DOI: 10.6060/mhc256913t

Study of the Competition between Binding Sites within a Ditopic Crown-Containing Imidazo[4,5-f][1,10]phenanthroline Ligand for Metal Cations, Depending on Their Nature

S. D. Tokarev,[@] R. R. Alekseev, D. S. Kharkovskaya, A. Botezatu, Yu. V. Fedorov, and O. A. Fedorova

A.N. Nesmeyanov Institute of Organoelement Compounds of Russian Academy of Sciences (INEOS RAS), 119334 Moscow, Russia
[@]Corresponding author E-mail: tokarev@ineos.ac.ru

The complexation behavior of two ditopic ligands, featuring both a 1,10-phenanthroline unit and an aza-15-crown-5 or azadithia-15-crown-5 ether moiety, was studied with a series of metal cations (Fe^{2+}, Cu^{2+}, Cd^{2+}, Hg^{2+}, Ba^{2+}). Using a combination of spectrophotometric, fluorimetric, NMR, and cyclic voltammetry titrations, it was determined that for all cations, regardless of their hard/soft character (from the hard Ba^{2+} to the soft Hg^{2+}), the 1,10-phenanthroline fragment serves as the primary and preferential binding site. Notably, only Cu^{2+} and Hg^{2+} were found to additionally coordinate to the crown ether fragments, and this secondary binding occurs exclusively after the phenanthroline site is occupied. The modification of the crown ether by replacing two oxygen atoms with sulfur significantly enhanced the stability of the resulting bimetallic complex with Hg^{2+}, increasing its binding constant by two orders of magnitude. This work highlights the dominant role of the phenanthroline subunit in these ditopic systems and provides insight into the stepwise binding of metal cations with heterotopic ligands.

Keywords: Complex formation, 1,10-phenanthroline, crown ether, optical titration, CVA titration.

Изучение конкуренции сайтов связывания в составе одного дитопного краун-содержащего имидазо[4,5-f][1,10]фенантролинового лиганда за катион металла

С. Д. Токарев,[@] Р. Р. Алексеев, Д. С. Харьковская, А. Ботезату, Ю. В. Федоров, О. А. Федорова

Институт элементоорганических соединений им. А.Н. Несмеянова Российской академии наук (ИНЭОС РАН), 119334 Москва, Россия
[@]E-mail: tokarev@ineos.ac.ru

Изучено комплексообразование двух дитопных лигандов, содержащих фрагмент 1,10-фенантролина, а также остаток аза-15-краун-5 или азадитиа-15-краун-5 эфира, с рядом катионов металлов (Fe^{2+}, Cu^{2+}, Cd^{2+}, Hg^{2+}, Ba^{2+}). Методами спектрофотометрического, флуориметрического, ЯМР и ЦВА титрований установлено, что для всех катионов, независимо от их жесткости (от жесткого Ba^{2+} до мягкого Hg^{2+}), фрагмент 1,10-фенантролина является первичным и предпочтительным центром связывания. Только Cu^{2+} и Hg^{2+} способны к последующей координации с краун-эфирными фрагментами, и это вторичное связывание происходит исключительно после занятия фенантролинового сайта. Замена двух атомов кислорода на атомы серы в краун-эфирном фрагменте значительно повысила устойчивость образующегося биметаллического комплекса с Hg^{2+}, увеличив его константу связывания на два порядка. В работе продемонстрирована доминирующая роль фенантролинового ионофорного фрагмента в данных дитопных системах, что дает представление о ступенчатом связывании катионов металлов гетеротопными лигандами.

Ключевые слова: Комплексообразование, 1,10-фенантролин, краун эфиры, оптическое титрование, ЦВА титрование.

Introduction

The class of 2-substituted imidazo[4,5-f][1,10]phenanthroline derivatives represents a versatile organic platform with a wide range of potential applications. Such compounds have been used as photoactive materials, luminescent sensors, components of OLED devices, nonlinear optical materials.[1-5] They also show biological and medical relevance due to their ability to penetrate cells, intercalate into DNA, and disable its functions.[6,7] The 1,10-phenanthroline fragment also serves as a versatile coordination platform for a wide range of metal cations. The resulting complexes often exhibit useful practical properties, such as pronounced photo- or electroluminescence,[8,9] nonlinear optical features,[10] biological activity,[11] ability to form porous organic materials,[12] and metal-organic frame-works.[13] So, the phenanthroline derivatives are universal and versatile ligands which was recognized more than 30 years ago.[14] Nevertheless, the literature contains few systematic data on how the nature of the metal cation, substituents on the phenanthroline core, or the presence of competing ligands affect the stability of the resulting complexes.

In our laboratory, a series of studies has been carried out devoted to investigating the interactions of mono- and ditopic imidazophenanthroline derivatives with various metal cations. In the manuscript[15] the formation of complexes of a series of monotopic imidazophenanthroline derivatives with Fe^{2+}, Co^{2+}, Cd^{2+}, and Zn^{2+} cations in 3:1 and 2:1 (ligand:metal) stoichiometries was demonstrated by means of NMR spectroscopy and mass spectrometry. Absorption and fluorometric spectroscopy provided responses to the complexation process, allowing the calculation of stability constants for the resulting complexes and the determination of how both the spectroscopic responses and complex stabilities depend on the ligand structure and the nature of the metal cation. In another study,[16] a ditopic ligand containing two coordination sites: a benzoaza-15-crown-5 ether and a 1,10-phenanthroline fragment within a single conjugated system was synthesized and investigated. The study focused on the competition between these binding sites within the same ligand for Zn^{2+} and Ca^{2+} cations. It was shown that the calcium(II) cation binds equally to both coordination sites, whereas zinc(II) does not interact with the crown ether and preferentially coordinates to the 1,10-phenanthroline fragment. The authors were able to isolate a trimetallic biligand complex, in which the calcium(II) cations occupied the crown ether fragments of two ligands, while the zinc (II) cation coordinated phenanthroline fragments of these two ligands.

Earlier, we reported on a new type of bimetallic ruthenium complexes with crown-containing imidazophenanthroline derivatives acting as a shared ligand for two cations. In the work,[17] the application of such complexes to enhance the performance of gas semiconductor sensors was described. It was demonstrated that both cations in the bimetallic complex simultaneously contribute properties that improve the sensing process. In another study,[18] the synthesis and key physicochemical properties of one such complex were reported. It was shown that coordination of the Cu(II) cation to the imidazo[4,5-f][1,10]phenanthroline-containing Ru(II) complex via the azadithia-15-crown-5 ether fragment only slightly affects the electrochemical properties of the Ru(II)-containing part of the bimetallic complex and minimally alters the absorption spectrum of the monometallic complex, while significantly enhancing its luminescence intensity.

In the present work, as a continuation of this research series, the interactions of two ditopic crown-containing imidazophenanthroline derivatives with a series of metal cations were studied. Our aim is to expand and systematize knowledge on the competition between crown ether fragments and the 1,10-phenanthroline moiety, depending on the electronic properties and size of the cation, as well as on the composition of heteroatoms within the crown ether.

Experimental

All reagents were purchased from Acros, Aldrich, Merck and used without additional purification. Solvents were purified by standard procedures. Spectroscopic grade MeCN, was used for spectroscopic and fluorometric measurements.

^{1}H NMR spectra were recorded on a Bruker AVANCE-400 and "INOVA-400" (VarianUSA) spectrometers. The chemical shifts and spin-spin coupling constants were determined with accuracy of 0.01 ppm and 0.1 Hz, respectively.

Fluorescence spectra were measured at 20±1 °C with an Agilent Cary Eclipse spectrofluorometer. UV-vis spectra were measured using a two-channel spectrophotometer Varian-Cary 300. Optical and fluorimetric titrations were carried out as follows: small portions of $1\cdot10^{-3}$ M solutions of $Cd(ClO_4)_2$, $Cu(ClO_4)_2$, $Fe(ClO_4)_2$, $Hg(ClO_4)_2$, or $Ba(ClO_4)_2$ were successively added to 2.5 mL of a 10^{-5} M solution of the ligand **1** or **2**, and the changes in the spectra of the resulting solutions were recorded. Titration was stopped when no noticeable spectral changes were observed upon addition of the next portion of titrant. The obtained sets of absorption spectra were processed using the SPECFIT 32 program to determine the stability constants of the resulting complexes. All measured luminescence spectra were corrected for the non-uniform spectral sensitivity of the detector. Quinine bisulfate (φ_{fl} = 0.6, λ_{exc} = 350 nm) in 1 M H_2SO_4 was used as standard for measuring luminescence quantum yields. The quantum yield of luminescence was calculated using the equation:

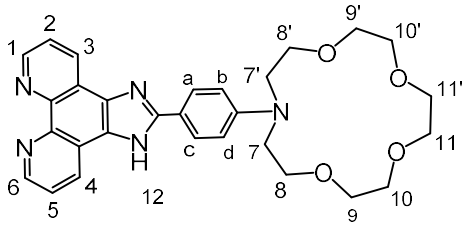
$$\varphi_i = \varphi_0 \frac{(1-10^{-A_0}) * S_i * n_i^2}{(1-10^{-A_i}) * S_0 * n_0^2},$$

where φ_i and φ_0 are the luminescence quantum yields of the sample and the standard, respectively; A_i and A_0 are the absorbances of the sample and the standard at the excitation wavelength; S_i and S_0 are the integrated areas under the luminescence curves of the sample and the standard; n_i and n_0 are the refractive indices of the solvents used for the sample and the standard (n_i = 1.3288 for acetonitrile; n_0 = 1.3391 for 1 M H_2SO_4).

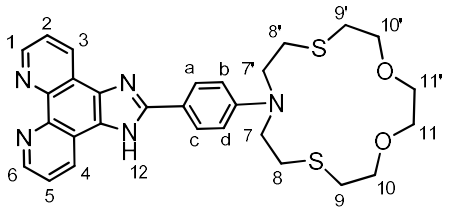
Electrochemical measurements were carried out at 22 ˚C using a PGSTAT128N potentiostat (Metrohm Autolab B.V., Netherlands). The experiments were performed in a three-electrode cell equipped with a glassy carbon (GC) working electrode (disk d = 2 mm), an Ag/AgCl/saturated KCl reference electrode, and a platinum auxiliary electrode. The compounds were dissolved in degassed dry CH_3CN containing TBAHFP (tetrabutylammonium hexafluorophosphate) as a supporting electrolyte (0.1 M). Prior to cyclic voltammetry experiments, the solutions were purged with dry argon for 15 min. The scan rate was 200 mV s^{-1}.

Synthesis

*2-[4-(1,4,7,13-Tetraoxa-10-azacyclopentadec-10-yl)phenyl] -1H-imidazo[4,5-f][1,10]phenanthroline (**1**).* According to the literature procedure[16] in a flask, 4-(1,4,7,10-tetraoxa-13-aza-cyclopentadec-13-yl)benzaldehyde (0.97 mmol, 314 mg), 1,10-phenanthroline-5,6-dione (0.95 mmol, 200 mg), ammonium acetate (19.3 mmol, 1449 mg), and glacial acetic acid (10 mL) were combined. The mixture was stirred and heated at reflux for 18 hours. After cooling to room temperature, an aqueous solution of NH_4OH (13%) was added to adjust the pH to 8. The resulting precipitate was filtered through a glass frit and washed with water and diethyl ether. The solid was dried on a rotary evaporator at 75 °C for 1 hour. The pure product was obtained as a light-orange precipitate in 54% yield. ^{1}H NMR (DMSO-d_6) δ_H ppm (J, Hz): 2.77 (t, 4H, 3J=5.5, H(9,9'), 2.88 (t, 4H, 3J=7.2, H(8,8'), 3.59 (m, 4H,H(11,11')), 3.72 (m, 8H, H(7,7',10,10')), 6.82 (d, 2H, 3J=8.8, H(b, d)), 7.82 (m, 2H, H(2,5)), 8.11 (d, 2H, 3J=8.8, H(a, c)), 8.91 (m, 2H, H(3,4)), 9.01 (m, 2H, H(1,6)), 13.41 (s, 1H, H(12)).



*2-[4-(1,4-Dioxa-7,13-dithia-10-azacyclopentadec-10-yl)-phenyl]-1H-imidazo[4,5-f][1,10]phenanthroline (**2**).* According to the literature procedure[19] in a flask, 4-(1,4-dioxa-7,13-dithia-10-azacyclopentadec-10-yl)benzaldehyde (0.338 mmol, 120 mg), 1,10-phenanthroline-5,6-dione (0.338 mmol, 710 mg), ammonium acetate (6.6 mmol, 520 mg), and glacial acetic acid (5 mL) were combined. The mixture was heated at reflux for 7 hours. An aqueous solution of NH_4OH (13%) was added to the mixture to adjust the pH to 8. The pure product was obtained as a beige precipitate (118 mg, 0.216 mmol) in 64% yield. ^{1}H NMR (DMSO-d_6) δ_H ppm (J, Hz): 2.77 (t, 4H, 3J=5.5, H(9,9'), 2.88 (t, 4H, 3J=7.2, H(8,8'), 3.59 (m, 4H,H(11,11'), 3.72 (m, 8H, H(7,7',10, 10'), 6.82 (d, 2H, 3J=8.8, H(b, d)), 7.82 (m, 2H, H(2,5)), 8.11 (d, 2H, 3J=8.8, H(a, c)), 8.91 (m, 2H, H(3,4)), 9.01 (m, 2H, H(1,6)), 13.41 (s, 1H, H(12)).



Results and Discussion

For the study, a set of d-metal cations of varying hardness was selected: intermediate Fe^{2+} and Cu^{2+} with partially filled d-orbitals, Cd^{2+} with a d^{10} configuration, the soft cation Hg^{2+}, and Ba^{2+} as a hard p-element. Within the ligand framework, the crown ether fragment was varied by changing the heteroatom composition: benzoaza-15-crown-5 in ligand **1** or benzoazadithia-15-crown-5 in ligand **2** (Chart 1).

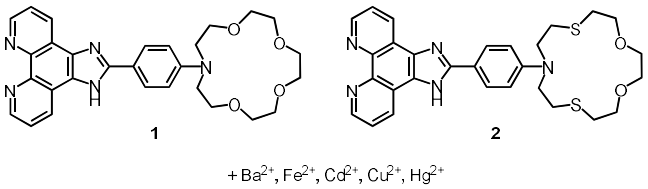


Chart 1.

The interaction of metal cations with the ligands was investigated using a set of methods: NMR spectroscopy, optical and fluorometric measurements, and cyclic voltammetry (CVA) titration. Coordination of the cation to the 1,10-phenanthroline fragment should lead to a bathochromic shift of the absorption band due to the involvement of the phenanthroline nitrogen lone pairs in the conjugated system, whereas binding to the azacrown ether induces a hypochromic shift of the absorption band due to coordination of the nitrogen lone electron pair, which is thereby removed from conjugation with the chromophore.

The optical and electrochemical properties of the ligands are shown in Figure 1 and Table 1. Both ligands contain the same chromophoric system, resulting in nearly identical positions of the absorption and emission maxima, as well as the redox waves in CVA. Nevertheless, replacing the two oxygen atoms in the crown ether fragment with sulfur atoms leads to a twofold enhancement of fluorescence intensity and an 8 nm bathochromic shift. These atoms are not part of the chromophore and therefore cannot directly affect the electronic long-wavelength transitions. Apparently, this substitution enhances fluorescence due to a decrease in the intensity of possible rotations in this part of the molecule, thereby reducing the efficiency of non-radiative relaxation processes.[20] This substitution also results in the loss of reversibility of the first oxidation wave, which can be explained by the tendency of sulfur-containing compounds to undergo electropolymerization reactions.[19] This also allows us to conclude that the first oxidation, and therefore the HOMO, is localized on the crown ether moiety.

The addition of various metal perchlorates induces significant changes in the optical properties of ligands **1** and **2**. Successive addition of small aliquots of iron(II) perchlorate to an acetonitrile solution of **2** leads to a bathochromic shift of the long-wavelength absorption band, indicating coordination through the phenanthroline moiety of the ligand (Figure 2). Simultaneously, a shoulder appears in the absorption spectrum within the 420–600 nm region, corresponding to a metal-to-ligand charge transfer transition, which is characteristic of Fe^{2+} phenanthroline complexes.[21] The ligand luminescence is completely quenched upon complex formation.

Similar bathochromic shift of the long-wavelength absorption band and quenching of luminescence are observed upon titration with cadmium(II) perchlorate, indicating its coordination exclusively at the phenanthroline moiety of ligand **2**; the corresponding spectra are provided in the ESI (Figures S1, S2, *Supporting Information*).

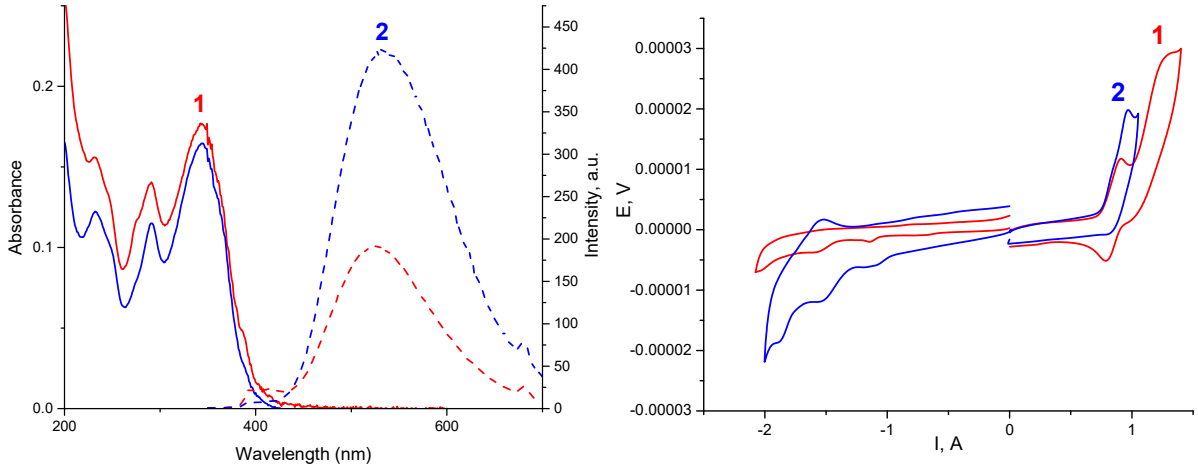


Figure 1. Left: absorption (solid line) and emission (dashed line) spectra of ligands **1** (red) and **2** (blue), $C_{\mathbf{1}\text{ or }\mathbf{2}} = 10^{-5}$ M in acetonitrile; Right: CVA curves of ligands **1** (red) and **2** (blue) in acetonitrile solution versus a $Ag/AgCl/KCl_{sat}$ reference electrode on a Pt working electrode, in the presence of a 100-fold excess of NBu_4PF_6 as the supporting electrolyte.

Table 1. Spectroscopical and electrochemical properties of ligands **1** and **2** in acetonitrile solution.

Ligand	λ_{abs}, nm	λ_{fluo}, nm	Fluorescence quantum yield, %	E_{ox}[a] *vs.* Fc/Fc^+	E_{red}[a] *vs.* Fc/Fc^+	HOMO[b]	LUMO[b]
1	342, 291, 232	524	12.9	0.364/0.490 0.830	–1.572 –1.992 –2.453	–5.2	–3.2
2	345, 291, 230	532	28.8	0.547	–1.561 –1.962 –2.301	–5.3	–3.2

[a] Oxidation and reduction potentials are reported relative to the internal Fc/Fc^+ standard, for which $E_{1/2} = 0.426$ V;
[b] The HOMO and LUMO energy levels for the complexes were calculated using ferrocene as an internal standard (4.8 eV below the vacuum level): HOMO/LUMO = –(E_{ox} or E_{red} *vs.* Fc/Fc^+) – 4.8 eV.

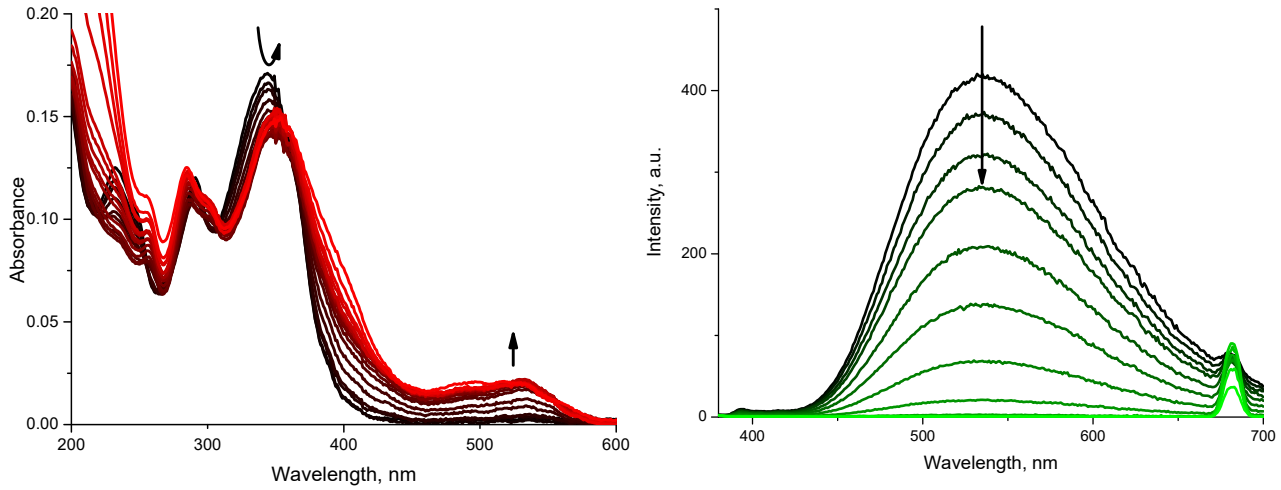


Figure 2. Left: Electronic absorption spectra of a solution of ligand **2** in acetonitrile at varying concentrations of iron(II) perchlorate. $C_2 = 1 \cdot 10^{-5}$ M; the concentration of iron(II) perchlorate varies in the range of $(0–1) \cdot 10^{-3}$ M. Right: Emission spectra of a solution of ligand **2** in acetonitrile at varying concentrations of iron(II) perchlorate. Arrows indicate the directions of the changes.

Upon addition of barium(II) perchlorate to an acetonitrile solution of ligand **2**, a bathochromic shift of the long-wavelength absorption band by 7 nm and an emission band shift by 38 nm are also observed, suggesting coordination of the barium(II) cation to the 1,10-phenanthroline fragment (Figure 3). This represents an unusual phenomenon, as it indicates that the intermediate Lewis base sites – the 1,10-phenanthroline nitrogen atoms – outcompete the azadithia-15-crown-5 ether moiety for the hard barium(II) cation.

A new type of spectral changes was observed upon the sequential addition of mercury(II) or copper(II) perchlorates to a solution of ligand **2**. In both cases, after an initial bathochromic shift of the long-wavelength absorption band, corresponding to the coordination at the phenanthroline fragment, then came a hypsochromic shift upon further increase in the cation concentration. This suggests the formation of bimetallic complexes and the coordination of a second cation at the crown ether moiety (Figure 4). In the corresponding emission spectra, quenching of the luminescence is observed (Figures S3, S4, *Supporting Information*).

According to the literature, the azadithia-15-crown-5 ether fragment forms very stable complexes with the mercury(II) cation, which can exist in aqueous media, and serves as an ionophoric moiety in molecular sensors for this metal.[22] However, spectrophotometric titration data indicate that Hg^{2+} preferentially binds first to the 1,10-phenanthroline fragment within ligand **2**, and only subsequently coordinates to the crown ether moiety. This behavior contradicts Pearson's Hard and Soft Acids and Bases (HSAB) principle, as the soft Lewis acid Hg^{2+} should primarily coordinate to soft sulfur-containing bases.

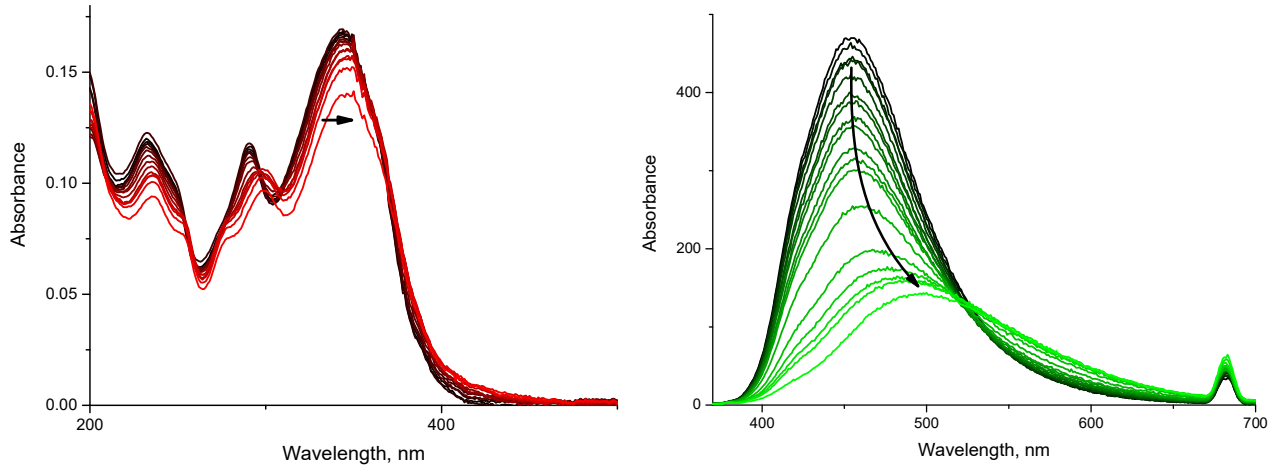


Figure 3. Left: Electronic absorption spectra of a solution of ligand **2** in acetonitrile at varying concentrations of barium(II) perchlorate. $C_2 = 1 \cdot 10^{-5}$ M; the concentration of barium(II) perchlorate varies in the range of $(0–1) \cdot 10^{-3}$ M. Right: Emission spectra of a solution of ligand **2** in acetonitrile at varying concentrations of barium(II) perchlorate. Arrows indicate the direction of the changes.

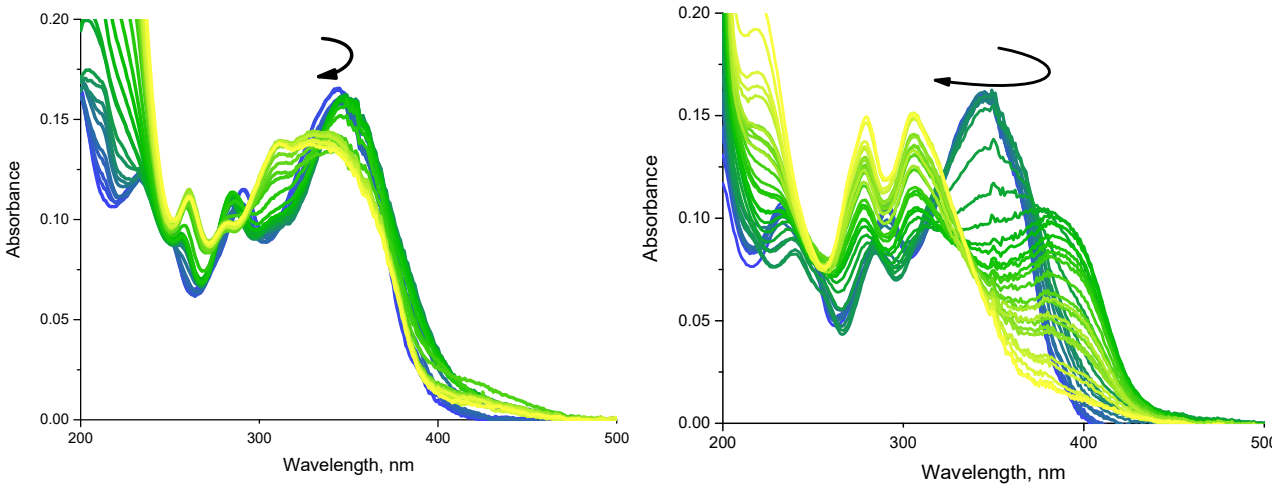


Figure 4. Electronic absorption spectra of ligand **2** solution in acetonitrile at varying concentrations of: (left) copper(II) perchlorate, (right) mercury(II) perchlorate. In both cases, $C_2 = 1 \cdot 10^{-5}$ M, and the concentration of the metal perchlorate varies in the range of $(0 - 1) \cdot 10^{-3}$M.

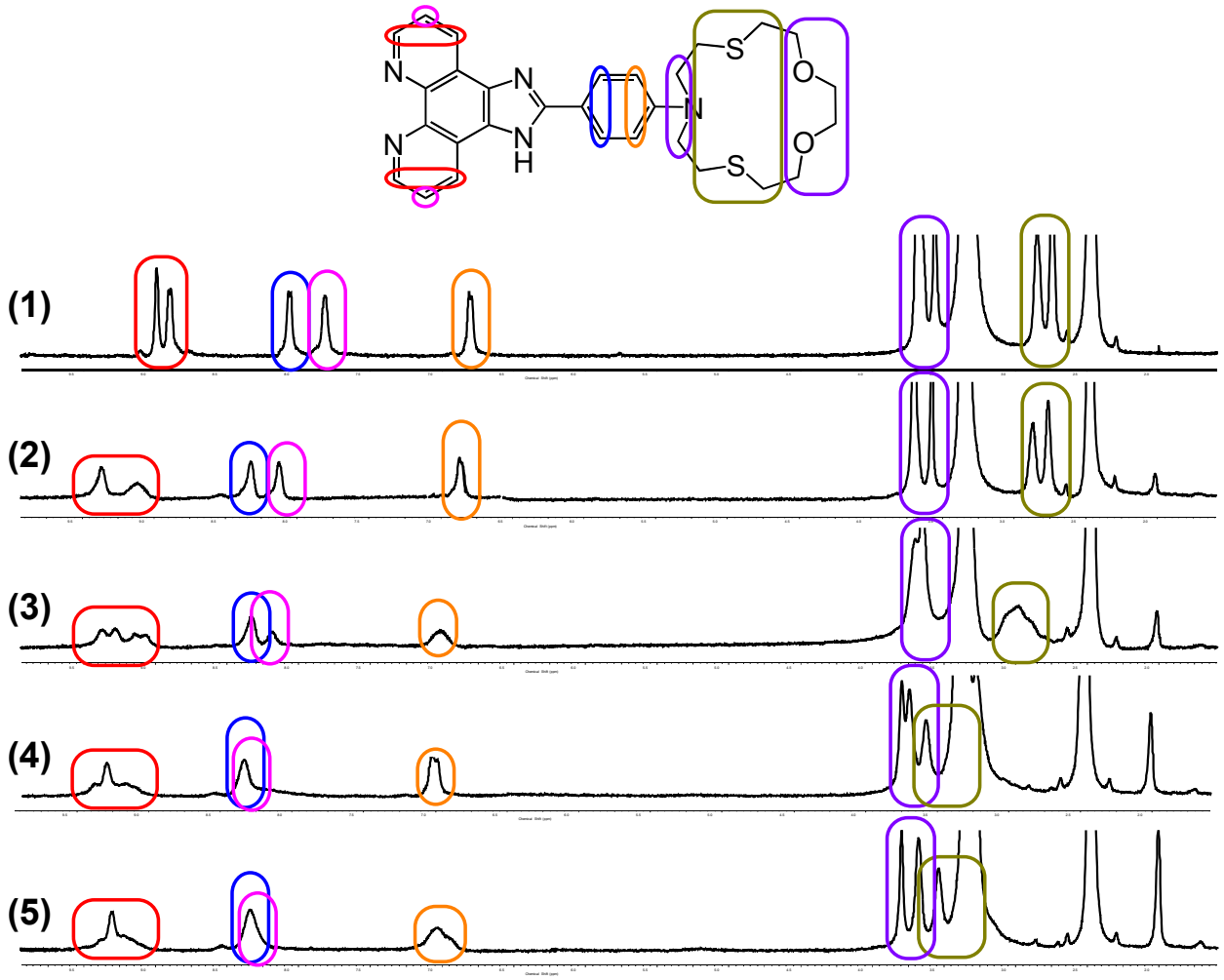


Figure 5. ^{1}H NMR spectra recorded upon addition of 1) 0 equiv. Hg^{2+}, 2) 0.5 equiv. Hg^{2+}, 3) 1 equiv. Hg^{2+}, 4) 2 equiv. Hg^{2+}, 5) 4 equiv. Hg^{2+} to a solution of ligand **2** in MeCN-d_3.

To confirm the preferential coordination of the 1,10-phenanthroline unit, NMR titration was performed (Figure 5). The signals of the 1,10-phenanthroline protons undergo a slight downfield shift upon the first addition of mercury(II) perchlorate. In contrast, the signals of the crown-ether protons begin to shift only after the addition of 1 equivalent of the metal cation. The most significant shift is observed for the protons of the CH_2 groups adjacent to the sulfur atoms, confirming coordination specifically through these heteroatoms of the crown ether. It is also important to note that the changes cease after the addition of 2 equivalents of Hg^{2+}, which may suggest the formation of stable 1:2 (ligand:metal) complexes.

The titration of ligand **2** with Cd^{2+}, performed in an analogous manner, resulted in shifting of only aromatic protons signals, with no change observed for the crown-ether proton signals. This finding fully corroborates the conclusions drawn from optical spectroscopy (Figure S5).

Regarding the interaction between the Cu^{2+} cation and ligand **2**, previous reports[19] have described the spontaneous, intramolecular reduction of Cu^{2+} to Cu^{+} within the complex upon a single addition of 5 equivalents of copper over several tens of seconds. In our study, such reduction was not observed, likely due to the stepwise addition protocol and the coordination of a second cation to the crown ether moiety upon exceeding 1 equivalent. This process presumably blocks the pathway for metal cation reduction via the lone electron pair of the crown ether nitrogen.

Titration of ligand **1** with Ba^{2+}, Fe^{2+}, Cd^{2+}, and Hg^{2+} revealed changes analogous to those observed with ligand **2** (Figures S6–S12). Specifically, a purely bathochromic shift of the long-wavelength absorption band was observed for the first three cations, even with an excess of up to 20 equivalents. For Hg^{2+}, an initial bathochromic shift followed by a hypsochromic shift upon the addition of approximately 1 equivalent of the cation was observed. In the case of titration with copper(II) cations, an intense absorption band appeared at 490 nm in the absorption spectrum (Figure S13). This band subsequently decreases in intensity over time, accompanied by a simultaneous increase in the band at 280 nm. Such behavior is interpreted as a ligand-to-metal charge transfer (LMCT) band, indicative of cation reduction to Cu^{+}.[23] The literature describes prerequisites for the intramolecular reduction of the copper(II) cation: the presence of a donor fragment in the ligand conjugated with the coordination site, and the use of acetonitrile as a solvent, in which the Cu^{+} cation is thermodynamically stabilized.[19] In the case of ligand **1**, the donor dialkylamino fragment in the crown ether fulfills this role. Notably, this phenomenon was not observed for ligand **2**. This is likely due to the faster coordination of excess copper to the crown ether moiety after the phenanthroline site is occupied, which

blocks the charge transfer pathway. Luminescence is quenched in the copper(II) complex, similarly to the behavior observed with Fe^{2+}, Cd^{2+}, and Hg^{2+} (Figure S14).

Further evidence for the sequential coordination of Hg^{2+} first to the 1,10-phenanthroline fragment and then to the crown ether moiety was obtained from CV titration (Figure 6). According to the obtained curves, the second irreversible oxidation potential undergoes an anodic shift starting from the first addition of Hg^{2+} to a solution of **1** in DMSO. In contrast, the first reversible oxidation potential at approximately 0.830 V *vs*. the reference electrode begins to shift only after the addition of 1 equivalent of Hg^{2+}. Comparison of the CV curves for ligands **1** and **2** established that the first oxidation wave corresponds to the oxidation of the crown ether heteroatoms. Thus, the influence of the mercury(II) cation on the oxidation of this fragment becomes apparent only when the cation is present in excess relative to the ligand. The increase in the oxidation potentials of the organic ligand upon complexation is attributed to the hindered oxidation process at the electrode in the presence of a positively charged cation, which competes with the electrode for the electron. Concurrently, from the first cation additions, reduction signals of the mercury(II) cation within the complex appear in the cathodic region at potentials lower than those for free Hg^{2+}. This cathodic shift is associated with a partial transfer of electron density from the ligand's heteroatoms to the cation, which impedes electron injection from the working electrode.

During the titration of ligand **1** with Fe^{2+} (Figure 7), no shifts in the first oxidation wave were observed at any ligand-to-metal ratio. A shift in the second oxidation wave was detected from the first additions, which apparently indicates complexation at the 1,10-phenanthroline fragment. Another interesting feature of the titration with iron(II) was the appearance of signals corresponding to the free cation upon transitioning from a ligand:metal ratio of 1:0.25 to 1:0.5.

It is known that iron forms extremely stable complexes with the 1,10-phenanthroline fragment, and tris(1,10-phenanthroline)iron(II) (ferroin) is employed as a redox indicator or sensor molecule for Fe(II) determination.[24] By analogy, we propose the formation of a stable complex with a ligand:metal stoichiometry of 3:1 (or equivalently, 1:0.33) in our case. Subsequent additions of the metal only lead to an increase in the intensity of the redox waves for free iron, as all ligand molecules are already coordinated.

Based on the literature data[15-18] and the results of spectrophotometric titration, the formation of complexes with compositions 1:1, 2:1, and 1:2 (ligand:metal) is proposed for both copper(II) and mercury(II) cations with both ligands. For the cadmium(II) cation, 1:1 and 2:1 complexes are suggested; for the iron(II) cation, only a 3:1 complex; and for the barium(II) cation, solely a 1:1 complex (ligand: :metal in all cases). Structures of all complexes are shown in Figure 8.

The stability constants of the formed complexes were calculated from the changes in the absorption spectra during spectrophotometric titration using the SpecFit32 program. The calculated stability constant values are presented in Table 2.

An interesting observation is the notable difference in the stability of bimetallic complexes with the mercury(II) cation. For ligand **1**, containing the aza-15-crown-5 ether fragment, the complex stability is two orders of magnitude lower than for ligand **2** with the sulfur-containing crown ether, reflecting the affinity of the soft cation for sulfur atoms. Also the weak binding of the extremely hard Ba^{2+} cation and the extremely soft Hg^{2+} cation to the phenanthroline fragment in the 1:1 and 2:1 complexes is pronounced when compared to the intermediate Lewis acids Cu^{2+} (for ligand **2**), Fe^{2+}, and Cd^{2+}.

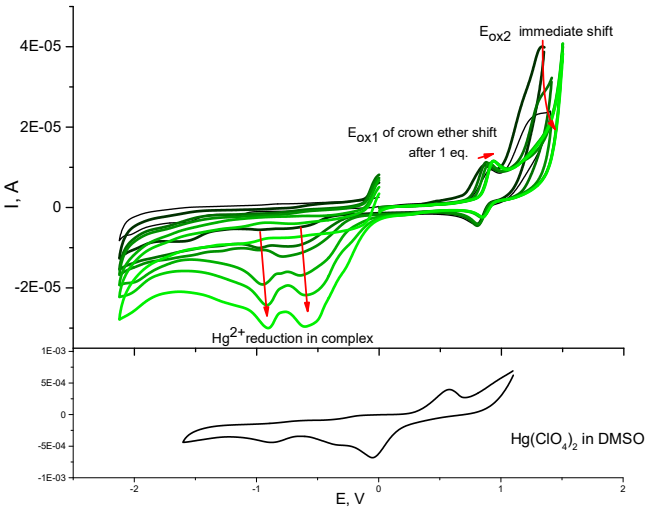


Figure 6. Top: Changes in the CV curve of ligand **1** in DMSO upon sequential addition of mercury(II) perchlorate (molar ratio **1**:Hg^{2+} = 1:0; 1:0.25; 1:0.5; 1:0.75; 1:1; 1:1.5; 1:2, from black to bright green). Red arrows indicate the direction of the changes. Bottom: CV curve of $Hg(ClO_4)_2$ in DMSO.

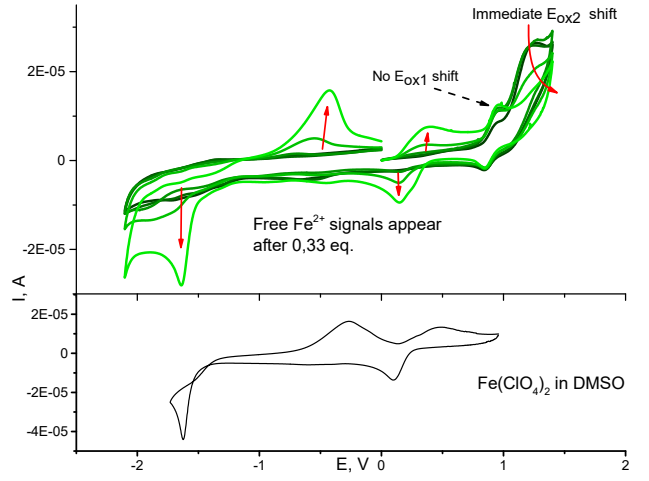


Figure 7. Top: Changes in the CV curve of ligand **1** in DMSO upon sequential addition of iron(II) perchlorate (molar ratio **1**:Fe^{2+} = 1:0; 1:0.25; 1:0.5; 1:1; 1:2, from black to bright green). Red arrows indicate the direction of the changes. Bottom: CV curve of $Fe(ClO_4)_2$ in DMSO.

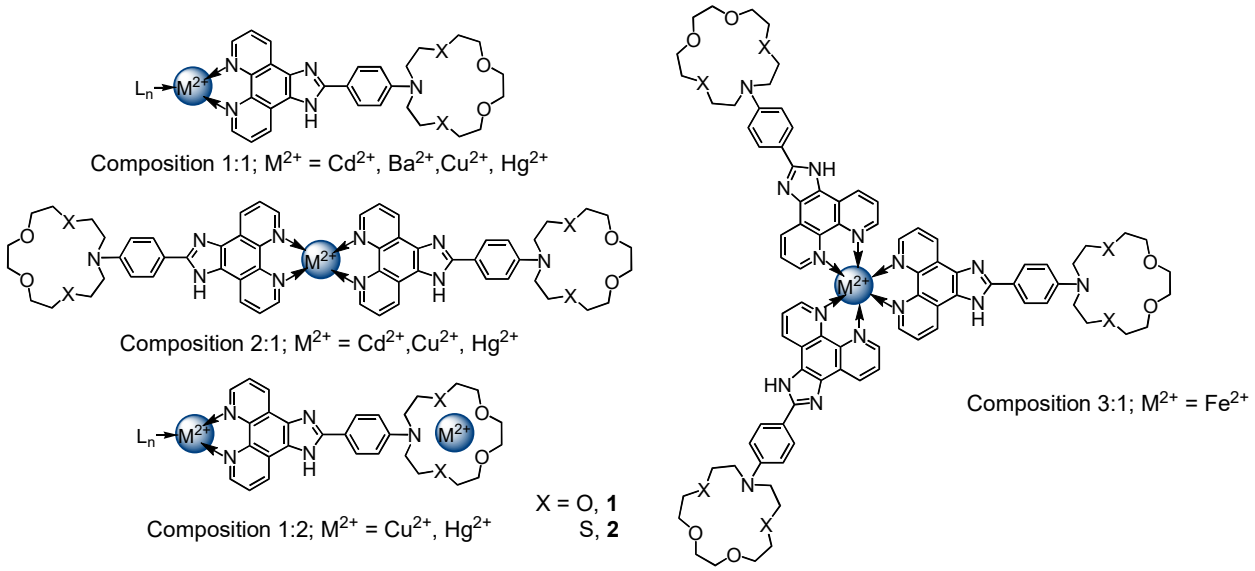


Figure 8. Proposed structures of complexes. The composition is given in ligand:metal ratio.

Table 2. Decimal logarithms of the stability constants for the formed complexes.

Ligand, metal	Complex composition ligand:metal			
	1:1	1:2	2:1	3:1
1, Cd^{2+}	6.2±0.3	-	11.8±0.6	-
1, Fe^{2+}		-	-	17.4±0.8
1, Ba^{2+}	6.1±0.3		-	-
1, Cd^{2+}	6.2±0.3	-	11.8±0.6	-
1, Cu^{2+}	Time dependent changes in the spectra, calculation is impossible			
1, Hg^{2+}	4.5±0.3	7.7±0.1	9.8±0.4	-
2, Cd^{2+}	6.3±0.6	-	11.7±0.4	-
2, Fe^{2+}	-	-	-	14.9±0.2
2, Ba^{2+}	5.7±0.5		-	-
2, Cu^{2+}	8.0±0.4	13.7±0.5	15.0±0.5	-
2, Hg^{2+}	4.4±0.2	9.7±0.2	9.6±0.3	-

Conclusions

This study investigated the interaction of two ditopic crown-containing imidazophenanthroline derivatives with a series of different metal cations. Each ligand contained two ionophoric fragments: a 1,10-phenanthroline moiety common to both compounds, and either an aza-15-crown-5 or a softer azadithia-15-crown-5 ether fragment.

A selection of five metal cations with diverse properties was chosen for investigation: intermediate Lewis acids Fe^{2+} and Cu^{2+} (with unfilled d-orbitals), Cd^{2+} (d^{10} configuration), the soft cation Hg^{2+}, and Ba^{2+} as a hard p-block element.

Using spectrophotometric, fluorimetric, NMR, and CV titrations, it was established that for all investigated cations, regardless of their nature, the 1,10-phenanthroline residue is the primary coordination site. Among the entire series of metal cations, only Cu^{2+} and Hg^{2+} form complexes involving the crown-ether fragments, and this occurs exclusively when the phenanthroline binding site is already occupied, which has not been reported before.

The replacement of two oxygen atoms with sulfur atoms within the aza-15-crown-ether fragment increases the binding strength towards the Hg^{2+} cation by two orders of magnitude.

Acknowledgements. Financial support from the Russian Science Foundation (RSF No. 25-73-20122) is gratefully acknowledged. There are no conflicts to declare.

Author Contribution. S.D. Tokarev: conceptualization; writing – original draft; formal analysis; writing – review and editing, R. R. Alekseev: investigation, formal analysis, D.S. Kharkovskaya: investigation, formal analysis, A. Botezatu: investigation, formal analysis, Yu.V. Fedorov: methodology, supervision, writing – review and editing; O.A. Fedorova: conceptualization, writing – review and editing, supervision.

References

1. Wang R.Y., Jia W.L., Aziz H., Vamvounis G., Wang S., Hu N.X., Coggan J.A. *Adv. Funct. Mater.* **2005**, *15*, 1483–1487.
2. Xiao T., Yi T., Zhou Y., Zhao Q., Li F., Huang C. *Tetrahedron* **2006**, *62*, 10072–10077.
3. Lee J.F., Chen Y.C., Wu C.C., Chen C.Y., Dai C.A., Chao C.Y., Liau W.B. *Tetrahedron* **2011**, *67*, 1696–1703.
4. Bing Y.J., Leung L.M., Menglian G. *Tetrahedron Lett.* **2004**, *45*, 6361–6363.
5. Peng J., Sun J., Gong P., Xue P., Zhang Z., Zhang G., Lu R. *Chem. Asian J.* **2015**, *10*, 1717–1725.
6. Zhen N., Yang Q., Zheng K., Han Z., Sun F., Mei W., Yu Y. *Int. J. Biochem. Cell Biol.* **2016**, *79*, 158–167.
7. Liao S., Zhang Z., Wu Q., Wang X., Mei W. *Bioorg. Med. Chem.* **2014**, *22*, 6503–6510.
8. Bian Z.Q., Wang K.Z., Jin L.P. *Polyhedron* **2002**, *21*, 313–319.
9. Liu Q.Q., Geng J., Wang X.X., Gu K.H., Huang W., Zheng Y.X. *Polyhedron* **2013**, *59*, 52–57.
10. Wang Y., Zhang Y., Zhu D., Ma K., Ni H., Tang G. *Spectrochim. Acta A.* **2015**, *147*, 31–42.
11. Shilpa M., Latha J.N.L., Devi A.G., Nagarjuna A., Kumar Y.P., Nagababu P., Satyanarayana S. *J. Incl. Phenom. Macrocycl. Chem.* **2011**, *70*, 187–195.
12. Bakhvalova E.S., Nikoshvili L.Z., Sulman M.G. *ChemChemTech* **2026**, *69*(5), 23–35.
13. Sun H.Y., Liu C.B., Cong Y., Yu M.H., Bai H.Y., Che G.B. *Inorg. Chem. Commun.* **2013**, *35*, 130–133.
14. Sammes P.G., Yahioglu G. *Chem. Soc. Rev.* **1994**, *23*, 327–334.
15. Tokarev S.D., Fedorov Y.V., Fedorova O.A. *Mendeleev Commun.* **2020**, *30*, 445–448.
16. Sotnikova Y., Lukovskaya E., Bobylyova A., Fedorov Y., Novikov V., Peregudov A., Fedorova O. *Inorg. Chim. Acta* **2016**, *445*, 103–109.
17. Nasriddinov A., Sadikova D., Zelenetskaya D., Sivaev I., Avetisov I., Obraztsov I., Kovalenko A., Mikhailov I., Rumyantseva V., Tokarev S., Vasilchenko A., Emets V., Borshchev O., Burenkova A., Agafonov A. *Molecules* **2022**, *27*, 5058.
18. Tokarev S.D., Botezatu A., Fedorov Yu.V., Fedorova O.A. *Chem. Heterocycl. Compd.* **2021**, *57*, 799–805.
19. Fedorova O.A., Shepel N.E., Tokarev S.D., Lukovskaya E.V., Sotnikova Y.A., Moiseeva A.A., Fedorov Y.V. *New J. Chem.* **2019**, *43*, 2817–2827.
20. Khatua S., Schmittel M. *Org. Lett.*, **2013**, *15*, 4422–4425.
21. Yang Z., Yan C., Chen Y., Zhu C., Zhang C., Dong X., He W. *Dalton Trans.* **2010**, *40*, 2173–2176.
22. Panchenko P.A., Efremenko A.V., Feofanov A.V., Ustimova M.A., Fedorov Y.V., Fedorova O.A. *Sensors* **2021**, *21*, 470.
23. Berdnikova D.V., Fedorov Y.V., Fedorova O.A. *Dyes Pigm.* **2013**, *96*, 287–295.
24. Fortune W.B., Mellon M.G. *Ind. Eng. Chem. Anal. Ed.* **1938**, *10*(2), 60–64.

Received 11.12.2025
Accepted 10.03.2026