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Electrochemical Reduction and Oxidation of 3,4-Disubstituted 1,2,5-Thiadiazoles

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Abstract — The electron-acceptor nitrogen and sulfur atoms in 3,4-disubstituted 1,2,5-thiadiazoles are responsible for much decreased reduction potentials and much increased oxidation potentials of these compounds compared with the corresponding carbocyclic derivatives. The thiadiazole ring is resistant to oxidation, and the reversible electron transfer gives rise to fairly stable radical cations. Reductive stability of the heterocycle depends on the nature of its substituents and on the medium: When nucleofuge substituents are present, two-electron transfer in aprotic media results in heteroring opening with iminonitrile formation, whereas in the presence of two readily leaving groups, the electron transfer induces cleavage of the complete heteroring into inorganic anions.

Nitrogen-containing heterocyclic compounds occupy an important place in modern chemistry. They are widely used in industry, medicine, veterinary, and agriculture [1]. Electrochemical reactions of heterocyclic compounds attract attention in terms of synthesis of new derivatives and assessment of the specific role heteroatoms play in electron-transfer processes in chemical and biochemical systems. Electrochemical reactions of this class of compounds not infrequently occur similarly to those of carbocyclic analogs which commonly preserve the cycle in electron-transfer processes [2–5]. The role of heteroatoms is to facilitate or hinder electron-transfer processes. However, electron transfer may induce a principally new direction of transformation of heterocyclic compounds, uncharacteristic of their carbocyclic analogs, specifically, heteroatom–heteroatom bond cleavage with heteroring opening [6–10]. Taking account of the great scientific and practical interest in heterocyclic compounds, as well as the high probability of electron-transfer reactions in chemical and biochemical systems, we consider it important to gain insight into the regularities of transformations of heterocyclic compounds in electrochemical reactions.

We earlier studied [10–12] electrochemical reduction of certain 1,4-disubstituted phthalazines and found that the reduction direction depends on the nature of substituents in positions *1* and *4* and on the medium. Heteroring opening with phthalodinitrile formation was observed in the reduction of 1-chlorophthalazines in aprotic media when the 4-substituents are readily leaving groups. In the absence of halogens, electron transfer results in no heteroring opening. By analogy one might suppose that such processes are characteristic not only of the phthalazine system, but also of other heterocyclic compounds with heteroatom–heteroatom bonds. Of particular interest in this context are substituted 1,2,5-thiadiazoles, compounds that exhibit broad-spectrum biological activity [13–17].

Unsubstituted 1,2,5-thiadiazole, benzothiazole, and their carboxy derivatives are reduced similarly to phthalazine. In aprotic media, reversible one-electron reduction occurs to form radical anions [18], and in proton-donor aqueous-organic media, the reduction is accompanied by heteroring opening to form finally ethylene diamines and phenylene diamines, respectively [19–22]. Chemical reduction of substituted 1,2,5-thiadiazoles with sodium hydride and lithium aluminum hydride [23], and metallic tin [24], too, yields diamines. Heteroring opening with cleavage of C–C and two N–S bonds in substituted 1,2,5-thiadiazoles was also observed in their ionization in the gas

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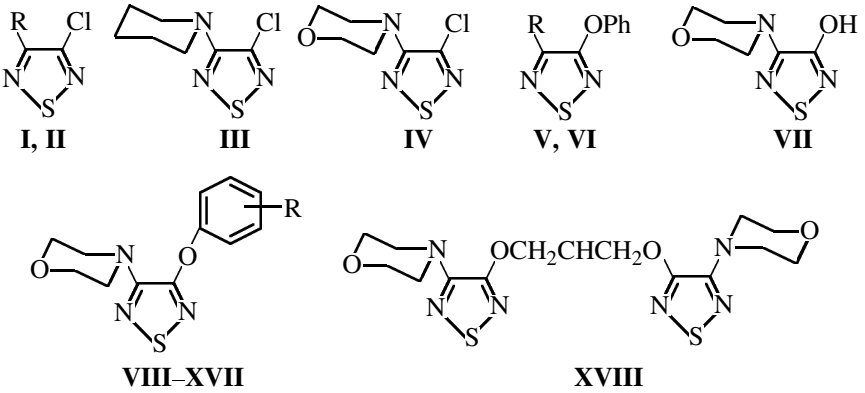
phase [25]. Electrochemical reductive ring cleavage in 3,4-diphenyl-1,2,5-thiaiazole 1-oxide in aprotic media gives rise to the symmetrical 2,4,6-triphenyl-1,3,5-triazine [8].

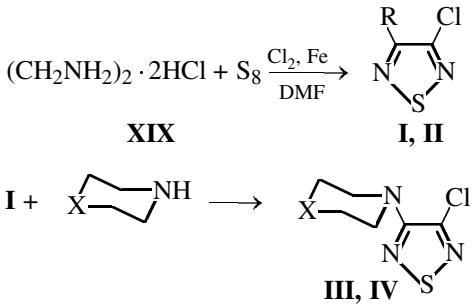
Here we present the results of our research into electrochemical reduction and oxidation of 1,2,5-thiadiazoles **I**–**XVIII** with various nucleofuge groups in positions *3* and *4*.



R = Cl (**I**), H (**II, V, VIII**), OPh (**VI**), 4-Me (**IX**), 2,6-Me_2 (**X**), 2-$CH_2CH{=}CH_2$ (**XI**), 4-OMe (**XII**), 3-OMe (**XIII**), 4-Br (**XIV**), 3-Br (**XV**), 4-NO_2 (**XVI**) 2-NO_2-4-CF_3 (**XVII**).

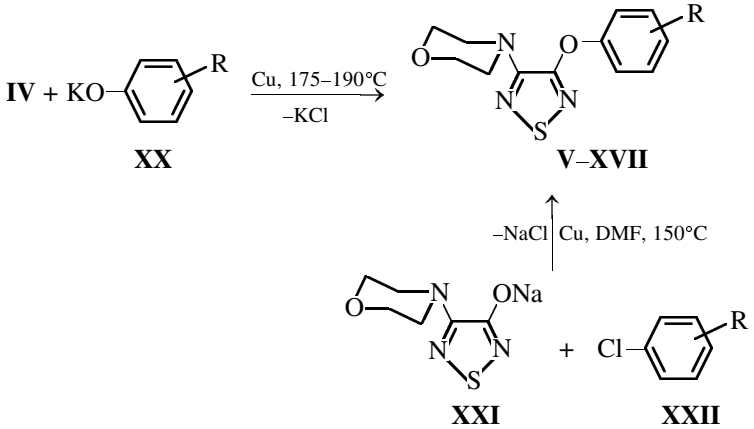
3,4-Dichloro- (**I**) and 3-chloro-substituted thiadiazoles (**II**), as well as 3-piperidino- (**III**) and 4-chloro-3-morpholino-1,2,5-thiadiazoles (**IV**) were synthesized by catalytic chlorination of ethylene diamine hydrochloride (**XIX**) with subsequent reaction of compound **I** with corresponding amine (Scheme 1) [16, 26]. 3-Aryloxy-4-morpholino-1,2,5-thiadiazoles **V**–**XVII** were synthesized by the Ullmann reaction [27] (Cu, 150–190°C) by Scheme 2 with use of potassium and sodium salts **XX** and **XXI**. The synthesis of compound **XVIII** has been described in [28].

Scheme 1.



X = CH_2 (**III**), O (**IV**).

Scheme 2.



XX, R = H, 2-Me, 2,6-Me_2, 2-$CH_2CH{=}CH_2$, 3-OMe, 3-Br, 4-OMe, 4-Me, 4-Br; **XXII**, R = 2-NO_2, 4-CF_3, 4-NO_2.

Voltammetric characteristics of 1,2,5-thiadiazoles **I**–**XVIII** (c 10^{-3} M, 25°C)

Comp. no.	Polarographic characteristics in DMF[a]			Cyclic voltammetry in acetonitrile[b]			Comp. no.	Polarographic characteristics in DMF[a]			Cyclic voltammetry in acetonitrile[b]		
	$E_{1/2}$, V[c]	$2.3RT/\alpha nF$, mV[d]	n[e]	E_p^{red}, V[c]	E_p^{ox}, V[c]	n[e]		$E_{1/2}$, V[c]	$2.3RT/\alpha nF$, mV[d]	n[e]	E_p^{red}, V[c]	E_p^{ox}, V[c]	n[e]
I	–1.66	63	3.7	–1.72	≥2.4		**IX**[f]	–2.56	63	1.9			
I[f]	–1.68	63	3.7					–2.89	105	1.7			
II	–1.92	105	2.0	–1.95	≥2.4		**X**	–2.64	63	2.0	–2.75	1.02[g]	1.0
	–2.40	70	0.8	–2.43				–2.97	105	2.0	–2.92		
	–2.65	68	0.7	–2.91			**X**[f]	–2.65	94	3.0			
II[f]	–1.92	112	2.0					–2.88	157	2.0			
	–2.39	75	1.5				**XI**	–2.58	63	1.7	–2.58	1.00[g]	1.0
	–2.63	210	1.5					–2.97	84	1.0	–2.92		
III	–2.15	83	2.1	–2.29	1.16[g]	1.0	**XI**[f]	–2.56	63	1.9			
	–3.06	240	2.1	–3.08				–2.84	200	1.8			
III[f]	–2.15	84	2.0				**XII**	–2.58	63	2.0	–2.57	0.97[g]	1.0
	–2.80	146	2.2					–2.99	63	1.5	–2.91		
IV	–2.07	73	2.1	–2.09	1.31[g]	1.2	**XII**[f]	–2.58	84	2.6			
	–2.94	209	1.3	–2.85				–2.89	270	3.3			
IV[f]	–2.08	94	2.0				**XIII**	–2.58	63	2.0	–2.57	0.98[g]	1.0
	–2.71	230	2.5					–2.99	63	1.5	–2.92		
V	–2.42	63	2.0	–2.43	1.95[h]	0.8	**XIV**	–2.48	84	3.8	–2.44	1.03[g]	0.9
	–2.77	73	1.2	–2.85				–2.98	73	2.0	–2.55		
V[f]	–2.40	62	3.1								–2.91		
	–2.80	314	4.0				**XIV**[f]	–2.46	115	3.8			
VI	–2.34	63	2.0	–2.27	1.67[h]	0.8		–2.86	136	2.1			
	–2.78	63	2.5	–2.58			**XV**	–2.50	146	3.9	–2.42	1.09	1.1
VI[f]	–2.37	63	2.0					–2.97	94	2.0	–2.57		
	–2.59	147	2.8				**XV**[f]	–2.50	126	4.0	–2.91		
	–2.85	162	1.6					–2.90	250	2.2			
VII	–2.65	209	4.7	–2.73	0.63[h]	1.1	**XVI**	–1.40	63	1.0	–1.40	1.09[g]	0.8
				–3.03				–2.01	84	3.0	–1.84		
VII[f]	–2.65	220	4.5					–2.66	98	3.0			
VIII	–2.57	64	2.0	–2.55	1.04[g]	1.0		–2.96	120	2.0			
	–2.97	73	1.0	–2.91			**XVII**	–1.26	73	1.0	–1.25	1.10[g]	1.0
VIII[f]	–2.58	63	2.5					–1.93	62	3.1	–1.75		
	–2.97	183	2.1					–2.89	136	3.1			
IX	–2.56	63	1.9	–2.59	1.00[g]	1.1	**XVIII**	–2.68	125	4.1	–2.78	0.95[g]	2.0
	–2.96	94	1.7	–2.86				–2.99	64	4.0			
							XVIII[f]	–2.64	125	4.0			
								–2.86	188	3.8			

[a] Mercury drop electrode. [b] Glassy carbon electrode. [c] Relative to $Ag/AgNO_3$ (c 0.01 M) in MeCN. [d] The wave slope was calculated by the formula $2.3RT/\alpha nF = (E_{3/4} - E_{1/4})/0.954$, where R is the universal gas constant, T is the absolute temperature, α is the transfer coefficient, n is the number of transferred electrons, and F is the Faraday number. [e] The number of electrons, determined with reference to the one-electron reduction wave of *p*-nitrobenzaldehyde. [f] In the presence of PhOH (c 0.01 M). [g] Reversible peak. [h] Irreversible peak.

Electrochemical reduction. 1,2,5-Thiadiazoles **I**–**XVIII** in DMF and acetonitrile on the background of Et_4NClO_4 (c 0.1 M) on mercury and glassy carbon electrodes are reduced in the available potential range. Certain voltammetric characteristics of the compounds are represented in the table. As seen, the number of

waves and their characteristics are almost independent on the solvent nature and the electrode material but strongly depend on substituents in positions *3* and *4*. A high sensitivity of the reduction potentials in the nature of the substituents is above all notable. The $E_{1/2}$ values of the compounds studied vary over a wide range (from –1.26 to –2.68 V). Nitroaryl derivatives **XVI** and **XVII** ($E_{1/2}$ –1.40 and –1.26 V, respectively) are reduced most easily, and the reduction involves the greatest number of steps. The first wave of these compounds is one-electron and reversible (Fig. 1). On electrolysis directly in an ESR resonator, stable paramagnetic species were detected, whose spectra (**XVI**: a_N 1.00, $a_{H^{3',5'}}$ 0.344, $a_{H^{2',6'}}$ 0.119 mT; **XVII**: a_N 0.920, $a_{H^{3',5'}}$ 0.333 and 0.459, $a_{H^{6'}}$ 0.109, a_F 0.128 mT] are characteristic of nitrobenzene radical anions. Consequently, the first electron is transferred to the nitroaromatic fragment. The second wave of these compounds is associated with further three-electron reduction of the nitro group to hydroxylamine by a scheme common for nitroaromatic compounds [2]. The thiadiazole ring is preserved in these stages and reduced at the following wave potentials.

With compounds **XIV** and **XV**, the limiting currents of the first irreversible waves correspond to transfer of four electrons to the molecule. Under conditions of cyclic voltammetry, the first wave comprises two well-defined irreversible peaks (Fig. 2), and the second peak is registered at the reduction potentials of compound **VIII**. Since the other thiadiazoles studied (**VIII**–**XIII**) have a two-electron first wave and always give a single reduction peak at these potentials, the above experimental observable suggests that in the first stage compounds **XIV** and **XV** undergo two-electron reduction with C–Br bond cleavage and formation of 3-substituted thiadiazole **VIII**. The following two peaks are associated with further reduction of compound **VIII**.

The other thiadiazoles studied have no substituents able to accept electrons independently of the heteroring, and the reduction process involves electron transfer directly to the thiadiazole ring. Therewith, the reaction center is almost insensitive to the nature and position of substituents in the aryl fragment of molecule **VIII**–**XIII** but is highly sensitive to the nature of groups directly attached to the thiadiazole ring. Electron-acceptor substituents (Cl, OAr) facilitate, whereas electron-donor (OH, OAlk, morpholino, piperidino) hamper reduction (see table). Thus, chlorothiadiazoles **I**–**IV** are much easier reduced that hydroxy (**VII**), alkoxy (**XVIII**), and aryloxy derivatives **VIII**–**XIII**. For instance, the difference in $E_{1/2}$ between chlorothiadiazole **II** and phenoxythiadiazole **V** is 0.5 V. An almost the same $E_{1/2}$ difference is

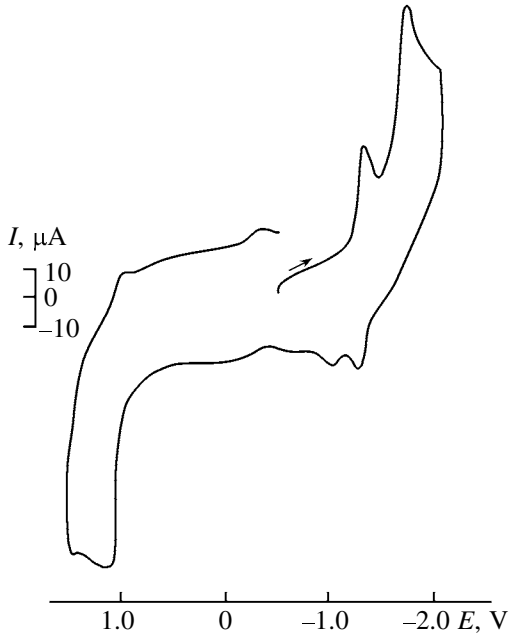


Fig. 1. Cyclic voltammogram of a 3×10^{-3} M solution of thiadiazole **XVI** in the $MeCN/Et_4NClO_4$ system (*c* 0.1 M) on a glassy carbon electrode at a potential sweep rate of 100 mV/s.

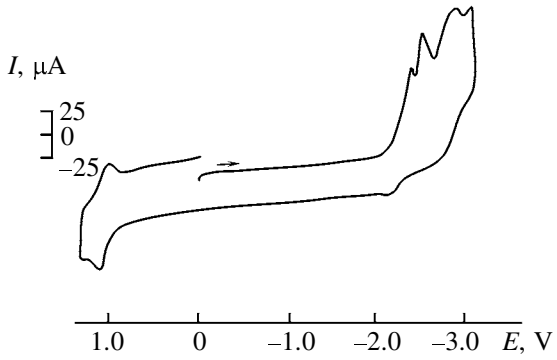


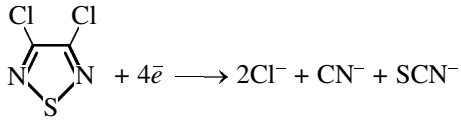
Fig. 2. Cyclic voltammogram of a 3×10^{-3} M solution of a solution of thiadiazole **XV** in the system $MeCN/Et_4NClO_4$ (*c* 0.1 M) on a glassy carbon electrode at a potential sweep rate of 100 mV/s.

characteristic of another pair of compounds (**IV** and **VIII**). It should be noted that chlorothiadiazole **II** ($E_{1/2}$ –1.92 V) is reduced 0.88 V easier than chlorobenzene ($E_{1/2}$ –2.80 V [2]), i.e. the thiadiazole ring exhibits a much higher electron affinity (~0.9 eV) compared with a carbocyclic aromatic compound (benzene).

Substituents in positions *3* and *4* affect not only reduction potentials, but also reaction mechanism. Evidence for this conclusion comes from the number

and characteristics of waves and the results of preparative electrolysis. The polarograms of thiadiazoles **I** and **VII** show one irreversible reduction wave with a limiting current corresponding to transfer of 4 and 4.7 electrons per one molecule. Chlorothiadiazole **II** is reduced in three steps at a more negative potential than compound **I** (see table). The polarograms of compound **I** show no waves at the correposponding potentials and thus rule out chlorothiadiazole formation from this compound. Reductive substitution of halogen by hydrogen, typical of aromatic compounds, is not observed in this case. Preparative reduction of compound **I** gave no ether-soluble organic compounds. In the reaction products by qualitative reactions and IR spectroscopy we detected thiocyanate and cyanide ions. Probably, transfer of four electrons to compound **I** results in thiazole ring opening with formation of four inorganic ions (Scheme 3).

Scheme 3.



The reaction direction with compound **VII** is not quite clear. In may only be noted that on a glassy carbon electrode, unlike a mercury electrode, two reduction peaks are observed (see table).

The electrochemical reduction of compounds **III**–**VI** and **VIII**–**XIII** occurs mostly in a similar way. Two irreversible reduction waves are observed in each case. The first wave corresponds to transfer of two electrons, while the second, to transfer of one to two electrons per one molecule. "Dimeric" compound **XVIII**, too, is reduced irreversibly in two steps, but here double the number of electrons is transferred, i.e. two thiadiazole fragments are reduced almost independently. The second thiadiazole fragment is slightly more difficult to reduce as evidenced by a slightly increased wave slope: The slope for thiadiazoles **VIII**–**XIII** is close to 60 mV, whereas for compound **XVIII** it is 125 mV.

It should be noted that the first wave potentials are different, whereas the second wave potentials of compound **IV** and alkoxy derivatives **VIII**–**XIII** and **XVIII** are almost coiciding. Probably, these compounds all give the same electrochemically active product that contains no halogen and aryloxy group. Apparently, this conclusion can be extended on compounds **III**, **V**, and **VI**. At the same time, in the product of two-electron transfer the 4-substituent (H, OAr, piperidino, morpholino) is always preserved, as evidenced by the fact that the $E_{1/2}$ of the first and second waves similarly vary from group to group (see table). To find out the nature of this product, we performed preparative reduction in DMF of one of the representatives of this series, thiadiazole **IV**. Upon passing 3 F/mol electricity we isolated 2-imino-2-morpholinoacetonitrile and proved formation of the thiocyanate ion by qualitative reactions. Consequently, the reduction of compounds **III**–**VI**, **VIII**–**XIII**, and **XVIII** results in elimination of the 3-substituent and opening of the thiadiazole ring. In the presence of a 10-fold excess of phenol as a proton donor, the second wave potential of all of these compounds shifts to less negative values, and the limiting current of the first and/or second waves increases (see table). The preparative reduction of phenoxythiodiazole **VIII** in the presence of anode-generated protons gave 3-morpholino-1,2,5-thiadiazole.

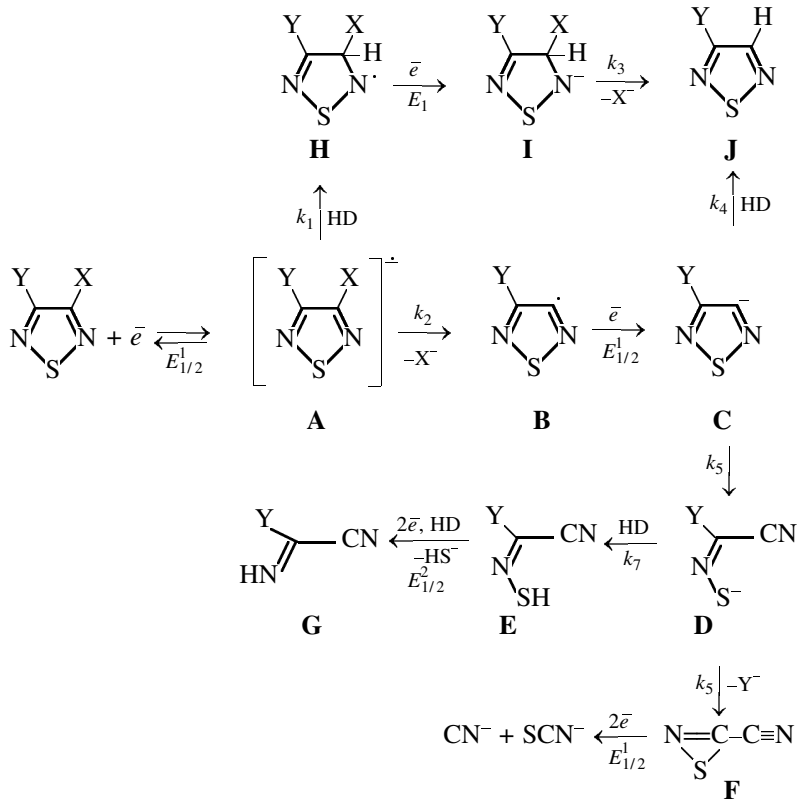
Together the above results allow us to propose a general scheme of reduction of thiadiazoles **I**, **III**–**VI**, **VIII**–**XIII**, and **XVIII** (Scheme 4).

Reversible one-electron transfer in aprotic media (DMF, MeCN) yields radical anions **A** which eliminate X^- at a certain rate (k_2). Radical **B** at first wave potentials takes up one more electron to form carbanion **C**, and the latter undergoes ring opening. Anion **D** at second wave potentials take up, with assistance of proton donors present in the background solution, two more electrons, giving iminonitrile **G**. The possibility of the last reduction step follows from the known fact that oximes can be electrochemically reduced to imines [29]. Moreover, anion **D** can be stabilized by elimination of anion Y^- to form, in the long run, thiocyanate and cyanide ions.

The rate constant of X^- elimination (k_2) is determined by the nucleofugic power of this group, the electronic properties of substituent R, and the temperature. Chloride ion is a better leaving group compared with alkoxy and aryoxy groups [30], and, therefore, will be much faster eliminated [k_2(**I**–**IV**) >> k_2(**V**, **VI**, **VIII**–**XIII**, **XVIII**)]. According to the Mairanovskii rule [31], the weaker is the electron acceptor, the more it is susceptible to further chemical reactions. In view of the aforesaid, the compounds studied can be arranged in the following series by increasing stability of their radical anions: **III** < **IV** < **II** < **I** < **VIII**–**XIII** ≈ **XVIII** < **V** < **VI**.

The radical anions of phenoxy derivatives **V** and **VI** should be the most stable. As noted above, at room temperature, all the compounds are irreversibly reduced, and no radical anions are detectable. However, at a reduced temperature (233 K), we could observe ESR spectra of electrochemically generated

Scheme 4.



radical anions of compounds **V** and **VI** in DMF and MeCN (Fig. 3) [compound **V** (MeCN): g 2.0039, a_{N^2} 0.84, a_{N^5} 0.65, a_H 0.36 mT; compound **VI** (MeCN): g 2.0039, a_{2N} 0.73 mT]. Actually, the radical anion of compound **VI** is the most stable, and the radical anion of compound **V** ranks slightly lower in stability. The other compounds of the series have unstable primary radical anions undetectable even at reduced temperatures. Dichlorothiadiazole **I** gives a fairly stable, even at room temperature, radical (Fig. 3) with four pairwise equivalent nitrogen atoms. As judged by the g factor (2.0040) and a_{2N} and a_{2N} coupling constants (0.70 and 0.03 mT, respectively), this radical species contains a 1,2,5-thiadiazole ring and two identical nitrogen-containing substituents in positions 3 and 4. There is some indirect evidence for the formation of the radical anions of 3-aryloxy derivatives **VIII**–**XIII**. In particular, the slopes of the reduction waves are characteristic of reversible electron-transfer processes followed by chemical reaction (60 mV at 298 K [32]) and the $E_{1/2}$ values are independent of the electrode material [33].

Chlorothiadiazoles **I**–**IV** eliminate chloride ion so fast that we could not obtain any experimental evidence for the formation of radical anions. Nevertheless, in view of the reported detection of primary radical anions derived from aromatic halides [34], we consider quite probable their formation and reduction to anion **D** by Scheme 4 with all the chlorothiadiazoles **I**–**IV**. However, further conversions of anion **D** are determined by the sensitivity of group Y to anodic elimination. In the case of a readily leaving group (Y = Cl), anion **D** is stabilized by Cl^- elimination to give intermediate thioazirine **F**, and the latter is reduced to thiocyanate and cyanide ions. In the case of difficultly leaving groups (Y = H, OPh, piperidino, morpholino), this direction is suppressed, and the preferred process is reduction to iminonitrile **G**.

In the presence of phenol as a proton donor, the reaction direction is preserved with chlorothiadiazoles **I**–**IV**, whereas with aryloxythiadiazoles **V**, **VI**, **VIII**–**XIII**, and **XVIII**, the rate constant k_2 is much lower and k_1 is much higher. Therefore, along with X^- elimination, protonation of the radical anion takes place, yielding radical **H**. Subsequent electron transfer and X^- elimination results finally in formation of 3-Y-1,2,5-thiadiazole **J**. Reduction of the latter is the reason for the current gain produced by phenol addition. Apparently, in the presence of stronger proton donors and their higher concentrations, the reaction direction of compounds **V**, **VI**, **VIII**–**XIII**, and **XVIII** will fully change to form compound **J**. There-

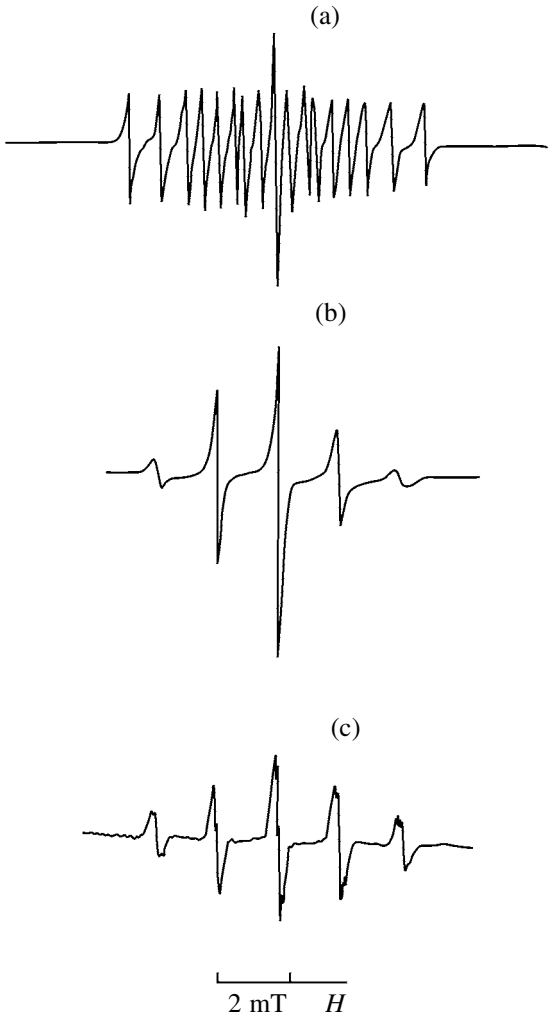


Fig. 3. ESR spectra of the radical anions of (a) **V** and (b) **VI**, and (c) secondary radicals generated by electrochemical reduction of 3×10^{-3} M solutions of thiadiazoles **V, VI**, and **I** in the system $MeCN/Et_4NClO_4$ (*c* 0.1 M) on a platinum helix electrode directly in an ESR resonator at first wave potentials.

with, protonation of anion **C**, too, should not be ruled out.

Electrochemical oxidation of compounds **I**–**XVIII** was studied on a glassy carbon electrode in acetonitrile on the background of Et_4NClO_4 (*c* 0.1 M) by means of cyclic voltammetry. Under such conditions, the working potential range reaches +2.4 V. Compounds **I** and **II** are not oxidized in this potential range. The other compounds are oxidized in one or several steps. The first wave potentials are listed in the table.

It is known [2] that phenols are oxidized easier than phenyl ethers, which is associated with the fact that the oxidation potential of the former is much contributed by the stage of deprotonation of the phenolic hydroxyl in phenol radical cations. The same trend is characteristic of the thiadiazoles studied. Hydroxy(morpholino)thiadiazole **VII** is oxidized much easier than aryloxythiadiazoles, and electron transfer is accompanied by proton elimination followed by one more electron transfer to form a cation. In this case, the hydroxythiadiazole fragment can be considered as a reaction center and the morpholino group, as an electron-donor substituent.

The situation with the other thiadiazoles is different. Since chlorothiadiazole **II** is not oxidized in the working potential range, the registration of reversible oxidation peaks with compounds **III** and **IV** implies that the HOMO energies are contributed by the morpholino and piperidino groups. Similarly, the morpholino group contributes most in the HOMO energies of aryloxy(morpholino)thiadiazoles **VIII**–**XIII** and **XVIII**, as evidenced by the fact that these compounds have much lower oxidation potentials compared with mono- and diphenoxy derivatives **V** and **VI**. Consequently, the reaction center in compounds **III**–**IV**, **VIII**–**XIII**, and **XVIII** is localized on the nitrogen lone electron pair of the substituents. Actually, compounds **III**–**IV** and **VIII**–**XIII** are oxidized as *N,N*-disubstituted anilines, with one-electron transfer and formation of rather stable radical cations. The only difference is that the electron-acceptor thiadiazole ring strongly hinders electron abstraction (by ~0.4 V). With compound **XVIII**, simultaneous reversible transfer of two electrons is registered, i.e. here, too, like in reduction, the two morpholinothiadiazole fragments are oxidized independently from each other.

The radical cations of compounds **III**–**IV**, **VIII**–**XIII**, and **XVII** were detected by cyclic voltammetry (Figs. 1, 2), as well as by ESR (compounds **VIII**–**XIII** and **XVIII**). The ESR spectra of the radical cations of compounds **VIII**–**XIII** and **XVIII** all are fully identical to each other (Fig. 4), implying that the alkoxy and aryloxy groups are only slightly involved in spin delocalization. The spectrum is fairly well resolved, but we failed to assign it. The radical cations decrease in stability with increasing ionization potential, in agreement with the Mairanovskii rule [31]. The most readily oxidized dimeric compound **XVIII** gives the most stable radical anions. By cyclic voltammetry, the reduction current of the diradical dication is observed at all the potential sweep rates (20 to 200 mV/s). With compounds **VIII**–**XIII**, at low rates (20 mV/s) no reduction current is observed, whereas the respective signal of chloro derivatives **III** and **IV** is very weak even at 200 mV/s.

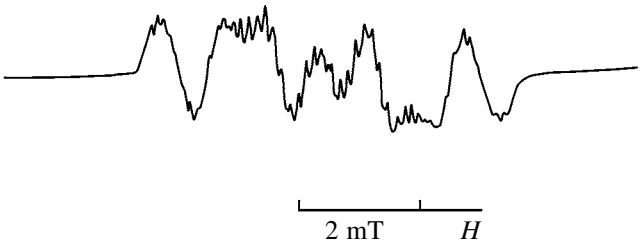


Fig. 4. ESR spectra of the radical cations generated by electrochemical oxidation of 3×10^{-3} M solutions of thiadiazoles **VIII–XIII** and **XVIII** in the system MeCN/Et_4NClO_4 (*c* 0.1 M) on a platinum helix electrode directly in an ESR resonator at first wave potentials.

Thus, the resulting data provide clear evidence showing that the 1,2,5-thiadiazole heterocyclic aromatic system not only differs from its carbocyclic analog, benzene, but is also destroyed by taking up an electron. Due to the presence of the electronegative nitrogen and sulfur atoms, 1,2,5-tiadiazoles have strongly reduced reduction potentials and strongly increased oxidation potentials, which is equivalent to increase in the electron affinity and ionization potential, respectively. If the substrate molecule contains a nucleofuge in position *3*, two-electron transfer results in heteroring opening with iminonitrile formation, whereas in the presence of two readily leaving groups in positions *3* and *4*, the electron transfer induces complete heteroring cleavage into inorganic ions.

EXPERIMENTAL

The IR spectra were obtained on a UR-20 spectrometer in mineral oil. The ^1H and ^{13}C NMR spectra were recorded on Varian T-60 (^1H, 60 MHz) and Bruker MSL-400 (^{13}C, 100.6 MHz) spectrometers, internal reference TMS. The electron-impact mass spectra were measured on an MKh-1310 mass spectrometer in the following conditions: resolution 15000, target current 60 μA, source temperature 60°C, direct inlet.

Electrochemical reduction of 3,4-disubstituted 1,2,5-thiadiazoles **I–XVIII** was studied by means of classical polarography, cyclic voltammetry, and electrolysis in combination with ESR in DMF and acetonitrile on the background of Et_4NClO_4 (0.1 M solution). The polarograms were recorded on a PU-1 polarograph. Capillary characteristics: *m* 0.71 mg/s, τ_1 0.5 s. The cyclic voltammograms were measured on a glassy carbon disc electrode (diameter 2 mm) embedded in Teflon, using a PI-50-1 potentiostat. The potential sweep rates were 20, 50, 100, and 200 mV/s. The reference electrode was an $Ag/AgNO_3$ electrode in MeCN (0.01 M solution) [$E_0(Fc/Fc^+)$ +0.16 V), and the auxiliary electrode was a platinum wire. The solution was deaerated with nitrogen. The substrate concentrations were 10^{-3} (polarography) and 3×10^{-3} M (cyclic voltammetry). Temperature 298 K. The solvents and background salts were purified, and the polarographic measurements were performed by the procedures described in [35].

Electrolysis combined with ESR spectroscopy was performed at 298 K on an apparatus comprising an SE/X-2544 ESR spectrometer, a PI-50-1 potentiostat, and an electrochemical cell designed at the Institute of Organic and Physical Chemistry [36]. The apparatus allows an electrochemical process to be performed directly in an ESR resonator. The working electrode was a platinum helix, the auxiliary electrode was a platinum wire, and the reference electrode was a silver wire. The solutions were deaerated by freezing–pumping–thawing repeated three times.

Electrochemical reduction of 3,4-dichloro-1,2,5-thiadiazole (I) was performed with a B5-70 power source in a diaphragm (cellulose) electrolyzer with a platinum goose as a cathode (*S* 40 cm^2) and a platinum wire as an anode in the galvanostatic mode (*I* 0.1 A). Quantity of electricity passed 4 F/mol. The working solution 50 ml in volume was prepared by dissolution in DMF of Et_4NCl (*c* 0.1 M) and 2 g (12.9 mmol) of 3,4-dichlorothiadiazole. After electrolysis had been complete, DMF was removed in a vacuum, and the residue was examined by means of IR spectroscopy and qualitative reactions [37]. The presence of SCN^- anions was proved by the appearance of a red color upon treatment of an aqueous solution of the reaction mixture with 0.1 M $FeCl_3$. The presence of cyanide and thiocyanate ions was revealed. IR spectrum, ν, cm^{-1}: 2140 (CN), 2065 (SCN).

Electrochemical reduction of 4-chloro-3-morpholino-1,2,5-thiadiazole (IV) was performed as described above. Sample weight 2 g (9.7 mmol). Quantity of electricity passed 3 F/mol. After electrolysis had been complete, DMF was removed in a vacuum, 20 ml of water was added to the residue, and the resulting solution was treated with diethyl ether and dried with $MgSO_4$. The solvent was removed, and the residue was first distilled in a vacuum, bp 72–80°C (0.09 mm), and then recrystallized from EtOH to obtain 0.7 g (52%) of 2-imino-2-morpholinoacetonitrile, mp 92–93°C (from ethanol). IR spectrum, ν, cm^{-1}: 1620 (C=N), 2234 (C≡N), 3290 (=NH). ^1H NMR spectrum ($CDCl_3$), δ, ppm: 3.49–3.64 m [4H, $(CH_2)_2N$], 3.70–3.85 m [4H, $(CH_2)_2O$], 7.69–8.01 br.s (1H, =NH). ^{13}C NMR spectrum ($CDCl_3$), δ_C,

ppm: 45.63 t [2CN (morpholine)], 66.21 t [2CO (morpholine)], 110.64 s ($1C^1$), 142.10 s ($1C^2$). Mass spectrum, *m/z* (relative intensity, %): 27 (20), 28 (70), 29 (65), 30 (27), 42 (10), 43 (80), 44 (22), 53 (50), 55 (48), 56 (50), 57 (20), 69 (31), 70 (32), 83 (83), 96 (20), 109 (84), 139 (100). Found *M* 139.075. $C_6H_9N_3O$. Calculated *M* 139.0746.

Electrochemical reduction of 3-(4-methylphenoxy)-4-morpholino-1,2,5-tiadiazole (IX) was performed as described above. Sample weight 0.5 g (1.8 mmol). Quantity of electricity passed 2 F/mol. After electrolysis had been complete, DMF was removed in a vacuum, 15 ml of water was added to the residue, the aqueous solution was treated with diethyl ether, and the extract was dried with $MgSO_4$. The solvent was removed, and the residue was first distilled in a vacuum, bp 60–64°C (0.02 mm), and then recrystallized from petroleum ether to isolate 0.08 g (26%) of 1-morpholino-1,2,3-thiadiazole, mp 73–74°C (from petroleum ether). IR spectrum, ν, cm^{-1}: 3080 (=CH). ^1H NMR spectrum (CCl_4), δ, ppm: 3.33–3.51 m [4H, $(CH_2)_2N$], 3.70–3.88 m [4H, $(CH_2)_2O$], 7.83 s (1H, =CH). Mass spectrum, *m/z* (relative intensity, %): 31 (18), 42 (23), 46 (10), 54 (11), 56 (14), 59 (15), 70 (7), 86 (42), 86 (52), 113 (100), 114 (240), 127 (7), 128 (8), 140 (7), 156 (15), 170 (6), 171 (61). Found *M* 171.049. $C_6H_9N_3OS$. Calculated *M* 171.0467.

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