C_{CdP} = 2.5 \cdot 10^{-5}$ M).

$C_{ZnCl_2} \cdot 10^2$, M	T, K	$k_{eff} \cdot 10^4$, s ⁻¹	$k_v \cdot 10^2$, L·mol ⁻¹ ·s ⁻¹	E_a , kJ·mol ⁻¹	ΔS^\ddagger , J·mol ⁻¹ ·K ⁻¹
1.25	298	0.81 ^a	6.48	36±8	-211±26
	333	3.79±0.09	30.32		
	343	5.10±0.07	40.80		
	353	7.89±0.37	63.12		
1.0	298	0.70 ^a	7.00	32±1	-224±4
	333	2.78±0.03	27.80		
	343	3.96±0.06	39.60		
	353	5.41±0.23	54.10		
0.75	298	0.52 ^a	6.93	32±8	-228±26
	333	2.07±0.10	27.60		
	343	2.67±0.12	35.60		
	353	3.97±0.15	52.94		

^a Calculated according to the Arrhenius equation.**Table 4.** Rates of exchange of Cd²⁺ for Co²⁺ in Cd(II) 5,10,15,20-tetra(2,6-difluorophenyl)porphyrin in DMF ($C_{CdP} = 2.5 \cdot 10^{-5}$ M).

$C_{CoCl_2} \cdot 10^3$, M	T, K	$k_{eff} \cdot 10^4$, s ⁻¹	$k_v \cdot 10^2$, L·mol ⁻¹ ·s ⁻¹	E_a , kJ·mol ⁻¹	ΔS^\ddagger , J·mol ⁻¹ ·K ⁻¹
2.5	298	1.35 ^a	5.40	71±13	-90±42
	303	2.27±0.09	9.08		
	313	4.76±0.11	19.04		
	323	12.86±0.32	51.44		
2.0	298	1.09 ^a	5.45	73±11	-84±38
	303	1.86±0.06	9.30		
	313	4.08±0.11	20.40		
	323	11.14±0.50	55.70		
1.5	298	0.91 ^a	6.07	69±17	-98±57
	303	1.55±0.06	10.33		
	313	3.02±0.09	20.13		
	323	8.46±0.29	56.40		

^a Calculated according to the Arrhenius equation.**Table 5.** Rates of exchange of Cd²⁺ for Zn²⁺ in Cd(II) 5,10,15,20-tetra(2,6-difluorophenyl)porphyrin in DMF ($C_{CdP} = 2.5 \cdot 10^{-5}$ M).

$C_{ZnCl_2} \cdot 10^3$, M	T, K	$k_{eff} \cdot 10^4$, s ⁻¹	$k_v \cdot 10^2$, L·mol ⁻¹ ·s ⁻¹	E_a , kJ·mol ⁻¹	ΔS^\ddagger , J·mol ⁻¹ ·K ⁻¹
2.5	298	0.38 ^a	1.52	57±22	-148±74
	323	2.35 ± 0.07	9.40		
	333	3.46 ± 0.09	13.84		
	343	7.93 ± 0.20	31.72		
2.0	298	0.31 ^a	1.55	54±20	-159±68
	323	1.73 ± 0.07	8.65		
	333	2.52 ± 0.10	12.60		
	343	5.52 ± 0.18	27.60		
1.5	298	0.24 ^a	1.60	53±25	-164±85
	323	1.33 ± 0.05	8.87		
	333	1.81 ± 0.06	12.07		
	343	4.14 ± 0.12	27.60		

^a Calculated according to the Arrhenius equation.

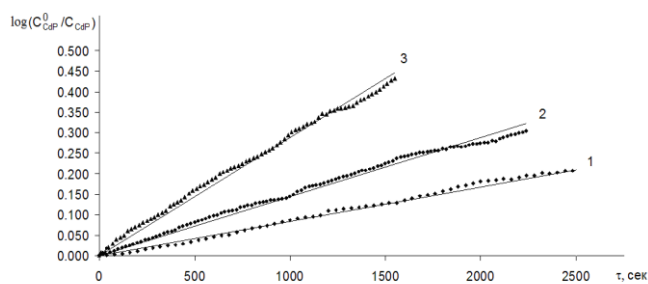


Figure 5. The dependence of $\log(C_{CdP}^0/C_{CdP})$ on the time of interaction of **II** with $ZnCl_2$ in DMF at $T = 323$ (1), 333 (2), 343 K (3) ($C_{ZnCl_2} = 2.5 \cdot 10^{-3}$ M).

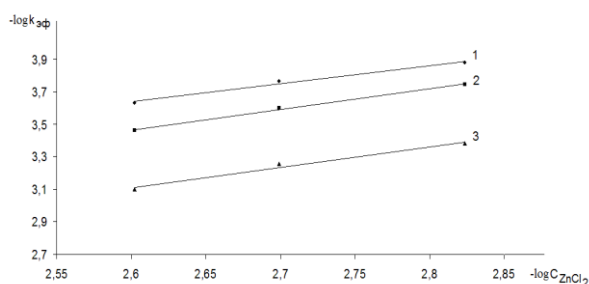


Figure 6. The dependence of $\log k_{eff}$ on $\log C_{ZnCl_2}$ in the reaction of metal exchange **II** with $ZnCl_2$ in DMF at $T = 323$ (1), 333 (2), 343 K (3).

Experimental data show that the rate of metal exchange reaction of **III** and **IV** with $CoCl_2$ and $ZnCl_2$ in DMF are described by a first-order equation for the cadmium complex. This is evidenced by the linear dependence of $\log(C_{MP}^0/C_{MP})$ on the reaction time τ . The character of this dependence is shown in Figure 5.

The order of the metal exchange reaction of **III** and **IV** with $CoCl_2$ and $ZnCl_2$ in DMF with respect to the salt determined as the tangent of the slope of the straight-line dependence $\log k_{eff} = f(\log C_{salt})$ is equal to 1 in all cases (Figure 6).

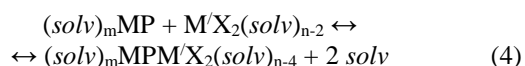
Thus, the kinetic equation for the metal exchange reaction of **III** and **IV** with $CoCl_2$ and $ZnCl_2$ in DMF can be written as equation (3):

$$-dC_{MP}/d\tau = k_v[MP][MCl_2], \quad (3)$$

where MP is **III** and **IV**, MCl_2 is $CoCl_2$ and $ZnCl_2$.

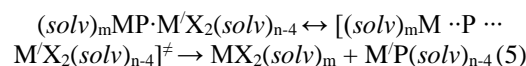
Based on the experimental data (Tables 2-5), it was found that the metal exchange reaction of **III** and **IV** with $CoCl_2$ and $ZnCl_2$ in DMF proceeds according to a bimolecular associative mechanism.

At the first bimolecular stage, an intermediate binuclear complex (intermediate) is formed:^[45]



It can be formed immediately after the solutions are merged and then it can be easily determined spectrally, or this stage can be inhibited. At the second slow monomolec-

ular stage, the intermediate dissociates to form the final products:



This stage is observed in the UV-Vis spectra by the change in the intensity of the absorption bands.

The size of the metal ion in the initial complex is one of the factors contributing to metal exchange. The large size of the $Cd(II)$ ion leads to its out-of-plane arrangement and, hence, to a more efficient solvation of the ion by the coordinating solvent. All of the abovementioned together with the activation of out-of-plane vibrations of N-M bonds facilitates the course of reaction (2).

The influence of the solvate salt nature on the rate of the metal exchange reaction was revealed. A comparison of the true rate constants of the metal exchange reaction of complexes **III** and **IV** with $CoCl_2$ and $ZnCl_2$ in DMF has been carried out. It was found that the metal exchange reaction of dichloro-substituted $Cd(II)$ porphyrin **III** with $CoCl_2$ in DMF proceeds twice as fast as with $ZnCl_2$ (Tables 2, 3). The metal exchange reaction of difluoro-substituted $Cd(II)$ porphyrin **IV** with $CoCl_2$ in DMF proceeds four times faster than with $ZnCl_2$ (Tables 4, 5).

The influence of *ortho*-fluoro- and *ortho*-chloro- substituents in $Cd(II)$ tetraphenylporphyrin is considered. Comparison of the rate constants (k_v) of the metal exchange reactions of **III** and **IV** with $CoCl_2$ and $ZnCl_2$ in DMF showed that the rate of metal exchange of **IV** with $CoCl_2$ in DMF is 3.6 times higher than that of **III**. The rate of metal exchange **IV** with $ZnCl_2$ in DMF is 2.3 times higher than of **III**. This fact is most likely due to the fact that *ortho*-fluoro-substituted $Cd(II)$ tetraphenylporphyrins have the most pronounced *-I*-effect compared to *ortho*-chlorosubstituted ones.

In this work, it was shown that, under comparable conditions, the metal exchange reaction of $Cd(II)$ tetra(2,6-dichlorophenyl)porphyrin with zinc acetate in DMF proceeds ~6 times slower than with zinc chloride.

The true rate constant of the metal exchange reaction of $Cd(II)$ tetraphenylporphyrin with $Zn(OAc)_2$ ($k_v = 1.4 \text{ L} \cdot \text{mol}^{-1} \cdot \text{s}^{-1}$),^[46] $Cd(II)$ 5,10,15,20-tetra(2,6-dichlorophenyl)porphyrin ($k_v = 6.48 \cdot 10^{-3} \text{ L} \cdot \text{mol}^{-1} \cdot \text{s}^{-1}$) and $Cd(II)$ -5,10,15,20-tetra-(2,6-difluorophenyl)porphyrin with $ZnCl_2$ in DMF ($k_v = 1.52 \cdot 10^{-2} \text{ L} \cdot \text{mol}^{-1} \cdot \text{s}^{-1}$) were calculated. It was found that the rate of the action of metal exchange of unsubstituted Cd tetraphenylporphyrin with $Zn(OAc)_2$ is 200 times higher than the rate of metal exchange of $Cd(II)$ 5,10,15,20-tetra(2,6-dichlorophenyl)porphyrin and 90 times more $Cd(II)$ 5,10,15,20-tetra(2,6-difluorophenyl)porphyrin with $ZnCl_2$ in DMF.

Conclusions

Thus, the complex formation reactions of tetra(2,6-dichlorophenyl)- and tetra(2,6-difluorophenyl)porphyrins and the metal exchange reactions their $Cd(II)$ complexes with cobalt and zinc salts in dimethylformamide were studied. The strong influence of *ortho*-substitution and the salt nature on the reactions of the coordination of dihalogenated porphyrins and metal exchange of their cadmium complexes in DMF was found. The optimal conditions for the synthesis of $Zn(II)$ and $Co(II)$ complexes with 5,10,15,20-tetra(2,6-dichlorophenyl)porphyrin and 5,10,15,20-tetra(2,6-

difluorophenyl)porphyrin were determined. The obtained compounds were identified using UV–Vis and ^1H NMR spectroscopy and mass-spectrometry. It is shown that the metal exchange reaction proceeds under milder conditions compared to complexation of the corresponding porphyrin ligands with metal cations. The mechanism of the metal exchange reaction is proposed, which suggests the formation of a binuclear intermediate. The kinetic parameters of the metal exchange reaction were calculated. These results obtained are of interest for the coordination chemistry of macrocyclic compounds and will find practical application in the synthesis of hard-to-reach complexes of natural and synthetic porphyrins, which are currently widely used as catalysts, agents for photodynamic therapy of cancer, and sensors in detecting ions and gaseous substrates of various natures.

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