5-(Pyridylmethylidene)-substituted 2-thiohydantoins and their complexes with Cu^{II}, Ni^{II}, and Co^{II}: synthesis, electrochemical study, and adsorption on the cystamine-modified gold surface

E. K. Beloglazkina, * A. G. Majouga, I. V. Yudin, N. A. Frolova, N. V. Zyk, V. D. Dolzhikova, A. A. Moiseeva, R. D. Rakhimov, and K. P. Butin[†]

Department of Chemistry, M. V. Lomonosov Moscow State University, 1 Leninskie Gory, 119992 Moscow, Russian Federation. E-mail: bel@org.chem.msu.ru

A series of Cu^{II}, Ni^{II}, and Co^{II} complexes with 5-(pyridylmethylidene)-substituted 2-thiohydantoins (L) were synthesized by the reactions of the corresponding organic ligands with $MCl_2 \cdot nH_2O$. The resulting complexes have the composition $LMCl_2$ (M = Cu or Ni) or L_2MCl_2 (M = Co). The reactions with N(3)-unsubstituted thiohydantoins afford complexes containing four-membered metallacycles, in which the metal ion is coordinated by the S and N(3) atoms of the thiohydantoin ligand. The reactions of N(3)-substituted thiohydantoins give complexes in which the S and N(1) atoms are involved in coordination. Study by IR spectroscopy demonstrated that the pyridine nitrogen atom is not involved in coordination. Based on the results of electrochemical study of the ligands and complexes by cyclic voltammetry and calculation of their frontier orbitals by the PM3(tm) method, the mechanism of oxidation and reduction of these compounds was proposed. In the first reduction and oxidation steps, the metal atom in the copper and nickel complexes remains, apparently, intact, and these processes occur with the involvement of the ligand fragments, viz., the coordinated thiohydantoin ligand and chloride anion, respectively. In the cobalt complexes, the first reduction step occurs at the ligand; the first oxidation state, at the metal atom. Measurements of the contact angle of aqueous wetting and electrochemical study demonstrated that carboxy-containing 2-thiohydantoins and their complexes can be adsorbed on the cystamine-modified gold surface. The structures of the complexes on the surface differ from the structures of these complexes in solution.

Key words: 5-(pyridylmethylidene)-2-thiohydantoins; Cu^{II}, Ni^{II}, and Co^{II} complexes; cyclic voltammetry; quantum chemical calculations by the PM3(tm) method; adsorption.

2-Thiohydantoins (4-oxoimidazolidine-2-thiones) exhibit anticonvulsant, antibacterial, antiviral, and antithrombotic activities.¹⁻⁴ It is known⁵ that coordination with transition metal ions sometimes increases antiviral and antitumor activities of such drugs.

2-Thiohydantoin molecules contain the thioamide fragment and can undergo the thione-thiol tautomerism $(NH-C=S \implies N=C-SH)^6$ due to which they can be coordinated to metal ions through the lone electron pairs of the nitrogen or sulfur atoms, or both. The resulting complexes can contain 2-thiohydantoins as either neutral ligands or monoanions.^{5–12}

Complexes of hydantoins and thiohydantoins with Cu^{II} , 9,10 Fe^{III}, 9,10 Co^{II}, 9,10 Ni^{II}, 9,10 Mn^{II}, 9 Cs^I, 7 Pt^{II}, 5 Tl^{III}, 6,8 Hg^{II}, 8,10 Zn^{II}, 10 Cd^{II}, 10 V^{III}, V^{IV}, and V^V (see Ref. 11) have been synthesized. Most of the

resulting complexes contain four-membered metallacycles.

Hydantoin or thiohydantoin molecules containing a fragment with an additional donor atom can form chelate^{12–16} or surpamolecular¹⁷ complexes in which the metal atom is coordinated by one or two thiohydantoin ligands in the neutral or deprotonated form. The factors responsible for the composition of the complexes and the charge of the thiohydantoin ligand remain unknown. For example, the reactions of 5-[(Z)-2-pyridy] hydantoin (LH) with Ni^{II} and Cu^{II} salts under the same conditions give¹³ the chelate complexes [LNi(H₂O)₄]Cl and (LH)CuCl₂(H₂O)₂, respectively (structures of these complexes are presented below), whereas the reactions with copper(II) chloride in the presence of melamine (MA) produce the supramolecular complex $CuL_2(MA)_2$, in which chelating coordination bonds between two nitrogen atoms (of the pyridine and hydantoin fragments) and

Published in Russian in Izvestiya Akademii Nauk. Seriya Khimicheskaya, No. 6, pp. 978-990, June, 2006.

1066-5285/06/5506-1015 © 2006 Springer Science+Business Media, Inc.

[†] Deceased.

the Cu^{II} ions are combined with binding of MA through hydrogen bonds.¹⁷



These complexes are of practical interest because the introduction of a transition metal ion into supramolecular crystalline systems imparts the optical, conducting, and magnetic properties of this ion to the complexes. As a result, such materials hold promise as materials in nonlinear optics and as conductors and ferromagnets.

The aim of the present study was to synthesize a series of 5-(pyridylmethylidene)-substituted 2-thiohydantoins, investigate their complexation with Co^{II}, Ni^{II}, and Cu^{II} salts and the electrochemical behavior of the resulting ligands and complexes, and examine their adsorption on the cystamine ($(H_2NCH_2CH_2S)_2$)-modified gold surface.

Results and Discussion

Synthesis of ligands. We synthesized 5-(pyridylmethylidene)-substituted 2-thiohydantoins 1-9 and studied these compounds in complexation reactions with nickel, cobalt, and copper chlorides. The structures of compounds 1-9 are given below.





5-(Pyridylmethylidene)-substituted thiohydantoins 1, 5, and 8 containing no substituents at the N(3) atom were synthesized by condensation of 2-thiohydantoin with the corresponding pyridinecarbaldehydes in a glycine—Na₂CO₃ buffer solution (Scheme 1).

Earlier,¹³ the Z configuration of the C=C bond in compound 1 has been established by X-ray diffraction. Compounds 5 and 8, which we prepared for the first time, are also formed as one geometric isomer. Based on the criteria developed from ¹H NMR spectroscopic Scheme 1



R = 2-pyridyl (1), 3-pyridyl (5), 4-pyridyl (8)

data, 13,18,19 we assigned the Z configuration to these compounds.

The synthesis of 3-phenyl-5-(pyridylmethylidene)-2thiohydantoins **3**, **6**, and **9** has been documented earlier.²⁰ Thiohydantoins **2**, **4**, and **7** containing the methyl or 4-carbethoxyphenyl substituent at position 3 were synthesized according to analogous procedures (Scheme 2).

Scheme 2



R' = 2-pyridyl (**2**, **4**), 3-pyridyl (**7**)

Carbethoxy-containing thiohydantoins **4** and **7** were hydrolyzed to prepare the corresponding acids **10** and **11** (Scheme 3). The resulting compounds containing salt-forming groups were used to modify the gold surface (see below).

Scheme 3





Synthesis of complexes. Copper(II), nickel(II), and cobalt(II) complexes with compounds 1-9 were synthesized by refluxing mixtures of the corresponding ligands and metal chlorides in aqueous dioxane (Scheme 4). The compositions and the melting points of the complexes based on ligands 1, 3, 6, 7, and 9 are given in Table 1. In other cases, crystalline complexes were not isolated. However, coordination apparently occurs with other ligands as well because mixing of their solutions with metal chloride solutions is accompanied by a change in the color.

Scheme 4



n = 2 (M = Cu), 6 (M = Ni, Co); R = Ph (**6**, **9**), 4-EtO₂CC₆H₄ (**7**); Py = 2-pyridyl (**1**), 3-pyridyl (**6**, **7**), 4-pyridyl (**9**)

The resulting copper and nickel complexes have the composition $LMCl_2$ (sometimes, with the inclusion of one or two MeCN or H_2O molecules). The cobalt complexes have the composition L_2MCl_2 (see Table 1).

The structural formula of the complex compounds were established by electronic and IR spectroscopy and are presented in Scheme 4. According to the published data, chelate *N*-pyridyl-*N*-hydantoin-coordinated complexes would be expected to be formed with 2-pyridyl-containing ligands 1-4 (see above). For the steric reasons, 3-pyridyl- (5–7) and 4-pyridyl-containing (8 and 9) ligands would be expected to form either polynuclear (bridged) N,S-complexes, in which each metal atom is

Table 1. Characteristics of the complexes of 5-(pyridylmethyl-
idene)-substituted thiohydantoins with $MCl_2 \cdot 6H_2O$ (M = Co
Ni, or Cu)

Li- gand	Compo- sition	Yield (%)	Color	M.p. /°C	Found (%) Calculated		
	of the complex				С	Н	N
1	$1 \cdot \text{NiCl}_2$	55	Yellow	276	33.07	<u>2.22</u>	<u>12.94</u>
6	6 • CuCl ₂	55	Brown	266	33.92 <u>43.10</u>	2.13 <u>2.81</u>	12.80 <u>9.87</u>
	6 ⋅ NiCl ₂	64	Yellow	317	43.27 44.10	2.64 2.37 2.68	10.10 10.20 10.22
	$(6)_2 \cdot \text{CoCl}_2$	• 57	Green	282	<u>51.20</u>	2.08 <u>2.89</u> 2.10	<u>10.22</u> <u>10.80</u>
7	$7 \cdot \text{CuCl}_2$	62	Crim-	269	$\frac{44.46}{44.32}$	$\frac{3.10}{3.23}$	<u>8.57</u> 8.61
	7•NiCl ₂ • •2MeCN	74	Yellow	273	<u>39.31</u> 39.22	<u>3.02</u> 3.12	<u>10.33</u> 10.40
9	$9 \cdot \text{CuCl}_2$	52	Brown	310	$\frac{43.05}{43.27}$	<u>2.85</u> 2.64	<u>9.76</u> 10.10
	$9 \cdot \text{NiCl}_2$	43	Yellow	>300	<u>43.63</u> 43.80	<u>2.01</u> 2.71 2.68	10.10 10.14 10.22
	$(9)_2 \text{CoCl}_2 \cdot H_2 O$	50	Yellow	310	<u>50.12</u> 50.80	<u>3.45</u> 3.10	<u>11.34</u> 11.68

coordinated by the N and S atoms of two different ligands (see, for example, Refs 20 and 21), or four-membered metallacycles analogous to those described above. However, complexes containing four-membered metallacycles were isolated in all cases (see Scheme 4). Therefore, the presence and character of the pyridylmethylidene substituent at position 5 of the thiohydantoin ring has no significant effect on complexation, and the presence or the absence of a substituent at the N(3) atom of the thiohydantoin fragment and the nature of the complexforming metal play the decisive role.

In the IR spectra of all the complexes with pyridylcontaining ligands under consideration, the C=S absorption band $(1190-1210 \text{ cm}^{-1})$ is shifted to higher frequencies compared to that in the spectra of the free ligands $(1145-1170 \text{ cm}^{-1})$ (Table 2). This is evidence that the sulfur atom is involved in coordination in all complexes. The N–H absorption band in the complexes with the 3- and 4-pyridyl-containing ligands is also shifted compared to that of the free ligands (see Table 2). Consequently, the N(3) atom is also presumably involved in coordination. By contrast, the position of the v(N(1)-H)band in the spectrum of the nickel complex with 2-pyridylcontaining ligand 1 is virtually identical to that in the spectrum of the starting ligand, whereas the v(N(3)-H)band is shifted by 120 cm^{-1} (see Table 2). This is evidence for coordination through the N(3) atom.

The positions of the absorption bands in the IR spectra of the starting ligands at \sim 1500 and \sim 1610 cm⁻¹ corre-

Compound			Electronic spectrum, λ/nm				
	N(1)-H	N(3)—H	C=0	C=C	Ру	C=S	$(\epsilon \cdot 10^{-4}/L \text{ mol}^{-1} \text{ dm}^{-1})$
1	3160	3280	1760, 1720	1660	1620, 1475	1170	_
$1 \cdot \text{NiCl}_2$	3180 br	3400	1750, 1710	1650	1620, 1475	1195	_
2	3200	_	1760	1650	1610, 1480	1160	_
3	3330	_	1745	1665	1590, 1495	1170	_
4	3270	_	1750, 1710	1650	_	1160	_
5	3080	3170	1760	1660	1620, 1480	1165	_
6	3260	_	1740	1670	1610, 1500	1145	_
$6 \cdot CuCl_2$	3200	_	1745	1650	1610, 1500	1190	_
$6 \cdot \text{NiCl}_2$	_	_	_	_	_	_	448 (3.62), 670 (1.75),
							674 (1.75), 689 (1.74)
$(6)_2 \cdot \text{CoCl}_2 \cdot \text{H}_2\text{O}$	3300 br	_	1740	1655	1610, 1500	1190	445 (4.27), 608 (2.17),
							672 (2.32)
7	3290	_	1750, 1700	1650	1610, 1495	1165	_
$7 \cdot CuCl_2$	3160	_	1740, 1720	1655	1610, 1495	1185	_
$7 \cdot \text{NiCl}_2 \cdot 2\text{MeCN}$	3060	_	1740, 1725	1655	1610, 1495	1180	_
8	3155	3250	1740	1650	1615, 1495	1165	_
9	3180	_	1750	1660	1610, 1500	1160	_
$9 \cdot CuCl_2$	3190	_	1735	1645	1605, 1500	1190	440 (4.07), 568 (1.02),
-							635 (1.32)
$9 \cdot \text{NiCl}_2$	3165	_	1740	1645	1610, 1500	1210	432 (3.67), 598 (1.94),
-							607 (1.94), 666 (1.98)
$(9)_2 \cdot \text{CoCl}_2 \cdot \text{H}_2\text{O}$	3450 br,	_	1740	1650	1610, 1495	1190	440 (4.15), 666 (1.60),
	3180						674 (1.60), 682 (1.60)

Table 2. Results of electronic and IR spectroscopic studies of 5-(pyridylmethylidene)-2-thiohydantoins and their complexes

sponding to stretching vibrations of the pyridine ring^{22,23} are virtually identical to those in the spectra of the corresponding complexes. This indicates that the pyridine nitrogen atom in all complexes is not involved in coordination; otherwise (according to the published data^{23–25}), these bands should be shifted to higher wavenumbers by ~15 cm⁻¹.

The electronic spectra of the cobalt complexes with 3- and 4-pyridyl-containing ligands 6 and 9 show an intense absorption band in the visible region at ~440 nm, which is apparently assigned to the metal-ligand charge transfer, and two or three medium-intensity bands at 600-680 nm (see Table 2). These spectral patterns are consistent with the octahedral coordination environment.^{26,27} Analogous spectra of the nickel and copper complexes with ligands 6 and 9 have, along with absorption bands at 440-450 nm, three low-intensity bands at 660-690 nm, which is typical of tetrahedral complexes.^{24,27} Based on the results of optical spectroscopy, it can be concluded that the cobalt complexes with ligands 6 and 9 correspond to the structure B (see Scheme 4), whereas the structures A and C should be apparently assigned to the nickel and copper complexes with 3-phenylsubstituted and 3-unsubstituted ligands, respectively.

Electrochemical study of 5-(pyridylmethylidene)-substituted 2-thiohydantoins and their complexes with Cu^{II}, Ni^{II}, and Co^{II}. *Ligands*. Polarographic reduction of 5-benzylidene-2-thiohydantoins in aqueous or alcoholic media at a dropping mercury electrode was documented in several publications, $^{28-30}$ but the only voltammetric

Scheme 5



Ar = Ph, $4 - NO_2C_6H_4$, $4 - CIC_6H_4$, $4 - MeOC_6H_4$, $4 - HOC_6H_4$, $4 - Me_2NC_6H_4$ study of aryl-substituted 5-benzylidene-2-thiohydantoins in an aprotic medium was published.³¹

We studied the electrochemical behavior of ligands 1 and 3-9 and their complexes with metal chlorides by cyclic voltammetry (CV) and using a rotating disk electrode (RDE) at glassy-carbon (GC) and Pt electrodes and, in some cases, at an Au electrode in DMF solutions. The electrochemical oxidation and reduction potentials are given in Table 3.

According to the published data,³¹ oxidation of 5-arylidene-2-thiohydantoins affords a biradical, which reacts with solvents with recovery of the starting compound. Reduction of 5-arylidene-2-thiohydantoins gave thiol **A**, which was isolated as the reaction product after preparative electrolysis (Scheme 5).³¹

A similar mechanism of oxidation and reduction can be proposed for the pyridyl-substituted thiohydantoins under consideration. To validate this hypothesis, we per-

Table 3. Electrochemical reduction potentials (E^{Red}) and oxidation potentials (E^{Ox}) of 5-(pyridylmethylidene)-2-thiohydantoins and their complexes measured relative to Ag/AgCl/KCl(satur.) by the CV (E_p is the peak potential) and RDE ($E_{1/2}$ is the half-wave potential) methods at a glassy-carbon electrode^{*a*}

Com-	$E_{\rm p}^{\rm Red}$	$E_{1/2}^{\text{Red}}$	<i>E</i> _p Ox	$E_{1/2}^{Ox}$	Com-	$E_{\rm p}^{\rm Red}$	$E_{1/2}^{\text{Red}}$	$E_{\rm p}^{\rm Ox}$	$E_{1/2}^{Ox}$
pound		V			pound		V		
1	-1.16, -1.80, -2.38, -2.80	-1.11 (2), -1.80 (1), -2.81	1.60	1.50 (1)	6•NiCl ₂	$-1.24^{b}, -1.90, -2.43, -2.75$	-1.10(1), -1.43(2), $-1.88(\leq 1)$	1.12	1.10 (2)
$1 \cdot \text{NiCl}_2$	$-1.10^{b}, -1.73, -2.45, -2.68$	-1.05(1), -1.73(1)	1.20, 1.62	1.21 (1), 1.59 (2)	8	$-0.95, -1.44^{f}, -1.73, -2.21,$	-0.93(1), -1.72(1),	1.17	1.52
$(1)_2 \cdot \operatorname{CoCl}_2^c$	$-1.04^{a}, -1.28, -1.76, -2.42$	-1.04(1), $-1.42^{e},$ -1.76^{e}	1.34	1.36 (1)	9	-2.82 $-0.85, -1.41^{f},$ $-1.51^{f}, -1.64,$	-2.40(0.6) -0.81(1), -1.62(1).	1.13	1.13, 1.51
3	-1.16, -1.70, -2.27, -2.78	-1.02 (1), -1.70 (1)	_	1.08 (2)	9 ⋅ CuCl ₂	$-1.99^{f}, -2.69$ -0.84, -1.34,	-2.08 (0.59) 0.54 (1),	1.30	1.25 (2)
$(3)_2 \cdot \operatorname{CoCl}_2^c$	-1.19^d , -1.63 , -1.86, -2.44	-1.15(1), -1.47(1.5), -1.80(0.3)	1.30	1.25 (1)		-1.60, -1.90	$\begin{array}{r} -0.48 \ (0.25)^{g_{*}} \\ -0.84 \ (0.7), \\ -1.34 \ (0.5), \end{array}$	h,	
5	-1.30, -1.84, -1.97, -2.51, -2.83	-1.27 (1), -1.90 (1)	1.52	1.32 (1)	9 · NiCl ₂	-0.90^{f} , -1.14 .	-1.63 (0.6), -2.01 (0.3) -0.84 (1).	1.12	1.10 (2)
$(5)_2 \cdot \operatorname{CoCl}_2^c$	-1.01^d , -1.68 , -1.91, -2.38 ,	-0.97 (1), -1.71 (1)	1.21, 1.56	1.30 (1)		-1.64, -2.36	-1.07 (0.8), -1.51 (1.8)		
6	-2.87 -1.21, -1.84, -2.37, -2.77	-1.14(1), -1.84(1.5), -2.54(1.3)	1.53	1.38 (1)	$(9)_2 \cdot \text{CoCl}_2 \cdot \text{H}_2\text{O}$ CuCl_2 \cdot 2H_2O	$-0.92^{e}, -1.70,$ -2.00 $+0.45/+0.58^{h},$ -0.51/-0.16	-0.85(1), -1.65(1) +0.50(1) ^h	-	1.35 (2) —
6 · CuCl ₂	$\begin{array}{c} 0.44/0.52, \\ -1.19^{f}, \\ -1.57^{f}, \\ -1.82, -2.13, \\ -2.52 \end{array}$	$\begin{array}{c} 0.50 \ (1), \\ -0.52 \ (0.5)^{g,h}, \\ -1.17 \ (1), \\ -1.36 \ (0.9), \\ -1.84 \ (1) \end{array}$	0.52, 1.27	1.22 (2)	NiCl ₂ •6H ₂ O CoCl ₂ •6H ₂ O	-1.32/+0.16 -0.86, -1.21/+0.35	-1.30 (2) -1.30	1.20 1.53, 1.70	1.00 (2) 1.50 (1), 1.70 (1)

^{*a*} The number of electrons transferred in this step, which was determined on a rotating disk electrode by comparing with the oneelectron oxidation wave of ferrocene, is given in parentheses; the peak potentials on reverse scans in the CV curves are given after a slash.

^b Radical anions are stable at a glassy-carbon electrode; reduction at platinum or gold electrodes was accompanied by deposition of free metal.

^c The complex was not isolated; the *in situ* formation in DMF from equimolar amounts of the ligand and $MCl_2 \cdot nH_2O$ was confirmed by electrochemical methods.

^d In the case of accumulation at the potential of the first reduction wave, cobalt metal is deposited on a glassy-carbon electrode; in the case of reduction at Pt or Au electrodes, elimination of Co occurs without accumulation.

^e After this peak, the curve drops, which is indicative of adsorption of the product on the electrode.

^f Low-intensity peak.

^g The peak is weakly pronounced and is not always reproduced.

^{*h*} The initial potential is +0.7 V.

formed semiempirical quantum chemical calculations of the frontier orbitals by the PM3 method³² for compounds **1**, **3**, **5**, **6**, **8**, and **9**. The results of calculations demonstrated that the character of the highest occupied molecular orbitals (HOMO) and the lowest unoccupied molecular orbitals (LUMO) in the molecules of these compounds are independent of the nature of the pyridyl fragment (2-, 3-, or 4-pyridyl) and the substituent at the N(3) atom (Fig. 1). According to calculations, the orbitals of the conjugated Michael π -system of the carbonyl group and the C=C bond, as well as the orbitals of the C=S bond, make the major contribution to LUMO (see Fig. 1), which is consistent with the mechanism of reduction proposed earlier.³¹ However, the orbitals of the lone pairs of the sulfur atoms make the major contribution to HOMO (see Fig. 1, a-f). Consequently, initial oxidation should also occur at the C=S fragment. In addition, the proposed³¹ scheme of oxidation is inapplicable in the case of 3-substituted ligands because the N(3) atom in the resulting radical cation does not contain a hydrogen atom, which can be abstracted.

5-(Pyridylmethylidene)-substituted 2-thiohydantoins are successively reduced in four one-electron steps, 4-pyridyl-substituted compounds being more readily reduced, whereas 3-pyridyl-substituted compounds being most difficult to reduce (see Table 3 and Fig. 2). The first



Fig. 1. Frontier orbitals of 5-(pyridylmethylidene)-substituted 2-thiohydantoins 1 (a, b), 3 (c, d), 5 (e, f) and the product of their reduction, *viz.*, thiol A (g, h), calculated by the PM3(tm) method (see Schemes 5 and 6): HOMO (a, c, e, g) and LUMO (b, d, f, h).



Fig. 2. Cyclic voltammograms of compounds 1 and 5.

oxidation step of these compounds is one-electron irreversible (in the case of 3-unsubstituted compounds 1, 5, and 8) or two-electron irreversible (in the case of 3-substituted compounds 3, 6, and 9). Therefore, the mecha-

nisms of electrooxidation of these two groups of compounds should be different. Presumably, the radical cation that is generated in the first oxidation step is unstable. In the case of *N*-unsubstituted ligands, this radical cation is stabilized as a result of proton abstraction from the N(3) atom, but elimination of the Ar^+ cation from the radical cations of compounds **3**, **6**, or **9** is unlikely to occur. In the latter case, two-electron oxidation can immediately give rise to the sulfenium cation (Scheme 6). It should be noted that X-ray diffraction study²⁰ demonstrated that the plane of the Ph group at the N(3) atom in 5-(pyridylmethylidene)-substituted 2-thiohydantoins is virtually orthogonal to the plane of the pyrimidine ring and, consequently, this group cannot stabilize the cationic or radical center at the adjacent nitrogen atom.

Earlier,³¹ reduction of 5-arylidenethiohydantoins to thiol A (see Scheme 5) has been documented. For 5-(pyridylmethylidene)-substituted 2-thiohydantoins, we observed four one-electron reduction waves. According to quantum chemical calculations, LUMO of thiol of type A (see Scheme 6) is localized on the conjugated π -system of the carbonyl group (see Fig. 1, g, h) and the C=C bond, and reduction of thiol should occur at this fragment. As

Scheme 6



Beloglazkina et al.

a result, four-electron reduction of the starting compound affords, apparently, alcohol **B**.

For all the compounds under consideration, a peak at +0.7 V is observed on the reverse potential scan after the second or third reduction wave. This peak, apparently, corresponds to oxidation of the thiol group and additionally confirms the formation of thiol.

Therefore, the following mechanism of electrooxidation and reduction of 5-(pyridylmethylidene)-substituted 2-thiohydantoins can be proposed based on the experimental and calculated data (see Scheme 6).

Complexes. Cyclic voltammograms of all the complexes under study are similar to the CV curves of the free ligands (Fig. 3). Like the corresponding ligands, the 3-unsubstituted complexes undergo one-electron oxidation, whereas the 3-substituted complexes undergo two-electron oxidation. However, the peaks in the cathodic region of the CV curves of the cobalt complexes are shifted to more positive potentials compared to the free ligands, whereas these shifts for the nickel and copper complexes are insignificant and the reduction potentials of the latter complexes are close to those for the corresponding ligands (see Table 3 and Fig. 3). The CV curves of the complexes differ also from the corresponding data for the starting ligands in that they have an oxidation peak of the coordinated chloride ion at 1.1-1.2 V. This peak has low inten-



Fig. 3. Cyclic voltammograms of ligand **5** (solid line) and its complex with $CoCl_2$ (dashed line) (*a*), ligand **6** (solid line) and its complex with $NiCl_2$ (dashed line) (*b*).

sity on the potential scan from zero to the anodic region. However, initial reduction followed by oxidation leads to a considerable increase in the intensity of this peak.

The fact that the reduction curves of the free ligands are similar to those of their complexes, apparently, indicates that reduction of the complexes of this structural type occurs at the ligand rather than at the metal atom. This assumption is also evidenced by the fact that reduction of the complexes occurs more readily than reduction of the corresponding ligands. Coordination to the positively charged metal atom should decrease the electron density on the ligand molecule and lead to reduction at less negative potentials.

Analysis of the CV curves of all the complexes under study revealed the following characteristic features. First, the reduced forms of the complexes with 3-substituted ligands 3, 6, and 9 are less stable than the corresponding complexes with 3-unsubstituted ligands 1, 5, and 8. For all complexes of the former group, the first reduction peak is followed by a peak of oxidative desorption of a zero-valent metal from the electrode surface, whereas these peaks are absent for the complexes of the latter group (Fig. 4). Second, the reduced forms of the complexes of 3- and 4-pyridyl-substituted ligands with CoCl₂ are less stable than the corresponding complexes with NiCl₂ and CuCl₂. After the first reduction step of the cobalt complexes, cobalt metal is deposited on the electrode surface, whereas the radical anions of the nickel and copper complexes are stable.

Apparently, reduction of the complexes starts with the electron transfer to the ligand fragment followed by the slow electron density transfer to the metal atom (Scheme 7 for M = Cu and Ni; Py = 3- or 4-pyridyl). The resulting complex of the neutral ligand with M^{I} dissociates to form



Fig. 4. Cyclic voltammograms of the cobalt complexes with ligands 3(1) and 5(2).

the zero-valent metal, the ligand, and chloride anions (hence, at the potential of the first wave, the intensity of the peaks of oxidative desorption of metal and oxidation of chloride anions at 1.1-1.2 V increases). Apparently, the radical anion C of the complexes with 3-phenyl-substituted ligands (see Scheme 7) is less stable because the Ph group (inductive acceptor), which is orthogonal to the plane of the thiohydantoin ring, destabilizes the radical center in the ligand fragment. The structures of the radical anions of the 3-unsubstituted complexes are, apparently, similar to the structure of the radical anion C, *i.e.*, the electron density transfer to metal occurs more slowly.

Scheme 7



The copper complexes with ligands **6** and **9** give the weakly pronounced, sometimes irreproducible, second reduction peak at $-0.5 \text{ V} (\text{Cu}^{1} \rightarrow \text{Cu}^{0})$. Suppression of this peak can, in principle, be a consequence of the fact



Fig. 5. Frontier orbitals of the complexes $5 \cdot \text{NiCl}_2(a, b)$, $5 \cdot \text{CuCl}_2(c)$, and $(6)_2 \cdot \text{CoCl}_2 \cdot \text{H}_2\text{O}(d)$: HOMO (*a*), LUMO (*b*), and SOMO (*c*, *d*) calculated by the PM3(tm) method (chlorine atoms in Fig. 5, *d* are omitted).

that the electrode surface is blocked by an adsorbed electrolysis product because of poor solubility of copper(1) compounds.²⁰

The structures of the cobalt complexes with ligands **6** and **9** differ from those of the other complexes. According to calculations, the d orbitals of the metal atom in these complexes also make a contribution to singly occupied molecular orbitals (SOMO) as opposed to the copper and nickel complexes (Fig. 5, a-c). This is, apparently, responsible for the fact that reduction occurs more readily and the reduced forms are less stable.

The complexes can be oxidized at either the coordinated chloride anion (which is consistent with the calculated data, see Fig. 5) or the metal atom to the M^{III} state, which is stabilized by the donor ligand.

We compared the CV curves of oxidation of the complexes and starting metal chlorides. Anodic oxidation of $CoCl_2 \cdot 6H_2O$ at a rotating disk electrode gives rise to two one-electron waves (see Table 3), one of which is, apparently, associated with the $Co^{II} \rightarrow Co^{III}$ transition, whereas another wave is attributed to oxidation of one of the ligands, for example, of the water molecule

$$[\text{Cl}_2\text{Co}^{\text{III}}\text{--}\text{OH}_2]^+ - \text{e} \rightarrow 1/2 \ [\text{Cl}_2\text{Co}^{\text{III}}\text{--}\text{O}]_2 + 2 \ \text{H}^+$$

or chloride ions²⁰

 $3 \; [CoCl_2]^+ - 2 \; e \rightarrow 3 \; Co^+ + 2 \; Cl_3^-.$

In the anodic branch of the polarization curves of the cobalt complexes with ligands **5**, **6**, and **9**, the first peak is shifted to less positive potentials by ~400 mV compared to the starting ligands and $CoCl_2 \cdot 6H_2O$ (see Fig. 3, *a* and Table 3). Complexation of the metal ion with a donor ligand should facilitate oxidation at the metal atom but hinder oxidation at the ligand. Hence, this peak should be assigned to the $Co^{II} \rightarrow Co^{III}$ transition. Therefore, the first reduction step of the cobalt complexes presumably occurs at the ligand, whereas the first oxidation step occurs at the metal atom.

The first oxidation potentials of the nickel complexes with ligands 1, 6, and 9 are less positive than the oxidation potentials of the corresponding ligands and are higher than the oxidation potential of NiCl₂·6H₂O (see Table 3). Therefore, this process cannot be oxidation at the metal atom; otherwise, the donor ligand would facilitate reduction.

No oxidation peaks of CuCl₂ • $2H_2O$, which could correspond to the formation of copper(III), are observed in the anodic region up to +1.7 V. By contrast, a two-electron peak is observed at 1.22–1.25 V for the copper complexes, which rejects the hypothesis of oxidation at the metal. As in the case of the nickel complexes, the potential of this peak is less positive than the potential of the first oxidation peak of the ligands (see Table 3). Apparently, oxidation of the copper and nickel complexes oc-

curs at the coordinated chloride anions, which is confirmed by the calculated data. The HOMOs of these complexes are localized primarily on the chlorine atoms (see Fig. 5, c). Therefore, the metal atom in the copper and nickel complexes remains intact in the first reduction and oxidation steps, and these processes occur at the ligand fragments, *viz.*, the coordinated thiohydantoin ligand and the chloride anion, respectively.

Adsorption. We examined adsorption of thiohydantoin ligands and their metal complexes on the gold surface. Self-organized monolayers containing transition metal atoms involved in complexes are of interest from the point of view of their practical use in catalytic reactions on the surface³³ and for the design of ion-selective electrodes.³⁴ The gold surface was modified according to a two-step procedure (Scheme 8). Initially, a self-organized monolayer of cystamine (12) containing terminal amino groups³⁵ was prepared on the gold surface. Then this monolyaer was treated with a solution of carboxy-substituted thiohydantoin 10 or 11. We expected that the surface reaction producing a salt would give rise to a bilayer analogous to that described earlier³⁶ and containing the donor thiohydantoin fragments on the outer side.

Scheme 8



In each step of this modification, the aqueous wetting angle was measured and CV curves were recorded.

The contact angle after the modification of the cystamine plate was $50\pm1^{\circ}$, which agrees with the known data $(55\pm4^{\circ}$ for a gold film deposited onto the glass surface).³⁷ After the second modification, the contact angle decreases to $35\pm1^{\circ}$, which is, in our opinion, associated with an increase in the hydrophilicity of the surface upon the salt formation with carboxy-containing thiohydantoins.

The possibility of adsorption of compounds **10** and **11** and the complexes with ligand **11** on the gold surface was studied also by electrochemical methods. A bilayer on a gold electrode was prepared according to an approach analogous to the above-described two-step procedure (see Scheme 8). The data for the adsorbed ligands and complexes were compared with the electrochemical characteristics obtained for solutions of the corresponding compounds. The results are given in Table 4.

Di(2-aminoethyl) disulfide (12), which is either adsorbed on a gold electrode or is present in solution, is reduced at ~-0.9 V and is oxidized at ~-1.65 V. However, reduction becomes quasireversible in the case of formation of a monolayer (see Table 4). The formation of a bilayer leads to a change in the redox characteristics of the adsorbed compound (see Table 4 and Fig. 6). The second surface modification can, in principle, involve the following two competitive processes: the formation of a bilayer as a result of the surface salt formation reaction and the displacement of cystamine from the monolayer with thiohydantoin that is present in solution. In this case, thiohydantoin can be adsorbed on the surface through the thione sulfur atom. However, the treatment

Table 4. Electrochemical reduction potentials (E^{Red}) and oxidation potentials (E^{Ox}) of compounds **10–12** and their complexes with metal chlorides at Pt (in solution) and Au (in the adsorbed state) electrodes (MeCN, a 0.05 *M* Bu₄NBF₄ solution, relative to Ag/AgCl/KCl(satur.), 20 °C)

Compound	$E_{\rm p}^{\rm Red}$	$E_{\rm p}^{\rm Ox}$
	V	
12 (solution)	-0.97/0.00,	1.62/0.93 ^a
	-1.37	
12 (monolayer)	$-0.88/-0.62^{b}$	1.65/0.80 ^c
· - /	-1.56	
10 (solution)	-1.03/-0.51,	1.53/0.87
· · ·	-1.71/-1.63	
12 + 10 (bilayer)	-1.37	1.66/1.43
11 (solution)	-0.82/-0.51,	1.50/0.82
· · ·	-1.24/-1.08,	
	-1.78/-1.68	
12 + 11 (bilayer)	-0.96/-0.58	$1.61/0.82^{d}$
12 + 11 (bilayer) + CuCl ₂ · 2H ₂ O	-0.74/-0.53	1.64/0.85 ^{b,e}
12 + 11 (bilayer) + NiCl ₂ · 6H ₂ O	-0.93, -1.46	$1.39/0.78^{f}$
12 + 11 (bilayer) + CoCl ₂ · 6H ₂ O	-0.99/-0.52	$1.71/0.80^{b}$

^{*a*} The intensity ratio between the direct and reverse peaks $(I_d : I_r)$ is 3 : 1.

$${}^{b}I_{d}:I_{r}=2:1.$$

 ${}^{c}I_{d}: I_{r} = 5:1.$ ${}^{d}I_{d}: I_{r} = 4:1.$

^{*e*} On the reverse scan, two reduction peaks of free copper chloride are observed in the cathodic region at +0.40 and -0.64 V. ^{*f*} I_d : $I_r = 8 : 1$.



Fig. 6. Cyclic voltammograms of a monolayer of cystamine 12 on the gold electrode surface (solid line) and a bilayer of 12 + 11 (dashed line).

of the cystamine-modified surface of the gold electrode with a solution of thiohydantoin 7 does not lead to changes in the voltammetric curve, which is evidence for the former mechanism.

After soaking of the bilayer-modified electrode in a solution containing $MCl_2 \cdot 6H_2O$, the formation of complexes occurs on the surface, which is confirmed by the observed changes in the CV curves (see Table 4 and Fig. 7). For example, the nickel complex with compound **11** fixed on the surface is oxidized more readily than the corresponding ligand by 0.32 V, and reduction becomes a two-step process. For the copper complex with the same ligand, no considerable changes in the oxidation and reduction



Fig. 7. Cyclic voltammograms of the surface-adsorbed complex $12 + 11 + CuCl_2 \cdot 2H_2O$ (solid line) and the complex $7 \cdot CuCl_2$ in an MeCN solution (dashed line).

potentials compared to the starting ligand are observed. However, the formation of the complex was reliably established based on the appearance of two reduction peaks of free copper chloride after the anodic peak in the cathodic branch of the CV curve. Apparently, the structures of the complexes formed on the surface differ from those in solution because their redox characteristics are substantially different (*cf.* Tables 3 and 4; Figs 3, 4, and 7).

Presumably, in the case of formation of a close-packed layer of the thiohydantoin ligands on the electrode surface, coordination of the metal ion occurs only through the nitrogen atom of the pyridine fragment directed outward, whereas the nitrogen and sulfur atoms of the thiohydantoin ligands located inside the layer are not involved in coordination at all. This can account for the fact that we failed to prepare complexes with metal salts for 2-pyridyl-containing compounds **10** fixed on the surface, whereas 3-pyridyl-substituted ligand **11**, in which the pyridine nitrogen atom is more accessible for coordination from the outer side of the bilayer, forms such complexes.

Experimental

Commercial 2-thiohydantoin and di(2-aminoethyl) disulfide (Acros) were used without additional purification. 3-Phenyl-substituted 2-thiohydantoins and their 5-pyridylmethylidene derivatives **3**, **6**, and **9** were synthesized according to a known procedure.²⁰ The ¹H NMR spectra were measured on a Varian-VXR-400 instrument at 400 MHz. The IR spectra were recorded on an UR-20 instrument in Nujol mulls. The EI mass spectra were obtained on a JMS-D300 GLC-mass spectrometer equipped with a JMA-2000 computer and an HP-5890 chromatograph.

Quantum chemical calculations were performed by the semiempirical SCF PM3 method,³³ which was extended by including the parameters for all first-row transition metals and selected second- and third-row transition metals (HyperChem program package, HyperCube Inc., USA). Geometry optimization of the molecules was carried out with a gradient of no higher than 10 kal $Å^{-1}$ mol⁻¹ as the convergence criterion.

The contact angle was measured with the use of silicon plates containing a vacuum-deposited gold layer (layer thickness was 50 ± 10 nm, the plate size was 5×5 mm) purchased from HT-MDT. In the first modification step, the plates were soaked in a 10^{-3} *M* cystamine solution in ethanol for 1 day, washed several times with ethanol, and dried. Then the aqueous wetting angle was measured on a MG horizontal microscope equipped with a goniometer (drop volume was 0.01 mL, the measurement accuracy was $\pm1^{\circ}$). The surface was further modified by treatment with a 10^{-3} *M* solution of thiohydantoin **11** in ethanol analogously to the first step. The contact angle was determined as the average of four measurements.

Electrochemical measurements were performed on a PI-50-1.1 potentiostat. Glassy-carbon (d = 2 mm), platinum (d = 3 mm), or gold (d = 1 mm) disks were used as the working electrodes, a 0.05 *M* Bu₄NClO₄ solution in DMF served as the supporting electrolyte, and Ag/AgCl/KCl(satur.) was used as the reference electrode. The potential scan rates were 200 mV s⁻¹

(CV) and 20 mV s⁻¹, 2800 min⁻¹ (RDE). All measurements were carried out under argon. The samples were dissolved in the pre-deaerated solvent. Dimethylformamide (high-purity grade) was purified by refluxing followed by successive vacuum distillation over anhydrous CuSO₄ and P₂O₅.

To obtain a bilayer on a gold electrode, a monolayer of di(2-aminoethyl) disulfide (12) was prepared, and the electrode was soaked in its 10^{-3} M solution in EtOH for 1 day. Then the electrode was washed with ethanol and kept in a solution of acid 10 or 11 for 1 day to obtain a bilayer. The electrode with the bilayer was again successively washed with water, a supporting solution, and acetone and dried in air at ~20 °C. Then the CV curve was recorded. To prepare a surface-bound complex, the electrode was immersed in a solution of the corresponding metal salt in MeCN, soaked in this solution for one day, washed, and dried. Then the CV curve was recorded.

3-Substituted 2-thiohydantoins (general procedure). Glycine (1 equiv.) was dissolved in a 1 : 1 water—pyridine mixture. Then a 2 *M* sodium hydroxide solution was added to pH 9, and this pH was maintained until the reaction was completed. The reaction mixture was warmed to 40 °C. At this temperature, isothiocyanate (1.5 equiv.) was added. The reaction mixture was stirred at 40 °C for 1 h, pH being monitored from time to time. Pyridine and excess isothiocyanate were separated by extraction with an equal volume of benzene. Then concentrated HCl (3 mL) was added to the aqueous phase. The reaction mixture was refluxed for 2 h, concentrated to 1/2 of the initial volume, and cooled to ~20 °C. The pale-yellow precipitate that formed was filtered off and recrystallized from methanol.

3-Methyl-2-thioxoimidazolidin-4-one. The yield was 62%, m.p. 140 °C (*cf.* lit data³⁸: m.p. 140 °C).

3-(4-Carbethoxyphenyl)-2-thioxoimidazolidin-4-one. The yield was 72%, m.p. 176 °C. Found (%): C, 54.47; H, 4.50; N, 10.53. C₁₂H₁₂N₂O₃S. Calculated (%): C, 54.55; H, 4.55; N, 10.60. ¹H NMR (CDCl₃), δ: 1.40 (m, 5 H, Me, CH₂); 4.40 (q, 2 H, OCH₂, J = 7.0 Hz); 7.44 (d, β-H_{Ar}, J = 8.2 Hz); 8.19 (d, 2 H, α-H_{Ar}, J = 8.0 Hz); 11.98 (br.s, 1 H, NH). IR, v/cm⁻¹: 3280, 1750, 1710, 1650. MS, m/z (I_{rel} (%)): 264 [M]⁺ (9).

3-Unsubstituted 5-(pyridylmethylidene)-2-thiohydantoins 1, 5, and 8 (general procedure). A mixture of 2-thioxotetrahydro-4H-imidazol-4-one, Na₂CO₃, and glycine (1 equiv. each) was dissolved with stirring in a minimum volume of refluxing water and added to a solution of pyridinecarbaldehyde (1 equiv.). The reaction mixture was stirred for 1 h and cooled to ~20 °C. The precipitate that formed was filtered off and successively washed with water and diethyl ether.

5-[(*Z*)-2-Pyridylmethylidene]-2-thioxoimidazolidin-4-one (1). The yield was 92%, m.p. 260–262 °C. Found (%): C, 52.49; H, 3.35; N, 20.30. C₉H₇N₃OS. Calculated (%): C, 52.68; H, 3.41; N, 20.48. ¹H NMR (CDCl₃), δ: 7.23 (s, 1 H, =CH); 7.48 (t, 1 H, γ-H_{Py}, J = 8.3 Hz); 7.78 (t, 1 H, β-H_{Py}, J = 4.2 Hz); 8.69 (d, 1 H, β'-H_{Py}, J = 4.2 Hz); 8.81 (d, 1 H, α-H_{Py}, J = 8.4 Hz); 12.30 (br.s, 2 H, NH). MS, m/z (I_{rel} (%)): 205 [M]⁺ (28).

5-[(*Z*)-3-Pyridylmethylidene]-2-thioxoimidazolidin-4-one (5). The yield was 90%, m.p. 297 °C. Found (%): C, 52.40; H, 3.33; N, 20.35. C₉H₇N₃OS. Calculated (%): C, 52.68; H, 3.41; N, 20.48. ¹H NMR (CDCl₃), δ: 6.49 (s, 1 H, =CH); 7.43 (dd, 1 H, γ -H_{Py}, *J*₁ = 4.1 Hz, *J*₂ = 8.1 Hz); 8.17 (d, 1 H, β -H_{Py}, *J* = 8.0 Hz); 8.52 (d, 1 H, α -H_{Py}, *J* = 4.8 Hz); 8.84 (s, 1 H, α '-H_{Py}); 12.33 (br.s, 2 H, NH). MS, *m/z* (*I*_{rel} (%)): 205 [M]⁺ (23). **5-[(Z)-4-Pyridylmethylidene]-2-thioxoimidazolidin-4-one** (8). The yield was 88%, m.p. >315 °C. Found (%): C, 52.11; H, 3.75; N, 19.95. C₉H₇N₃OS. Calculated (%): C, 52.68; H, 3.41; N, 20.48. ¹H NMR (CDCl₃), δ: 6.39 (s, 1 H, =CH); 7.63 (d, 2 H, β-H_{Py}, β'-H_{Py}, J = 6.2 Hz); 8.59 (d, 2 H, α-H_{Py}, α'-H_{Py}, J = 6.3 Hz); 12.5 (br.s, 2 H, NH).

3-Substituted 5-(pyridylmethylidene)-2-thiohydantoins 2 and 4 (general procedure). 3-Substituted 2-thiohydantoin (1 equiv.) was dissolved in a 2% ethanolic solution of KOH (1.2 equiv.) with vigorous stirring. After complete dissolution of 2-thiohydantoin, pyridinecarbaldehyde (1 equiv.) was added dropwise and the reaction mixture was stirred for 12 h. The precipitate was filtered off and dissolved in water. The solution was neutralized with vigorous stirring with dilute HCl to pH 7. The precipitate that formed was filtered off and recrystallized from a 3 : 1 EtOH—DMF mixture.

3-Methyl-5-[(*Z*)-2-pyridylmethylidene]-2-thioxoimidazolidin-4-one (2). The yield was 73%, m.p. 230 °C. Found (%): C, 54.91; H, 4.06; N, 19.21. $C_{10}H_9N_3OS$. Calculated (%): C, 54.79; H, 4.11; N, 19.18. ¹H NMR (CDCl₃), δ : 3.23 (s, 3 H, Me); 6.72 (s, 1 H, =CH); 7.39 (dd, 1 H, γ -H_{Py}, J_1 = 4.8 Hz, J_2 = 1.2 Hz); 7.74 (d, 1 H, β '-H_{Py}, J = 7.8 Hz); 7.89 (dd, 1 H, β -H_{Py}, J_1 = 7.7 Hz, J_2 = 2.2 Hz); 8.75 (d, 1 H, α -H_{Py}, J = 3.9 Hz).

3-(4-Carbethoxyphenyl)-5-[(*Z*)-2-pyridylmethylidene]-2thioxoimidazolidin-4-one (4). The yield was 70%, m.p. 279 °C. Found (%): C, 61.14; H, 4.19; N, 13.20. C₁₈H₁₅N₃O₃S. Calculated (%): C, 61.18; H, 4.28; N, 13.11. ¹H NMR (CDCl₃), δ : 1.40 (t, 3 H, Me, *J* = 6.8 Hz); 4.40 (q, 2 H, OCH₂, *J* = 6.8 Hz); 7.21 (s, 1 H, =CH); 7.40 (d, 2 H, β -H_{Ph}, *J* = 8.2 Hz); 7.50 (t, 1 H, γ -H_{Py}, *J* = 8.3 Hz); 7.78 (t, 1 H, β -H_{Py}, *J* = 4.2 Hz); 8.20 (d, 2 H, α -H_{Ph}, *J* = 8.0 Hz); 8.70 (d, 1 H, β '-H_{Py}, *J* = 4.2 Hz); 8.81 (d, 1 H, α -H_{Py}, *J* = 8.4 Hz); 11.97 (br.s, 1 H, NH).

3-(4-Carbethoxyphenyl)-5-[(Z)-3-pyridylmethylidene]-2thioxoimidazolidin-4-one (7). A mixture of 4-carbethoxyphenyl isothiocyanate (2.07 g, 0.01 mol), glycine (0.75 g, 0.01 mol), and pyridine-3-carbaldehyde (1.07 g, 0.01 mol) in glacial acetic acid (10 mL) was refluxed with stirring for 3 h and then cooled. The precipitate that formed was filtered off, washed with water, and recrystallized from a 3:1 EtOH-DMF mixture. The yield was 2.53 g (71%), m.p. 284 °C. Found (%): C, 61.12; H, 4.22; N, 13.28. C₁₈H₁₅N₃O₃S. Calculated (%): C, 61.18; H, 4.28; N, 13.11. ¹H NMR (CDCl₃), δ : 1.40 (t, 3 H, Me, J = 6.9 Hz); 4.40 (q, 2 H, CH_2 , J = 6.9 Hz); 7.15 (s, 1 H, =CH); 7.39 (d, 2 H, β -H_{Ph}, J = 8.2 Hz); 7.43 (d, 1 H, γ -H_{Pv}, J = 8.1 Hz); 7.50 (d, 2 H, α -H_{Ph}, J = 7.9 Hz); 8.17 (t, 1 H, β -H_{Py}, J = 8.0 Hz); 8.51 (d, 1 H, α -H_{Py}, J = 4.8 Hz); 8.84 (s, 1 H, α '-H_{Pv}); 11.95 (br.s, 1 H, NH). ¹³C NMR (CDCl₃), δ: 0.56, 47.88, 95.54, 101.87, 110.27, 114.47, 115.55, 116.126, 122.94, 135.94, 137.56.

Hydrolysis of the ester group in 3-(4-carbethoxyphenyl)-5-[(Z)-pyridylmethylidene]-2-thioxoimidazolidin-4-ones 4 and 7 (general procedure). Compound 4 or 7 (0.34 g, 0.001 mol) was dissolved in a 1 : 3 MeOH-H₂O mixture (20 mL) and then a 15% KOH solution was added with stirring to pH 8-9. The reaction mixture was stirred at ~20 °C for 12 h. Then acetic acid was added with cooling to ~5 °C to neutral pH and stirred for 1 h. The precipitate that formed was filtered off and washed with water.

3-(4-Carboxyphenyl)-5-[(*Z***)-2-pyridylmethylidene]-2thioxoimidazolidin-4-one (10).** The yield was 95%, m.p. 288 °C. Found (%): C, 62.69; H, 3.28; N, 12.87. C₁₆H₁₁N₃O₃S. Calculated (%): C, 62.77; H, 3.38; N, 12.92. ¹H NMR (DMSO-d₆), δ : 7.23 (s, 1 H, =CH); 7.44 (d, β -H_{Ar}, *J* = 8.2 Hz); 7.50 (t, 1 H, β -H_{Py}, *J* = 4.1 Hz); 7.78 (t, 1 H, γ -H_{Py}, *J* = 8.3 Hz); 8.20 (d, 2 H, α -H_{Ar}, *J* = 8.0 Hz); 8.69 (d, 1 H, β '-H_{Py}, *J* = 4.2 Hz); 9.59 (d, 1 H, α -H_{Py}, *J* = 8.4 Hz); 11.95 (br.s, 1 H, NH). IR, v/cm⁻¹: 3380, 3280, 1745, 1730, 1600.

3-(4-Carboxyphenyl)-5-[(*Z*)-**3-pyridylmethylidene]-2**thioxoimidazolidin-4-one (11). The yield was 91%, m.p. 295 °C. Found (%): C, 62.71; H, 3.31; N, 12.88. C₁₆H₁₁N₃O₃S. Calculated (%): C, 62.77; H, 3.38; N, 12.92. ¹H NMR (DMSO-d₆), δ: 7.20 (s, 1 H, =CH); 7.36 (d, 2 H, β-H_{Ph}, *J* = 8.2 Hz); 7.43 (d, 1 H, γ-H_{Py}, *J* = 4.1 Hz); 7.49 (d, 2 H, α-H_{Ph}, *J* = 7.9 Hz); 8.19 (d, 1 H, β-H_{Py}, *J* = 8.0 Hz); 8.51 (d, 1 H, α-H_{Py}, *J* = 4.8 Hz); 8.86 (s, 1 H, α'-H_{Py}); 11.95 (br.s, 1 H, NH). IR, v/cm⁻¹: 3370, 3290, 1740, 1730, 1600.

Synthesis of complexes from 5-[(Z)-pyridylmethylidene]-2thioxoimidazolidin-4-ones (general procedure). 5-[(Z)-Pyridylmethylidene]-2-thioxoimidazolidin-4-one (0.7 mmol) was dissolved in a minimum volume of hot 1,4-dioxane, and a solution of a metal salt (0.35 mmol in a minimum volume of water in the case of ligands 1–3, 5, 6, 8, and 9 or 0.7 mmol in a minimum volume of MeCN in the case of ligands 4 and 7) was added. The reaction mixture was refluxed for 10 h and cooled to ~20 °C. The precipitate that formed was filtered off and successively washed with water, ethanol, and diethyl ether.

This study was financially supported by the Russian Foundation for Basic Research (Project No. 04-03-32845), the Program "Russian Universities" (Grant 05.03.046), and the Presidium of the Russian Academy of Sciences (Program "Theoretical and Experimental Studies of the Nature of Chemical Bonds and Mechanisms of Chemical Reactions and Processes").

References

- 1. V. Chazeau, M. Cossac, and A. Boucherle, *Eur. J. Med. Chem.*, 1992, **27**, 615.
- K. Kiec-Kononowich and J. Karolak-Wojciechowska, *Phosphorus, Sulfur, Silicon*, 1992, 73, 235.
- 3. A. El-Barbary, Y. Aly, A. Hashem, and A. El-Shehawy, *Phosphorus, Sulfur, Silicon*, 2000, **160**, 77.
- D. Kushev, G. Gorneva, V. Enchev, E. Naydenova, J. Popova, S. Taxirov, L. Maneva, K. Grancharov, and N. Spassovska, *J. Inorg. Biochem.*, 2002, **89**, 203.
- 5. J. A. Grim and H. G. Petring, Cancer Res., 1967, 27, 1278.
- 6. J. S. Casas, E. E. Castellano, A. Macfas, N. Playa, A. Sanchez, J. Sordo, J. M. Varela, and E. Vasques-Lopez, *Polyhedron*, 2001, **20**, 1845.
- M. Arca, F. Demartin, F. Davillanova, A. Garau, F. Isaia, V. Lippolis, and G. Verani, *Inorg. Chem.*, 1998, 37, 4164.
- 8. A. M. A. Hassaan, Sulfur Lett., 1991, 13, 1.
- 9. R. S. Srivastava, R. R. Srivastava, and H. N. Bhargava, Bull. Soc. Chim. Fr., 1991, 128, 671.
- M. M. Chowdhry, D. M. Mingos, A. J. White, and D. J. Williams, J. Chem. Soc., Perkin Trans. 1, 2001, 20, 3495.
- M. Kumar, A. Shaudhary, and T. Sharma, *Ind. J. Chem.*, Sect. A, 1986, 25, 281.
- J. Casas, E. Castellano, A. Macfas, N. Playa, A. Sanchez, J. Sordo, and J. Zukerman-Schpector, *Inorg. Chim. Acta*, 1995, 238, 129.

- M. M. Chowdhry, A. Burrows, D. M. Mingos, A. J. White, and D. J. Williams, J. Chem. Soc., Chem. Commun., 1995, 1521.
- 14. J. S. Casas, E. E. Castellano, M. D. Couce, N. Playa, A. Sanchez, J. Sordo, J. M. Varela, and J. Zukerman-Schpector, *J. Coord. Chem.*, 1999, 47, 299.
- J. Casas, A. Castineiras, N. Playa, A. Sanchez, J. Sordo, J. Varela, and E. Vazquez-Lopez, *Polyhedron*, 1999, 18, 3653.
- A. G. Majouga, E. K. Beloglazkina, S. Z. Vatsadze, A. A. Moiseeva, F. S. Moiseev, K. P. Butin, and N. V. Zyk, *Mendeleev Commun.*, 2005, 48.
- M. M. Chowdhry, D. M. Mingos, A. J. White, and D. J. Williams, J. Chem. Soc., Chem. Commun., 1996, 899.
- 18. A. G. Majouga, E. K. Beloglazkina, S. Z. Vatsadze, N. A. Frolova, and N. V. Zyk, *Izv. Akad. Nauk, Ser. Khim.*, 2004, 2734 [*Russ. Chem. Bull.*, *Int. Ed.*, 2004, **53**, 2850].
- S.-F. Tan, K.-P. Ang, and Y.-F. Fong, J. Chem. Soc., Perkin Trans. 2, 1986, 1941.
- E. K. Beloglazkina, S. Z. Vatsadze, A. G. Majouga, N. A. Frolova, R. B. Romashkina, N. V. Zyk, A. A. Moiseeva, and K. P. Butin, *Izv. Akad. Nauk, Ser. Khim.*, 2005, 2679 [*Russ. Chem. Bull., Int. Ed.*, 2005, 54, 2771].
- A. G. Majouga, Ph. D. (Chem.) Thesis, M. V. Lomonosov Moscow State University, Moscow, 2005, 131 pp. (in Russian).
- 22. N. Goswami and D. M. Eichhorn, *Inorg. Chem.*, 1999, **38**, 4329.
- 23. D. Zhu, Y. Xu, Y. Mei, Y. Sci, C. Tu, and X. You, J. Mol. Struct., 2001, 559, 119.
- 24. L. Zhang, L. Liu, D. Jia, and K. Yu, *Struct. Chem.*, 2004, **15**, 327.
- 25. M. Bakiler, I. V. Masliv, and S. Akyuz, J. Mol. Struct., 1999, 476, 21.
- I. Kuzniarska-Biernacka, A. Bartecki, and K. Kurzak, *Poly-hedron*, 2003, 22, 997.
- F. A. Cotton and G. Wilkinson, *Advanced Inorganic Chemistry*, 2 ed., J. Wiley and Sons, New York–London– Sydney, 1966.
- 28. S. Darwish, H. M. Fahmy, M. A. Abdel Aziz, and A. A. El Maghraby, J. Chem. Soc., Perkin Trans. 2, 1981, 344.
- 29. H. M. Fahmy, M. A. Abdel Aziz, and A. H. Badran, *J. Electroanal. Chem.*, 1981, **127**, 103.
- M. A. Aboutabl, H. M. Fahmy, M. A. Abdel Aziz, and H. Abdel Rahman, J. Chem. Techn. Biotechn., 1983, 33A, 286.
- 31. G. M. Abou-Elenien, N. A. Ismail, and A. A. Magd Eldin, *Monatsh. Chem.*, 1992, **123**, 1117.
- 32. J. J. P. Stewart, J. Comput. Chem., 1989, 10, 209.
- 33. K. V. Gobi, K. Tokuda, and T. Ohsaka, *J. Electroanal. Chem.*, 1998, **444**, 145.
- 34. W. Yang, E. Chow, G. Willett, D. B. Hibbert, and J. J. Gooding, *Analyst*, 2003, **128**, 712.
- 35. H. Y. Hu, A. M. Yu, and H. Y. Chen, J. Electroanal. Chem., 2001, 516, 119.
- 36. H. Z. Yu, J. W. Zhao, Y. Q. Wang, S. M. Cai, and Z. F. Liu, J. Electroanal. Chem., 1997, 438, 221.
- 37. H. Finklea and D. Hashew, J. Am. Chem. Soc., 1992, 114, 3173.
- 38. T. Johnson and B. Nicolet, J. Am. Chem. Soc., 1911, 33, 1973.

Received September 19, 2005; in revised form January 12, 2006