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Mechanism of electrochemical reduction of 5-thio derivatives of 2(5*H*)-furanone*

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The anionoid elimination of the substituent from position 5 of the lactone ring is the predominant pathway of electrochemical reduction of 5-arylsulfanyl- and 5-arylsulfonyl-3,4-dichloro-2(5*H*)-furanones in acetonitrile. The contribution of the competing elimination of the chloride ion increases on going to 3,4-dichloro-5-ethylsulfanyl-2(5*H*)-furanone. An experimental criterion based on the morphology of cyclic voltammograms was proposed for identification of a particular pathway of electroreduction of 2(5*H*)-furanone derivatives.

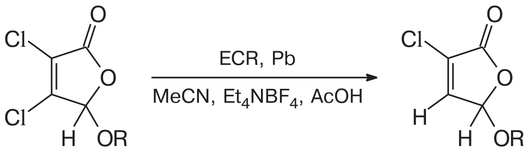
Key words: 2(5*H*)-furanones, thioethers, sulfones, mucochloric acid, electrochemical reduction, voltammetry, quantum chemical calculations.

Polyfunctional unsaturated heterocyclic derivatives attract considerable attention as promising compounds for solving both fundamental and practical problems. One of these heterocycles is a readily accessible and a highly reactive γ-lactone, 3,4-dichloro-5-hydroxy-2(5*H*)-furanone (mucochloric acid).[1—4] The unsaturated γ-lactone moiety is encountered in many biologically active natural products possessing antifungal, antibacterial, anti-inflammatory, and antitumor properties[4—9] and attracts considerable attention of researchers.

This work continues research into the synthesis, structures, and properties of sulfur-containing 2(5*H*)-furanone derivatives. Previously, we identified conditions for selective introduction of SR-substituents into positions 3, 4, and 5 of the lactone ring; this allowed the synthesis of a broad range of thioethers, bis-thioethers, and sulfur heterocycles of different structural types from mucochloric acid.[3,10—14] Also, we studied chemical and electrochemical oxidation of furanone thioethers and developed efficient protocols for the synthesis of sulfones and sulfoxides.[15—18]

Scanty data on the chemical reduction of 3,4-dihalo-5-hydroxy derivatives of 2(5*H*)-furanones are available from the literature.[19—23] The electrochemical reduction (ECR) of 2(5*H*)-furanone derivatives has been studied only in relation to mucochloric acid and its 5-alkoxy derivatives.[24,25] It is also noteworthy that for the ECR of 5-alkoxy-3,4-dichloro-2(5*H*)-furanones **1—4**, we found[25] an exceptional regioselectivity of chlorine substitution by the hydrogen atom in position 4 of the lactone ring giving 5-alkoxy-3-chloro-2(5*H*)-furanones (Scheme 1).

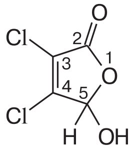
Scheme 1



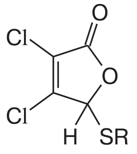
1—4

R = Me (**1**), Et (**2**), Pr^i (**3**), CH$_2$CH$_2$Cl (**4**)
ECR is electrochemical reduction.

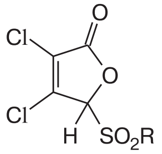
In this work, we intended to investigate the ECR of various 2(5*H*)-furanone thio derivatives that we obtained previously, including compounds **6—12** containing sulfanyl and sulfonyl groups in position 5 of the lactone ring.



5



6—9



10—12

R = 4-MeC$_6$H$_4$ (**6**, **10**), 4-ClC$_6$H$_4$ (**7**, **11**), 4-BrC$_6$H$_4$ (**8**, **12**), Et (**9**)

Along with solution of synthetic challenges, we attempted to gain insight into the mechanisms of the studied

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* Dedicated to Academician of the Russian Academy of Sciences A. I. Konovalov on the occasion of his 85th birthday.

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reactions. We used the same investigation algorithm as was applied to the ECR of 5-alkoxy derivatives **1—4**,[25] in particular, quantum chemical and voltammetric studies and preparative electrolysis under conditions similar to those used for the ECR of 5-alkoxy derivatives **1—4** (acetonitrile as the solvent, Bu_4NBF_4 and Et_4NBF_4 as supporting electrolytes, and acetic acid as the proton donor).

Experimental

Cyclic voltammograms (CV curves) were measured on a PI-50-1 potentiostat using an N307/2 two-coordinate recorder. The working electrodes included a glassy carbon (GC) disc electrode (d = 3.4 mm) and a copper disc electrode (d = 2 mm) pressed into a fluoroplastic; a lead disc electrode (d = 3 mm), a silver disc electrode (d = 0.8 mm), and a platinum disc electrode (d = 1.2 mm) sealed in glass; and a mercury disc electrode fabricated by mercury deposition on platinum (d = 2 mm) pressed into a fluoroplastic. Prior to each measurement, the electrodes were mechanically polished. The potential sweep rates were υ = 100 and 200 mV s^{-1}. The potentials were measured and presented *versus* an $Ag/AgNO_3$ silver reference electrode (0.01 mol L^{-1}) in acetonitrile; and a platinum wire served as an auxiliary electrode. Oxygen dissolved in the supporting electrolyte was removed by bubbling argon through the solution. All measurements were carried out at 295 K.

Organic solvents were purified and dried by standard procedures.[26] The supporting salts Et_4NBF_4, Bu_4NBF_4, Et_4NClO_4, $NaClO_4$, and $LiClO_4$ (Aldrich) were used as received. Commercially available 3,4-dichloro-5-hydroxy-2(5*H*)-furanone (mucochloric acid, **5**) (CJSC Vekton) was recrystallized from water, m.p. 127 °C (see Ref. 27). 3,4-Dichloro-5-[(4-methylphenyl)sulfanyl]-2(5*H*)-furanone[11] (**6**), 3,4-dichloro-5-[(4-chlorophenyl)sulfanyl]-2(5*H*)-furanone[11] (**7**), 5-[(4-bromophenyl)sulfanyl]-3,4-dichloro-2(5*H*)-furanone[11] (**8**), 3,4-dichloro-5-ethylsulfanyl-2(5*H*)-furanone[28] (**9**), 3,4-dichloro-5-[(4-methylphenyl)sulfonyl]-2(5*H*)-furanone[16] (**10**), 3,4-dichloro-5-[(4-chlorophenyl)sulfonyl]-2(5*H*)-furanone[16] (**11**), and 5-[(4-bromophenyl)sulfonyl]-3,4-dichloro-2(5*H*)-furanone[16] (**12**) were synthesized by known procedures.

NMR spectra were recorded on a Bruker Avance III-400 instrument operating at 400.17 (^{1}H) and 100.62 MHz (^{13}C) at 25 °C for $CDCl_3$ solutions. The chemical shifts were referred to the residual proton signals in $CDCl_3$. TLC analysis was carried out on Kieselgel 60 F_{254} plates (Merck, Germany) using 1 : 9 and 1 : 15 (v/v) acetone—toluene mixtures for elution. Column chromatography was carried out on silica gel 60 (Fluka, 70—230 mesh, 0.063—0.200 mm). Melting points were measured on an OptiMelt Stanford Research Systems MPA100 automated instrument and not corrected.

Gas chromatography—mass spectrometry study was conducted on a DFS Thermo Electron Corporation instrument (Germany). Electron impact ionization was used, the energy of ionizing electrons was 70 eV, and the ion source temperature was 280 °C. A 30-m long DB-5MS capillary column (Agilent) of diameter 0.254 mm was used. Helium served as the carrier gas. The mass spectral data were processed using the Xcalibur program. Prior to injection, the samples were diluted to a concentration of $1 \cdot 10^{-3}$ mol L^{-1} with chromatographically pure acetone or dichloroethane. The chromatograms were measured under the following conditions: injector temperature of 280 °C and split ratio of 1 : 50. The temperature was programmed from 120 °C (1 min) to 280 °C (15 min) with a heating rate of 10 °C min^{-1}. The carrier gas flow rate through the column was 1 mL min^{-1}. The temperature of the data exchange unit with the mass spectrometer was 280 °C. The sample volume was 1 μL.

The preparative ECR of compounds **6** and **9** was carried out in a divided (porous glass, cellulose) electrolytic cell in the galvanostatic mode at controlled potentials of the first reduction peak under inert gas (argon) atmosphere at room temperature (T = 295 K) using a B5-50 direct current source. During electrolysis, the solution was magnetically stirred and the potential was monitored with a PI-50-1 potentiostat. Lead (S = 18.4 cm^2) or glassy carbon cloth (S = 15.8 cm^2) cylinders served as the cathode, a platinum helix was used as the anode, and $Ag/AgNO_3$ (0.01 mol L^{-1}) in MeCN was the reference electrode; Et_4NBF_4 and Et_4NClO_4 served as supporting electrolytes (0.05 mol L^{-1}).

The reduction of 3,4-dichloro-5-[(4-methylphenyl)sulfanyl]-2(5*H*)-furanone (6) was carried out using two different electrodes, a GC electrode (experiment ***A***) and a lead electrode (experiment ***B***).

Experiment *A*. The working solution (total volume of 30 mL) was prepared by dissolution of furanone **6** (0.86 g, 3.1 mmol), Et_4NBF_4 (0.38 g, 1.8 mmol), and AcOH (ρ = 1.062 g mL^{-1}; 0.71 mL, 12.5 mmol) in MeCN. Electrolysis was carried out on a GC electrode (S = 15.8 cm^2) at I = 50 mA for 4 h 40 min (Q = 2.8 F mol^{-1}). For neutralization of the acid formed during electrolysis, Et_4NOH (0.6 mL) was added into the anode compartment. After electrolysis, the reaction mixture was concentrated under reduced pressure up to complete removal of MeCN. According to ^{1}H NMR data, the residue contained furanones **13** and **14** in 0.8 : 1 ratio and disulfide **15**, which were separated by column chromatography with gradual increase in the eluent polarity (acetone—toluene gradient, 1 : 15→1 : 2). Three major fractions were evaporated to dryness and the residues were additionally purified and analyzed.

The yellow solid residue of the fraction with R_f 0.77 (acetone—toluene, 1 : 15) contained **1,2-di(*p*-tolyl)disulfane (15)**. Yield 8%, colorless crystals, m.p. 43 °C (from hexane) (*cf.* Ref. 29: m.p. 43–44 °C). ^{1}H NMR, δ: 2.32 (s, 6 H, CH_3); 7.10, 7.38 (8 H, H arom., AA´BB´ system, $N = {}^3J_{AB} + {}^5J_{AB'} = 8.1$ Hz).

The solid colorless residue of the fraction with R_f 0.68 (acetone—toluene, 1 : 9) contained **4-chloro-5-[(4-methylphenyl)sulfanyl]-2(5*H*)-furanone (13)**. Yield 12%, colorless needle crystals, m.p. 46—47 °C. ^{1}H NMR, δ: 2.34 (s, 3 H, CH_3); 5.91 (d, 1 H, C(3)H, $^4J_{HH}$ = 1.4 Hz); 5.98 (d, 1 H, C(5)H, $^4J_{HH}$ = = 1.4 Hz); 7.14, 7.41 (4 H, H arom., AA´BB´-system, N = $= {}^3J_{AB} + {}^5J_{AB'} = 8.0$ Hz). ^{13}C NMR, δ: 21.25 (qt, CH_3, $^1J_{CH}$ = = 126.9 Hz, $^3J_{CH}$ = 4.2 Hz); 88.19 (dd, C(5), $^1J_{C(5)H}$ = 169.2 Hz, $^3J_{C(3)H}$ = 7.7 Hz); 119.06 (dd, C(3), $^1J_{C(3)H}$ = 187.9 Hz, $^3J_{C(5)H}$ = = 2.2 Hz); 122.41 (td, C_{ipso}, $^3J_{CH} = {}^3J_{C(5)H}$ = 7.3 Hz); 130.02 (ddq, C_m, $^1J_{CH}$ = 159.0 Hz, $^3J_{CH} = {}^3J_{CH(CH3)}$ = 5.2 Hz); 135.94 (dd, C_o, $^1J_{CH}$ = 163.1 Hz, $^3J_{CH}$ = 5.8 Hz); 140.63 (qt, C_p, $^2J_{CH(CH_3)} = {}^3J_{CH}$ = 6.6 Hz); 157.37 (d, C(4), $^2J_{CH}$ = 4.4 Hz); 168.07 (br.s, C(2)). MS, m/z (I_{rel} (%)): 240 $[M]^+$ (94), 123 $[pTolS]^+$ (51), 117 $[M - pTolS]^+$ (18), 92 $[pTol + H]^+$ (100).

The solid oily residue of the fraction with R_f 0.66 (acetone—toluene, 1 : 9) contained **4,5-di[(4-methylphenyl)sulfanyl]-2(5*H*)-furanone (14)**. Yield 33%. ^{1}H NMR, δ: 2.35 (s, 3 H, CH_3); 2.37 (s, 3 H, CH_3); 5.07 (d, 1 H, C(3)H, $^4J_{HH}$ = 1.2 Hz); 6.05 (d, 1 H, C(5)H, $^4J_{HH}$ = 1.2 Hz); 7.13—7.55 (m, 8 H, H arom.). ^{13}C NMR, δ: 21.27 (qt, CH_3, $^1J_{CH}$ = 126.8 Hz, $^3J_{CH}$ = 4.4 Hz); 86.37 (dd, C(5), $^1J_{C(5)H}$ = 168.7 Hz, $^3J_{C(3)H}$ = 8.8 Hz); 112.44 (dd, C(3), $^1J_{C(3)H}$ = 184.6 Hz, $^3J_{C(5)H}$ = 2.0 Hz); 124.49 (t, C(4)SAr C_{ipso}, $^3J_{CH}$ = 9.4 Hz); 129.76 (ddq, C_m, $^1J_{CH}$ = 158.7 Hz, $^3J_{CH}$ = $^3J_{CH(CH_3)}$ = 5.2 Hz); 130.84 (ddq, C_m, $^1J_{CH}$ = 160.3 Hz, $^3J_{CH}$ = $^3J_{CH(CH_3)}$ = 5.1 Hz); 134.29 (dd, C_o, $^1J_{CH}$ = 163.7 Hz, $^3J_{CH}$ = 5.9 Hz); 135.38 (dd, C_o, $^1J_{CH}$ = 163.1 Hz, $^3J_{CH}$ = 6.1 Hz); 140.04 (qt, C(4)SAr C_p, $^2J_{CH(CH_3)}$ = $^3J_{CH}$ = 6.6 Hz); 140.91 (qt, C(5)SAr C_p, $^2J_{CH(CH_3)}$ = $^3J_{CH}$ = 6.4 Hz); 169.46 (dd, C(4), $^2J_{CH}$ = 7.5 Hz, $^2J_{CH}$ = 2.6 Hz); 170.25 (d, C(2), $^3J_{C(5)H}$ = 3.3 Hz). $^{13}C\{^1H\}$ NMR, δ: 21.27 (CH_3); 86.37 (C(5)); 112.44 (C(3)); 124.13, 124.49 (C_{ipso}); 129.75, 130.84 (C_m); 134.29, 135.38 (C_o); 140.04, 140.91 (C_p); 169.46 (C(4)); 170.25 (C(2)). MS, *m/z* (I_{rel} (%)): 328 $[M]^+$ (5), 205 $[M - p\text{TolS}]^+$ (100), 177 $[M - p\text{TolS} - CO]^+$ (12), 149 $[M - p\text{TolS} - 2\,CO]^+$ (9), 124 $[p\text{TolSH}]^+$ (33), 91 $[p\text{Tol}]^+$ (52).

Experiment *B* was carried out in a similar way using a lead electrode (S = 18.4 cm^2). Experimental conditions: furanone **6** (0.87 g, 3.2 mmol), Et_4NBF_4 (0.38 g, 1.8 mmol), AcOH (1.43 mL, 25.4 mmol), I = 70 mA, electrolysis time 3 h (Q = 2.5 F mol^{-1}), $V(Et_4NOH)$ = 0.8 mL. According to ^1H NMR spectroscopy, the residue contained furanones **13** and **14** in 1 : 0.4 ratio and disulfide **15**.

The reduction of 3,4-dichloro-5-ethylsulfanyl-2(5*H*)-furanone (9) was conducted similarly to the reduction of compound **6**. Experimental conditions: furanone **9** (0.84 g, 4.0 mmol), Et_4NBF_4 (0.38 g, 1.8 mmol) AcOH (1.78 mL, 31.6 mmol), lead electrode (S = 18.4 cm^2), I = 70 mA, electrolysis time 3 h 30 min (Q = 2.3 F mol^{-1}), $V(Et_4NOH)$ = 1.4 mL. According to ^1H NMR spectroscopy, the obtained residue contained 4-monochloro derivative **16**, two unidentified products in 5 : 3 : 1 ratio, and **1,2-diethyldisulfane (17)**, which could not be separated by column chromatography.

Signals of **4-chloro-5-ethoxy-2(5*H*)-furanone (16)** in the ^1H NMR spectrum of the reaction mixture, δ: 1.32 (t, 3 H, X-part of the ABX_3-system, CH_3, J_{AX} = J_{BX} = 7.5 Hz); 2.54—2.69 (m, 2 H, OCH_2); 5.96 (d, 1 H, C(5)H, $^4J_{H(5)H(3)}$ = 1.6 Hz); 6.25 (d, 1 H, C(3)H, $^4J_{H(3)H(5)}$ = 1.6 Hz). MS, *m/z* (I_{rel} (%)): 178 $[M]^+$ (20), 149 $[M - Et]^+$ (10), 117 $[M - SEt]^+$ (100), 89 $[M - SEt - CO]^+$ (11), 61 $[EtS]^+$ (27).

The reduction of furanone **9** on a GC electrode afforded a more complex mixture of products, in which compound **16** did not predominate.

Quantum chemical calculations. Calculations for the gas-phase structures of the starting compounds, reduction products, and presumable intermediates were performed with full geometry optimization without symmetry constraints by the DFT//B3LYP/6-31++G(d,p) method using Gaussian 09 program package.[30] The calculations for solutions in acetonitrile were carried out by self-consistent reaction field and the PCM continuum model.[31]

Results and Discussion

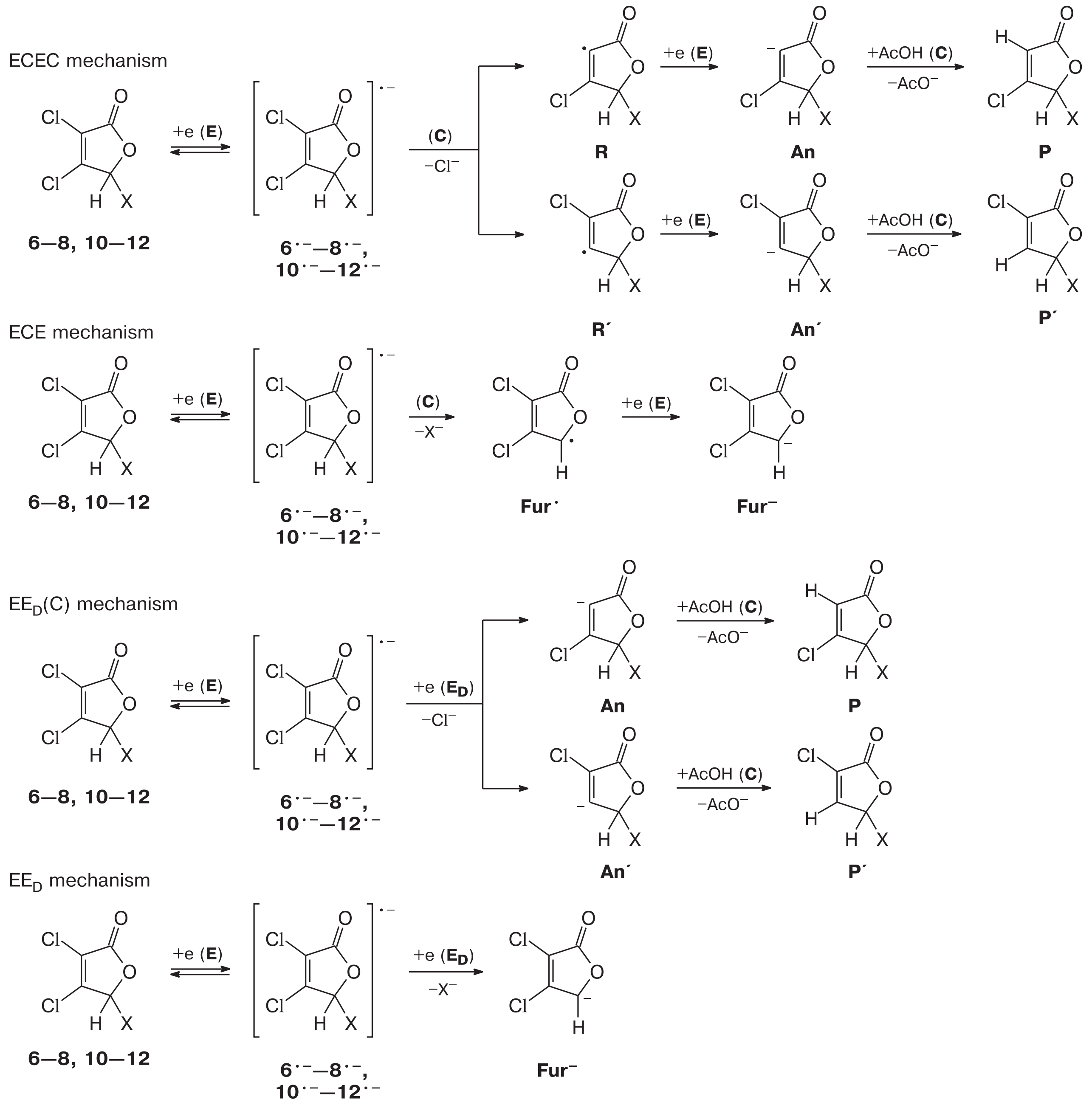
Quantum chemical study of the selectivity of electrochemical reduction of compounds 6—8 and 10—12. The results of quantum chemical calculations for a series of 5-thio-substituted 2(5*H*)-furanone derivatives are generally in line with the calculation data obtained previously for 5-alkoxy derivatives **1—4**.[25] The results of calculations for the radical anions of compounds **6—8** and **10—12** indicate that the single-electron transfer in the gas phase is accompanied by a slight elongation of both C—Cl bonds and a decrease in the dissociation energy (Table 1). The decrease in the dissociation energy is greater for thioethers **6—8** (2.0—2.3-fold) than for sulfones **10—12** (1.3—1.5-fold). The free energy values for the regioisomeric radicals and anions of sulfones **10—12** (Scheme 2) indicates a higher thermodynamic stability of 3-chloro-substituted species **R′** and **An′** compared with that of 4- chloro-substituted **R** and **An** (Table 2). Hence, in these reduction steps, like in the case of 5-alkoxy derivatives **1—4**, regioselectivity can be expected. For thioehers **6—8**, the **An′** species are also more stable than **An**; however, the

Table 1. DFT//B3LYP/6—31++G(d,p)-calculated characteristics of the C—Cl and C—S bonds in neutral molecules **6—8** and **10—12** and their radical anions in the gas phase (I) and in acetonitrile solution (II)*

Compound	Medium	l(C—Y)$_n$/Å			l(C—Y)$_{ar}$ – l(C—Y)$_n$/Å			E_{dis}(C—Y)$_n$/kJ mol^{-1}			E_{dis}(C—Y)$_{ar}$/kJ mol^{-1}		
		C(3)—Cl	C(4)—Cl	C(5)—S	C(3)—Cl	C(4)—Cl	C(5)—S	C(3)—Cl	C(4)—Cl	C(5)—S	C(3)—Cl	C(4)—Cl	C(5)—S
6	I	1.7095	1.7124	1.8418	0.0181	0.0194	1.0265	350.6	351.1	91.0	153.7	154.2	43.3
	II	1.7116	1.7084	1.8391	0.0161	0.0234	1.0293	349.3	349.7	88.1	38.4	38.9	–27.8
7	I	1.7087	1.7120	1.8431	0.0171	0.0186	1.0221	351.0	351.7	91.2	174.9	175.6	31.9
	II	1.7111	1.7081	1.8398	0.0116	0.0178	1.0393	349.3	349.7	88.1	38.4	38.9	–27.8
8	I	1.7087	1.7120	1.8432	0.0166	0.0175	1.0589	351.1	351.8	95.8	175.7	176.5	34.9
	II	1.7111	1.7082	1.8394	0.0115	0.0176	1.0292	349.1	342.3	91.8	38.3	31.4	–24.4
9	I	1.7095	1.7122	1.8274	0.0420	0.1750	0.0332	351.3	343.2	125.4	112.4	104.3	60.9
	II	1.7119	1.7086	1.8221	0.0392	0.1412	0.0217	349.0	342.6	124.6	3.0	3.4	16.8
10	I	1.7062	1.7134	1.9108	0.0103	0.0127	2.3701	352.6	336.0	44.2	248.0	231.4	39.1
	II	1.7074	1.7062	1.9060	–0.0011	0.0153	2.4165	348.4	333.7	45.3	119.9	105.3	–22.9
11	I	1.7054	1.7135	1.9107	0.0097	0.0084	2.1989	352.7	336.6	43.5	275.6	259.6	38.3
	II	1.7068	1.7060	1.9051	–0.0005	0.0153	2.3661	350.4	336.3	45.7	133.4	119.2	–21.7
12	I	1.7053	1.7136	1.9106	0.0091	0.0124	2.3544	353.0	337.1	46.5	266.3	250.4	30.8
	II	1.7068	1.7062	1.9055	–0.0007	0.0154	2.3206	350.8	335.9	48.2	131.7	116.8	–21.3

* l is the bond length, E_{dis} is the bond dissociation energy; the subscripts n and ar correspond to neutral molecules and radical anions, respectively.

Scheme 2



Compound	X	Compound	X
6	4-MeC_6H_4S	**10**	4-$MeC_6H_4SO_2$
7	4-ClC_6H_4S	**11**	4-$ClC_6H_4SO_2$
8	4-BrC_6H_4S	**12**	4-$BrC_6H_4SO_2$
9	EtS		

thermodynamic stabilities of the **R** and **R′** radicals are virtually equal.

In the case of sulfur-containing furanones **6—8** and **10—12**, the electron affinity of their **R** and **R′** radicals is higher than the electron affinity of neutral molecules (see Table 2), which enables the reductive C—Cl bond cleavage in these furanones by the ECE mechanism (see Scheme 2).

As in the case of 5-alkoxy derivatives **1—4**, the EE_D mechanism of ECR is also, in principle, possible for furanones **6—8** and **10—12** (see Scheme 2). The thermody-

Table 2. DFT//B3LYP/6—31++G(d,p)-calculated characteristics of the relative stability ($\Delta\Delta G_{298}$) and electron affinity (*EA*) of intermediates and regioisomeric reduction products of furanones **6—8** and **10—12** in the gas phase (I) and in solution in acetonitrile (II)

Compound	Medium	$\Delta\Delta G_{298}$/kJ mol^{-1}			*EA*/kJ mol^{-1}		
		R – **R′**	**An** – **An′**	**P** – **P′**	EA_n	EA_R	$EA_{R'}$
6	I	−0.5	13.5	17.3	159.6	289.9	303.4
	II	−0.651	0.386	3.5	320.0	485.0	485.4
7	I	−0.8	15.6	19.5	180.4	305.9	321.5
	II	−0.449	0.449	3.2	327.1	486.8	487.2
8	I	−0.8	15.8	29.3	181.2	306.6	322.3
	II	6.867	−6.263	2.2	327.1	486.5	480.2
9	I	8.2	10.2	23.1	117.7	284.6	294.7
	II	0.4	4.6	14.7	291.9	483.1	487.7
10	I	16.5	14.2	29.2	252.0	320.8	335.0
	II	14.654	5.597	12.0	409.5	505.5	511.1
11	I	16.1	14.4	14.8	279.5	337.1	351.5
	II	14.139	4.798	10.4	420.9	509.1	513.9
12	I	16.0	13.7	19.3	269.9	337.8	351.5
	II	14.859	7.034	16.2	418.8	508.5	515.5

namic preference (see Table 2) of formation of the **An′** carbanions over **An** carbanions ($\Delta\Delta G_{298}$(**An**—**An′**) = = 13.5—15.8 kJ mol^{-1}) is comparable with this value for the regioisomeric radicals ($\Delta\Delta G_{298}$(**R**—**R′**) = = 16.0—16.5 kJ mol^{-1}) for sulfones **10—12** and is much higher for thioethers **6**—**8**.

Quantum chemical calculations revealed some considerable differences of sulfur derivatives **6**—**8** and **10**—**12** from furanones **1**—**4**, namely, (1) the electron affinity is much higher (ΔEA = 40—170 kJ mol^{-1}); (2) the common trend towards weakening of C(4)—Cl and C(3)—Cl bonds upon single-electron transfer is much less pronounced; (3) the C(4)—Cl and C(3)—Cl bond dissociation energies for the radical anions of thioethers **6**—**8** are virtually equal; (4) the C(5)—S bond dissociation energy is considerably lower (see Table 1) than the C(5)—O bond dissociation energy in the radical anions. Whereas for radical anions of 5-alkoxy derivatives **1**—**4**, E_{dis}(C(5)—O) is higher than E_{dis}(C(4)—Cl) or E_{dis}(C(3)—Cl),[25] in the case of sulfur compounds **6**—**8** and **10**—**12**, E_{dis}(C(5)—S) is, conversely, markedly lower than the latter values (see Table 1).

Analysis of the calculation results indicates that the C(5)—S bond cleavage is preferred over the C(4)—Cl bond cleavage in both ECE and EE_D mechanisms (see Table 2). Hence, elimination of the arylthiolate ion rather than the chloride ion, as in the case of 5-alkoxy derivatives, may be predicted for these reduction steps.

In order to evaluate the possible influence of the solvent on the C(5)—S and C(4)—Cl bond cleavage steps, we calculated the structures of the starting compounds and intermediates in acetonitrile solutions by the polarized continuum method (PCM model).[31] However, in acetonitrile solutions, the dissociation energy was also considerably lower for the C(5)—S bond of radical anions than for the C(4)—Cl bond, and the products formed upon cleavage of this bond proved to be thermodynamically more stable (see Tables 1, 2).

Thus, the results of quantum chemical investigation of the structures of furanones **6**—**8** and **10**—**12** and the possible intermediates formed in their ECR provide evidence for the predominant formation of C(5)—S bond cleavage products, whereas the selective formation of 3-chloro derivatives **P′** proved to be unlikely. In the reaction pathway associated with C(5)—S bond cleavage, irrespective of the reaction mechanism, the leaving group is the arylthiolate ion, whose capability for elimination is roughly equal to that of the chloride ion, but is considerably lower than that of arylsulfinate ion.[32]

Electrochemical experiments. Cyclic voltammetry. The CV curves for the sulfur derivatives **6**—**8** and **10**—**12** measured in MeCN—Bu_4NBF_4 (0.1 mol L^{-1}) on a GC electrode have identical morphology similar to that of the CV curves of mucochloric acid **5**, but markedly differing from those of its 5-alkoxy derivatives **1**—**4** (Fig. 1). For each of thioethers **6**—**8** and sulfones **10**—**12** and also for furanone **5**, three irreversible reduction peaks of comparable intensity are observed (see Fig. 1, *a*—*c*), whereas in the case of alkoxy derivatives **1**—**4**, one peak is present (see Fig. 1, *e*). The first peak current $i_p^{\text{red},1}$ approximately corresponds to the transfer of one electron per molecule (Table 3) and increases in proportion with the compound concentration in the range of $5\cdot10^{-4}$—$5\cdot10^{-3}$ mol L^{-1}. The first peak has a diffusion nature, as follows from the linear dependence of the first peak current $i_p^{\text{red},1}$ on $\upsilon^{1/2}$.

As expected, in view of the higher electron affinity of the **R** and **R′** radicals in comparison with neutral molecules

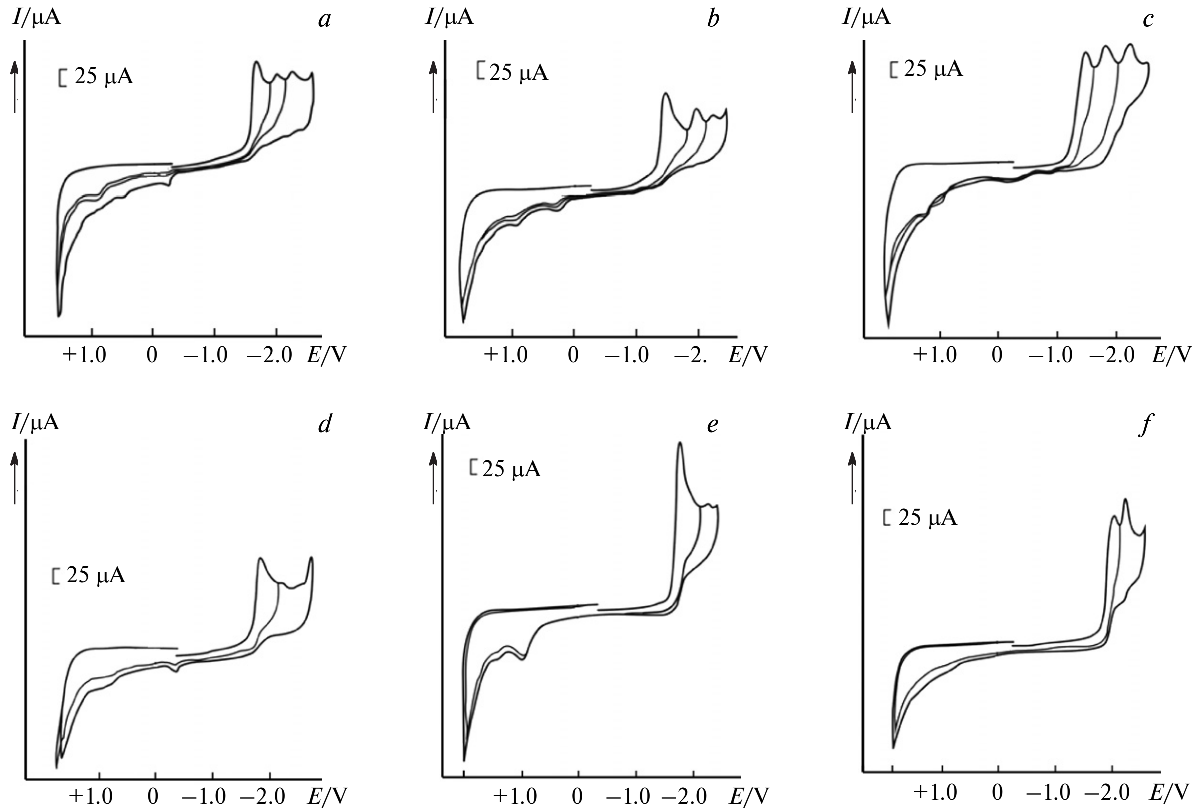


Fig. 1. Cyclic voltammograms of thioether **6** (*a*), sulfone **10** (*b*), mucochloric acid **5** (*c*), thioether **9** (*d*), furanone **1** (*e*), and 3-chloro-5-methoxy-2(5*H*)-furanone (*f*). $C = 3 \cdot 10^{-3}$ mol L^{-1}, MeCN—Bu$_4$NBF$_4$ (0.1 mol L^{-1}), glassy carbon electrode, υ = 200 mV s^{-1}. The potentials E are given *versus* Ag/AgNO$_3$ (0.01 mol L^{-1}) in MeCN.

(see Scheme 2 and Table 2), the potential values of the first reduction peaks of compounds **6—8** and **10—12** are shifted towards less cathodic values relative to those of 5-alkoxy derivatives **1—4** (in the case of 5-(*p*-tolyl)thio derivative **6**, which is least prone to reduction, the shift relative to 5-ethoxy furanone **2** is 200 mV). Note that sulfones **10—12** are reduced much more easily than respective sulfides **6—9** (ΔE_{p} = 170—260 mV). The halogen atoms (Br, Cl) in the *para*-position of the benzene ring also facilitate the reduction; this effect is more pronounced for sulfides than for sulfones (see Table 3). For mucochloric acid **5** and all of the derivatives **6—8** and **10—12**, the sec-

Table 3. Cyclic voltammetry data on the electrochemical reduction of compounds **5—12**[a]

Substrate	$-E_{\mathrm{p}}^{\mathrm{red}}$/V[b]	$i_{\mathrm{p}}^{\mathrm{red,1}}$/μA	$E_{\mathrm{p/2}} - E_{\mathrm{p}}$/mV[c]	n[d]	$E_{\mathrm{p}}^{\mathrm{reox}}$/V[b]
5	1.50, 1.88, 2.21	115	130	1.4	−0.38, +1.05, +1.23
6	1.72, 2.06, 2.33	110	105	1.3	−0.23[e], +0.49, +0.88, +1.23[e]
7	1.63, 1.98, 2.25	114	100	1.2	−0.13, +0.53, +0.95, +1.33
8	1.58, 1.95, 2.33	95	105	1.2	−0.13, +0.98, +1.33
9	1.86, 1.96, 2.22, 2.47	92	85	1.0	−0.36, +0.71, +0.88
10	1.46, 1.92, 2.20	93	95	1.1	+0.25, +0.94, +1.35
11	1.41, 1.95, 2.38, 2.56	93	85	1.0	+0.35, +0.98, +1.35
12	1.41, 1.95, 2.20	75	85	0.9	+ 0.37, +0.83, +1.00, +1.33

[a] $C = 3 \cdot 10^{-3}$ mol L^{-1}, MeCN—Bu$_4$NBF$_4$ (0.1 mol L^{-1}), glassy carbon electrode, υ = 100 mV s^{-1}.

[b] The potentials are given *versus* Ag/AgNO$_3$ (0.01 mol L^{-1}) in MeCN.

[c] The $E_{\mathrm{p/2}}$ and E_{p} values were corrected to the potential drop iR using the corresponding values for the reversible reduction of benzophenone.

[d] The number of electrons transferred at the first reduction potentials per molecule.

[e] Potentials of *p*-thiocresol oxidation peaks in the absence and in the presence of 1 equiv. Bu$_4$NOH are +1.14 and −0.25 v, respectively.

ond and third reduction peaks occur at approximately the same potentials (see Table 3). This means that the reduction of these compounds at the first peak potentials affords the same species, which are further reduced at higher potentials. This is possible only in the case of reductive elimination of the substituting group from position 5 of the lactone ring. The usual leaving groups in the reduction are anions (anionoid elimination); apparently, in this case, the leaving groups are also anions, namely, hydroxide, thiolate, and sulfinate ions. In the case of sulfone **11**, one more, fourth, irreversible reduction peak is observed at more negative potentials (see Table 3), which is caused by the two-electron reductive cleavage of the C—Cl bond of the aromatic moiety.[33] A similar reduction of the C—Br bond in bromobenzenes occurs more easily; probably, this is why in the case of sulfone **12**, this step is reflected in the CV curve as a separate additional intense peak between the second and third peaks (see Table 3).

The anionoid elimination of substituents from position 5 of the lactone ring directly follows from analysis of the reverse branches of CV curves. In the case of potential reversal at the first reduction peak, the CV curves of all compounds exhibit intense reoxidation peaks in the potential ranges of –0.43 to –0.50 V for thioethers **6—8** and –0.2 to +0.06 V for sulfones **10—12**. For compound **6**, the potential of this peak strictly corresponds to the oxidation potential of the *p*-tolylthiolate ion. Although no correlation of this type was made for reoxidation peaks of sulfones **10—12** with the corresponding sulfinic acids, the assignment of the observed reoxidation peaks to the sulfinate ions is beyond doubt, because arylsulfonyl is a good leaving group.[32] In addition, the sulfinate ion is expected to be less readily oxidized than the thiolate ion, which is actually observed in sulfide and sulfone reoxidation experiments. It is noteworthy that other reoxidation peaks are also present in the CV curves of all mentioned compounds, the intensity of these peaks increasing when the potential is reversed at the second or third reduction peak (see Table 3). In this case, it was impossible to find out whether these steps refer to the oxidation of chloride ions or some other species generated during reduction. The potentials of these peaks are similar, but do not correspond to the oxidation peak of chloride ions; for an Et_4NCl solution of the same concentration, this peak occurs at $E_p^{ox}(Cl^-) = +0.80\text{–}+0.90$ V *vs.* $Ag/AgNO_3$ (0.01 mol L^{-1}), depending on the state of the electrode surface.

Since the reduction of both thioethers and sulfones at potentials of the first peak is accompanied by elimination of substituent from position 5 of the ring to give the same heterocyclic moiety, we suggested that the addition of AcOH would have similar effect on both series of compounds. The addition of acetic acid has different effects on the shapes of CV curves of thioethers **6—8** and sulfones **10—12**. In the case of thioethers **6—8**, the addition of an equimolar amount of AcOH causes a twofold increase in the height of the first peak, which reaches the two-electron level. The subsequent reduction peaks and the reoxidation peak of the thiolate ion are retained (Fig. 2). At more negative potentials in the cathodic region, an additional reduction peak appears, which can be assigned to the reduction of AcOH (for AcOH, $E_p^{red} = -2.54$ V). The parameters of the first three reduction peaks are retained as the AcOH concentration in solution increases by a factor of up to eight. After two- or sixfold increase in the AcOH concentration, depending on the nature of the thioether, the reverse branch of the CV curve no longer exhibits the reoxidation peak for arylthiolate ions (–0.23 to –0.13 V), while the reoxidation peak of thiophenols occurs at +1.05 to +1.26 V.

As shown previously,[25] in the case of 5-alkoxy derivatives **1—4**, a reduction peak for the 3-monochloro derivative appears in the CV curves upon the addition of AcOH; this peak is shifted towards negative potentials relative to the peak of the starting furanone by 150—200 mV. The same trend could be expected of sulfur derivatives **6—8** and **10—12**, in particular, the reduction of monochloro derivatives will be more difficult than that of furanone 3,4-dichloro derivatives, approximately to the same extent. In the case of thioethers **6—8**, no peaks for monochloro derivatives are present in the predicted range of reduction potentials at any amount of AcOH (see Fig. 2). The reverse CV branch does not show the chloride oxidation peak either. It is evident that even in the presence of excess AcOH, the desired elimination of the chloride ion from position 4 does not proceed to any noticeable extent.

Thus, at any amount of AcOH used, (1) elimination of the sulfinate ion takes place at the first reduction potential of sulfones **10—12**; as the acid concentration increases, the reoxidation peak is retained and shifts towards the positive potentials (Fig. 3), (2) no reduction peaks for the corresponding monochloro derivatives are present, and (3) the second and third reduction peaks are retained, the height of the second peak increases with increasing acid concentration.

It is of interest that the effect of AcOH on the first step of reduction of sulfones **10—12** differs from its effect on the reduction of thioethers **6—8**. In the case of sulfones **10—12**, the addition of an equimolar amount of AcOH gives rise to additional peak 1′ just after the first peak at the same potential for all three sulfones. In the case of sulfone **10**, which is reduced less readily, peak 1′ is superimposed onto the first reduction peak, which is manifested as the first peak broadening and shift towards negative potentials (see Fig. 3). In the case of sulfones **11** and **12**, peak 1′ occurs as a separate peak with $E_p^{red,1'} = -1.55$ V, which is also partly superimposed onto the first reduction peak (Fig. 4). Therefore, it is impossible to determine the partial peak heights and the total height or the number of electrons in each step and the total number of electrons.

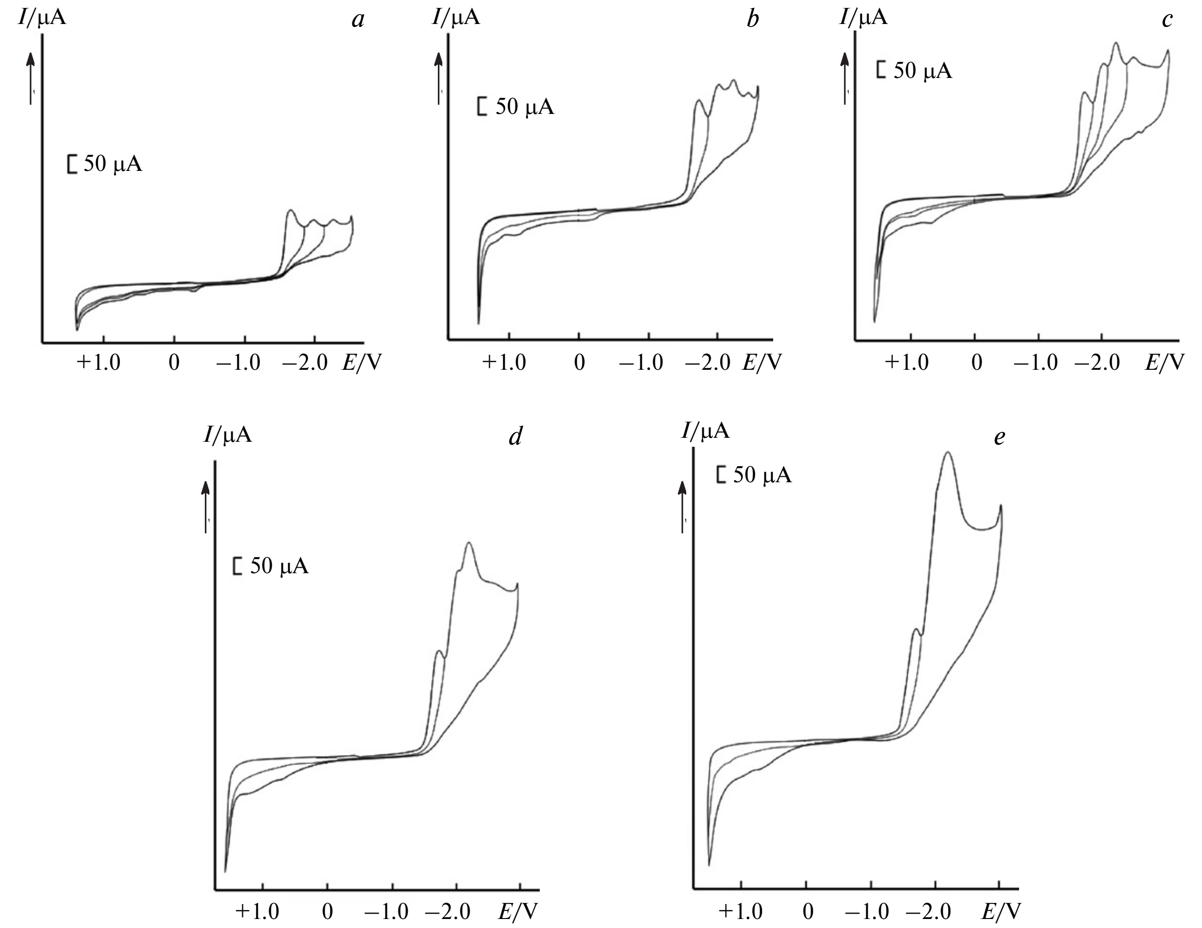


Fig. 2. Cyclic voltammograms of thioether **6** ($C = 3 \cdot 10^{-3}$ mol L^{-1}) in the absence (*a*) and in the presence of AcOH in concentrations of $3 \cdot 10^{-3}$ (*b*), $6 \cdot 10^{-3}$ (*c*), $12 \cdot 10^{-3}$ (*d*), $24 \cdot 10^{-3}$ mol L^{-1} (*e*). MeCN—Bu_4NBF_4 (0.1 mol L^{-1}), glassy carbon electrode, υ = 200 mV S^{-1}. The potentials *E* are given *versus* Ag/$AgNO_3$ (0.01 mol L^{-1}) in MeCN.

When the acid content increases up to eightfold, the additional peak of all compounds **10—12** coalesces with the first peak. This is indicated by some first peak broadening and shift towards negative potentials with respect to the first peak without the acid. At a large excess of AcOH, the first peak height reaches and exceeds the two-electron level. It is noteworthy that an additional reduction peak appears at the same potential in the reduction of the parent mucochloric acid **5** in the presence of stronger formic acid. It is evident that the reduction of furanone **5** gives a product analogous to the reduction products of sulfones.

Apparently, a similar additional peak 1′ is also present in the CV curves of thioethers **6—8**, but it is hidden under the first reduction peak, because thioethers are reduced less readily than sulfones. The twofold increase in the current of the first reduction peak of thioethers after the addition of an equimolar amount of AcOH is caused not only by the increase in the first peak height, but also by appearance of new peak 1′.

The whole set of obtained results indicates that the reduction of thioethers **6—8** and sulfones **10—12** occurs by the ECE or EE_D mechanism as the transfer of two electrons with C(5)—S bond cleavage to give arylthiolate (arylsulfinate) ions and heterocyclic carbanion (Schemes 2 and 3). The observed reoxidation peak refers to the oxidation of the corresponding arylthiolate and arylsulfinate anions. In the presence of AcOH, the arylthiolate ion is protonated; therefore, the peak for its reoxidation disappears. Arylsulfinic acid is stronger than acetic acid (pK_a(*p*-$MeC_6H_4SO_2H$) = 1.7, pK_a(AcOH) = 4.76[**34**]); therefore, the arylsulfinate ion is not protonated with AcOH and peak of its oxidation is still detected in the presence of the acid. The proposed scheme is also supported by equal potentials of the second and third reduction peaks corresponding to the reduction products that are formed upon elimination of the substituent from position 5 of the heterocyclic moiety.

This brings about the question of the subsequent transformations of the primarily generated heterocyclic **Fur**$^-$ carbanion (see Scheme 3), *i.e.*, what products are formed and reduced at the potentials of additional peak 1′ and subsequent peaks? Since the **Fur**$^-$ carbanion is not reduced

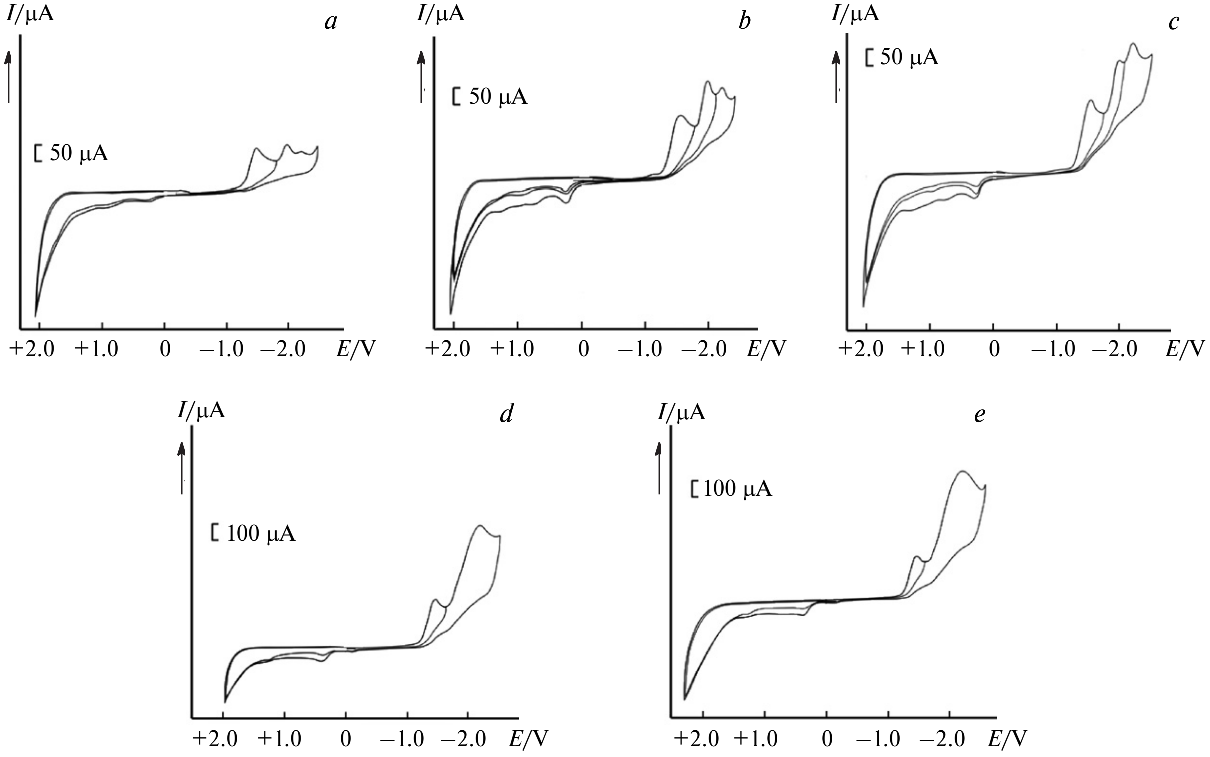


Fig. 3. Cyclic voltammograms of sulfone **10** ($C = 3 \cdot 10^{-3}$ mol L^{-1}) in the absence (*a*) and in the presence of AcOH in concentrations of $3 \cdot 10^{-3}$ (*b*), $6 \cdot 10^{-3}$ (*c*), $12 \cdot 10^{-3}$ (*d*), $18 \cdot 10^{-3}$ mol L^{-1} (*e*). MeCN—Bu$_4$NBF$_4$ (0.1 mol L^{-1}), glassy carbon electrode, $\upsilon = 200$ mV s^{-1}. The potentials *E* are given *versus* Ag/AgNO$_3$ (0.01 mol L^{-1}) in MeCN.

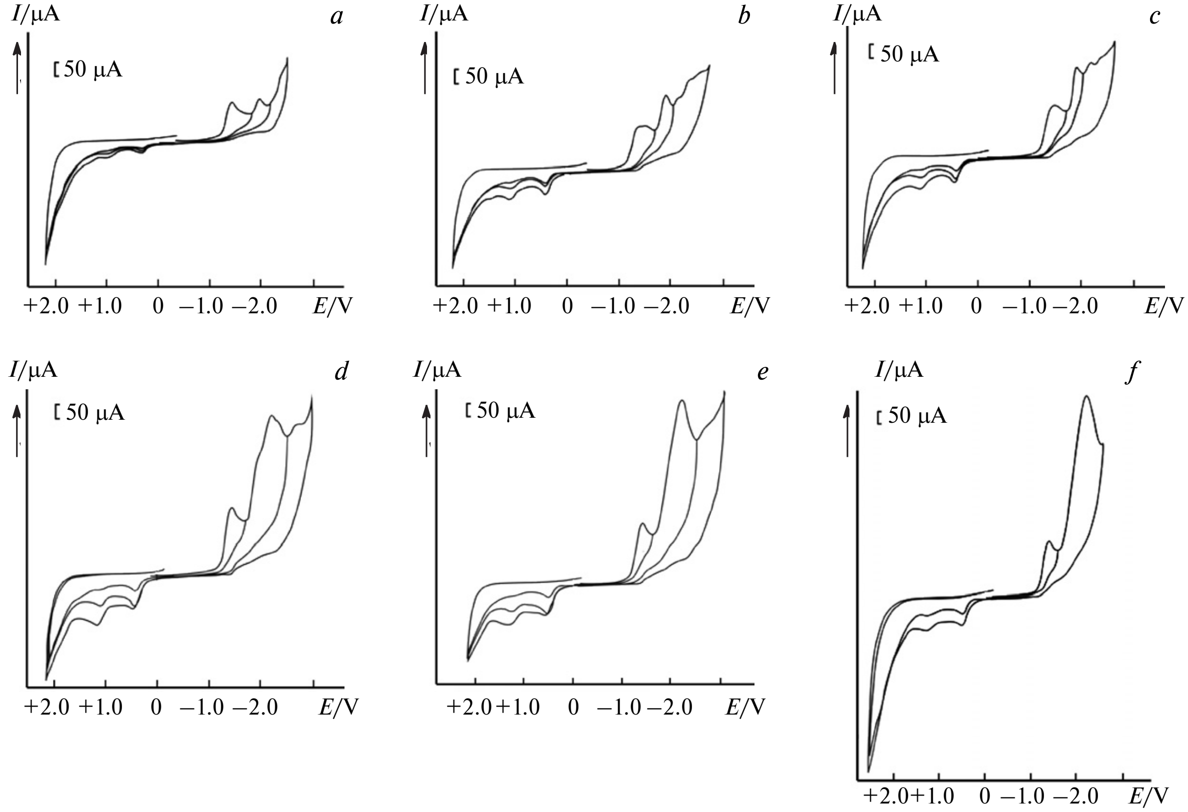
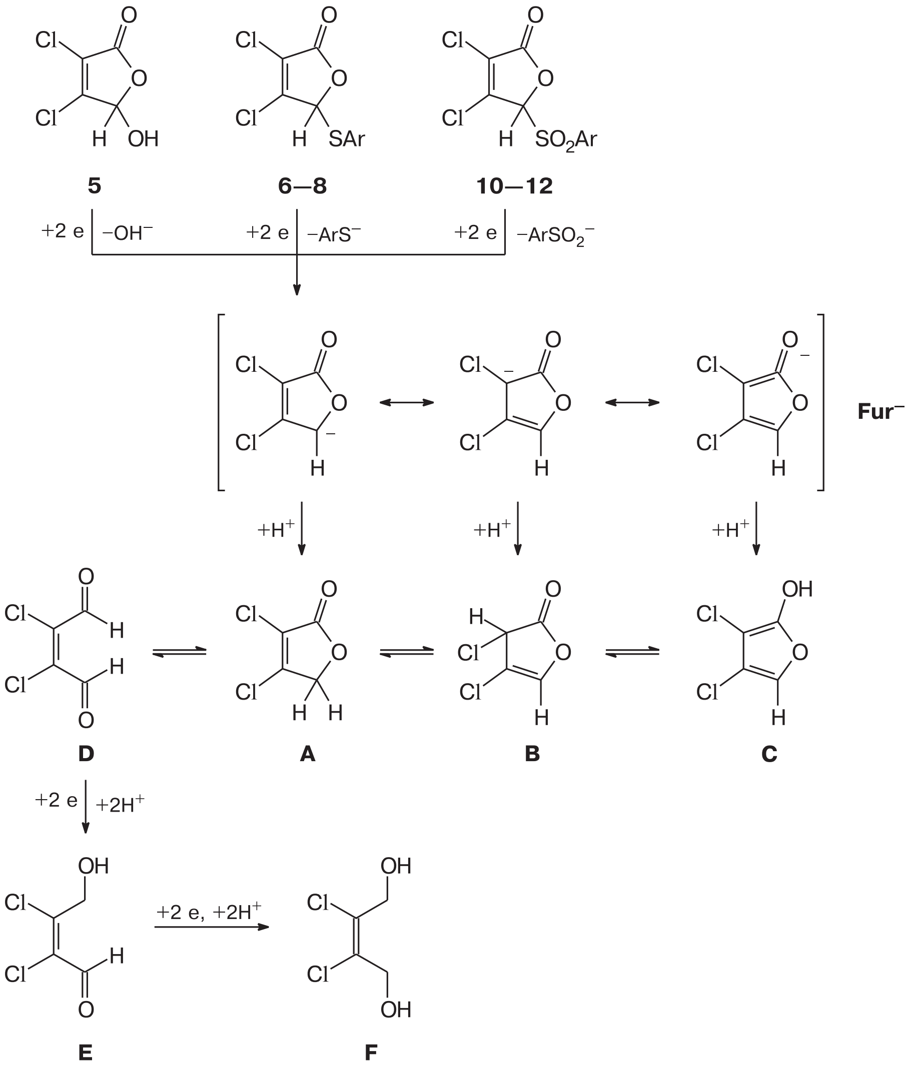


Fig. 4. Cyclic voltammograms of sulfone **12** ($C = 3 \cdot 10^{-3}$ mol L^{-1}) in the absence (*a*) and in the presence of AcOH in concentrations of $3 \cdot 10^{-3}$ (*b*), $6 \cdot 10^{-3}$ (*c*), $12 \cdot 10^{-3}$ (*d*), $18 \cdot 10^{-3}$ (*e*), $24 \cdot 10^{-3}$ mol L^{-1} (*f*). MeCN—Bu$_4$NBF$_4$ (0.1 mol L^{-1}), glassy carbon electrode, $\upsilon = 200$ mV S^{-1}. The potentials *E* are given *versus* Ag/AgNO$_3$ (0.01 mol L^{-1}) in MeCN.

Scheme 3



in the considered range of potentials (in the absence of a proton donor, the height of the first peak corresponds to the transfer of less than two electrons), then, apparently, under these conditions, this carbanion partly reacts with the initial molecule to give compounds that are not reduced at the first-peak potentials and that are apparently polymeric (oligomeric) products (resins). The **Fur⁻** carbanion is a rather strong base and it is the first to be protonated with AcOH. Therefore, when AcOH is added in an equimolar amount, it is entirely spent for the protonation of the carbanion, while arylthiolate is retained as an ion. Presumably, even in the absence of AcOH, the **Fur⁻** carbanion is not involved quantitatively in the reaction with the starting compound, but is partly protonated by the residual amount of water present in the solution. The resulting protonation products are probably reduced at the potentials of subsequent peaks.

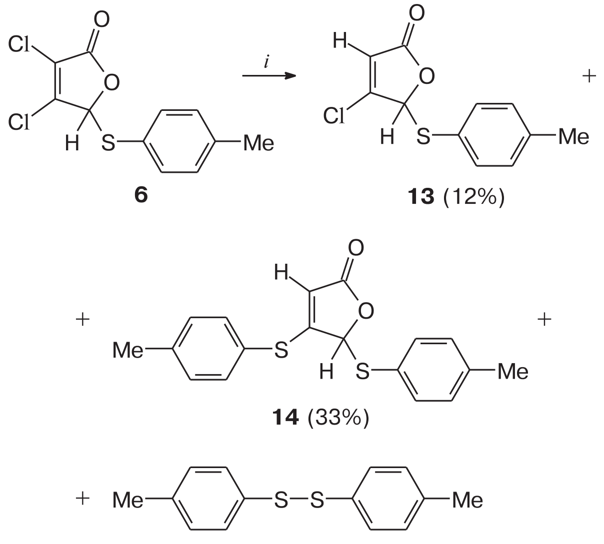
The **Fur⁻** carbanion can be represented as three resonance structures whose protonation would give rise to three cyclic tautomers **A**, **B**, and **C** and acyclic isomer **D** (see Scheme 3); the most stable of them are dialdehyde **D** and 3,4-dichlorofuranone **A**. The protonation rate and, hence, the ratio of products **A**—**D** can be different depending on the nature of the proton donor. For the protonation with water molecules, it cannot be ruled out that the formation of products **A**—**D** is thermodynamically controlled, because this generates the hydroxide ion, a strong base, which is able to eliminate protons from the products formed. However, when AcOH is used as the proton donor, this reaction pathway is relatively unlikely, because the acetate ion is a weak base. Out of the presented structures **A**—**D**, the conjugated dialdehyde **D** should be reduced most easily. The additional peak 1′ may be attributable to its reduction. The introduction of AcOH accelerates the protonation of the **Fur**$^-$ carbanion and, hence, increases the yield of the protonation products (therefore, the height of the second peak corresponding to the reduction of these compounds increases) and decreases the contribution of the parallel reaction of the carbanion with the starting compound. Consequently, the height of the first reduction peak also increases and, in the limiting case, when a large excess of AcOH is present and this reaction is completely eliminated, this height should reach the two-electron level. In view of the fact that additional peak 1′ is superimposed on the first peak, the height of the overall peak should exceed the two-electron level, which is actually observed in experiments.

Thus, the CV data agree with quantum chemical calculations and attest to elimination of the substituent from position 5 of the ring and low probability of selective elimination of chloride ions during the ECR of thioethers **6**—**8** and sulfones **10**—**12** in acetonitrile with Bu_4NBF_4 as the supporting electrolyte (C = 0.1 mol L^{-1}).

In solution, ions are solvated and form ion pairs. The supporting electrolyte cation (Bu_4N^+) also forms ion pairs with the chloride, arylthiolate, and arylsulfinate ions. Since the solvation energy and the ion pair interaction energy depend on the size of ions, we assumed that the probability of chloride ion elimination would increase with increasing polarity of the solvent and decreasing radius of the cation of the supporting electrolyte. Therefore, we carried out CV experiments in MeCN in the presence of Et_4NBF_4, $NaClO_4$, and $LiClO_4$ (C = 0.1 mol L^{-1}) and in mixed H_2O—MeCN and H_2O—EtOH solutions (1 : 1) in the presence of Et_4NBF_4 for 5-(*p*-tolyl) thioether **6**, in which elimination of *p*-tolylthiolate ion is most difficult and elimination of the chloride ion is most probable. However, in all cases, CV curves exhibit an intense reoxidation peak for *p*-tolylthiolate. Hence, in the reduction in the presence of any of the supporting electrolytes, elimination of the *p*-tolylthiolate ion is the predominant process in all media. In addition, with $NaClO_4$ and $LiClO_4$, complete passivation of the electrode surface is observed after the furanone **6** reduction peak is attained.

Preparative electrolysis. In order to prove elimination of the substituent from heterocycle position 5 at the preparative level and identify the products of reduction of thio derivatives, we carried out a series of preparative electrolyses in the presence of AcOH. The preparative reduction of thioether **6** was carried out in the presence of a fourfold excess of the acid, the reaction being monitored by CV. The exhaustive reduction (Q = 2.8 F mol^{-1}) on a GC cathode gave a mixture of products, which were separated by column chromatography, with disulfide **15**, 4-chloro-5-(*p*-tolylthio)-2(5*H*)-furanone (**13**), and 4,5-di-(*p*-tolylthio)-2(5*H*)-furanone (**14**) being isolated (Scheme 4). The structure of reduction products was proved by ^1H and ^{13}C NMR spectroscopy, 2D NMR spectroscopy, and gas chromatography—mass spectrometry.

Scheme 4



6

13 (12%)

14 (33%)

15 (8%)

i. Electrochemical reduction, GC electrode, MeCN, Et_4NBF_4, AcOH.

The reduction of the C—Cl bond in position 3 of the ring was evaluated from the 2D ^1H—^{13}C HMQC data, which made it possible to correlate the observed signal of the vinyl proton with the C(3) carbon signal. In the HMQC spectrum of compound **13**, the cross-peak at δ 5.98/88.19 corresponds to the coupled C(5)—H atoms, while the cross-peak at δ 5.91/119.06 is due to the correlation of coupled C(3)—H atoms.

Disulfide **15** is the product of oxidation of thiolate ion, while furanone **14** results from the nucleophilic attack by the thiolate ion on the C(4) carbon atom of the lactone ring of molecule **13** or **6** followed by reduction. The formation of these compounds at the preparative level confirms, to some extent, the data on the reductive elimination of the thiolate ion obtained by cyclic voltammetry and quantum chemical calculations. However, the formation of 4-monochlorinated furanone **13** upon the reductive elimination of the chloride ion from position 3 of the heterocycle was unexpected. After the preparative reduction of thioether **6** on a lead electrode, ^1H NMR spectroscopy revealed furanones **13** and **14** in 1 : 0.4 ratio and disulfide **15** to be present in the reaction mixture. In the case of using glassy carbon, the ratio of products **13** and **14** in the reaction mixture was 0.8 : 1. Apparently, lead electrode promotes the formation of compound **13**. The reduction both under cyclic voltammetry and under preparative electrolysis conditions on a GC electrode is characterized by slightly predominating elimination of the thiolate ion from position 5 of the heterocycle, while in the case of lead electrode, this process is accompanied by competing elimination of the chloride ion from position 3. The results of preparative macroelectrolysis are in line with CV data on elimination of the thiolate ion; however, the information on the major products of transformation of the heterocyclic moiety could not be obtained by preparative electrolysis.

Since according to CV data, the reduction of mucochloric acid **5** gives the same heterocyclic product as the reduction of thioethers **6**—**8** and sulfones **10**—**12**, we carried out additional macroelectrolysis by reducing compound **5** in the presence of a 1.5-fold excess of formic acid at low current densities ($Q = 1.5$ F mol^{-1}). These conditions were chosen deliberately to maximize the yield of the product reduced at potentials of additional peak 1′. However, as previously,[25] no single products were isolated from the reaction mixture.

Thus, the results of preparative electrolysis also attest to the predominant elimination of the thiolate ion during the ECR of thioether **6**, whereas in the reduction of 5-alkoxy-3,4-dichloro-2(5*H*)-furanones **1**—**4**, elimination of the chloride ion from position 4 of the lactone ring takes place quantitatively and selectively.[25]

This raises the question of what factor is responsible for the change in the reduction mechanism on going from 5-alkoxy- to 5-arylthio derivatives. In the case of 5-arylthio derivatives, the solvation energies of the anions attest in favor of chloride ion elimination, as its solvation energy in acetonitrile is higher than the solvation energy of the arylthiolate ion. However, lower C(5)—S bond energy than the C(5)—O bond energy and higher stability of the arylthiolate ion than the alkoxide ion stability are the reasons pointing to arylthiolate elimination. In view of the calculation and experimental results, these structural factors are likely to prevail over the solvation factor.

We assumed that the C—S bond energy can be increased and the leaving group stability can be decreased by replacing the arylthio by an alkylthio group; however, the solvation energy will also increase. Similarly, it is possible to decrease the C—O bond energy and increase the stability of the leaving anion, with simultaneous loss of solvation energy, by replacement of alkyl group in the molecules of 5-alkoxy derivatives by an aryl group. Therefore, presumably, 5-aryloxy and 5-alkylthio mucochloric acid derivatives would occupy an intermediate position between 5-alkoxy and 5-arylthio derivatives in the ability to eliminate the chloride ion from position 4 and substituent from position 5. In the case of 5-alkoxy and 5-arylthio derivatives, it is more likely that the two elimination processes occur in parallel, which is consistent with quantum chemical data. As the arylthio group is replaced by an ethylthio group, the C(5)—S bond rupture energy markedly increases both in the starting compound **9** and in the radical anion. In the gas phase, elimination of the ethylthiolate ion is energetically favorable, while in acetonitrile, the favorable process is chloride ion elimination from position 3 or 4 (see Table 2).

In order to verify these assumptions, we synthesized 5-ethylthio furanone derivative **9** and investigated its electrochemical properties (Fig. 5). The CV curves of thioether **9** measured on various electrodes (Table 4) show one intense irreversible two-electron reduction peak at a potential close to the reduction potential of the corresponding 5-ethoxy derivative **2**.[25] In addition, several more peaks with lower intensity are present.

The morphology of the CV curves of thioether **9** is similar to that of 5-alkoxy derivatives **1**—**4**, although dif-

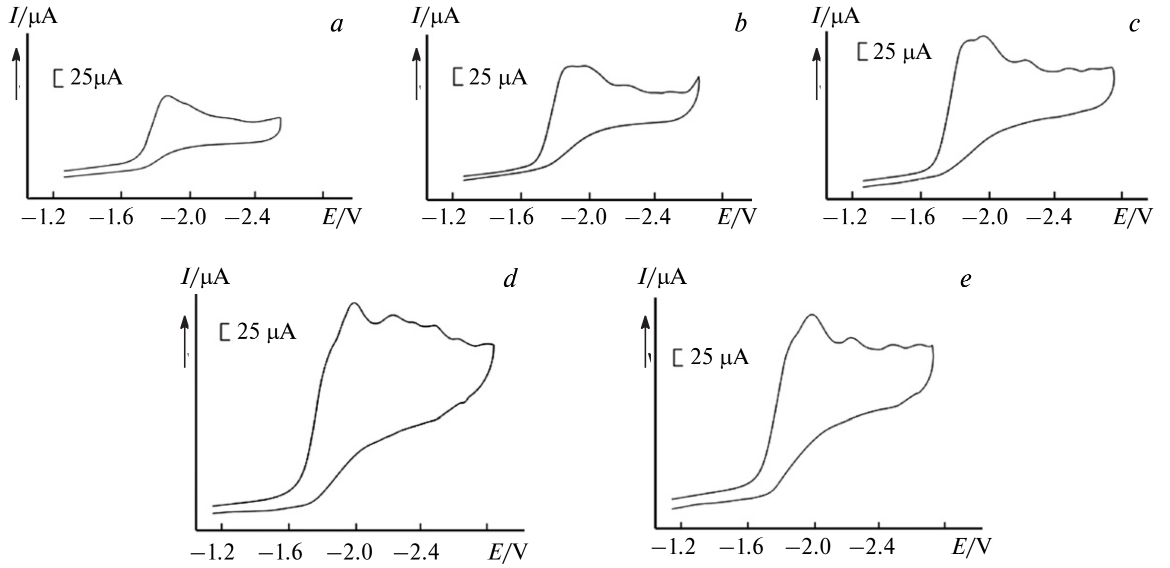


Fig. 5. Cyclic voltammograms of thioether **9** ($C = 3 \cdot 10^{-3}$ mol L^{-1}) in the absence (*a*) and in the presence of AcOH in concentrations of $3 \cdot 10^{-3}$ (*b*), $6 \cdot 10^{-3}$ (*c*), $12 \cdot 10^{-3}$ (*d*), $24 \cdot 10^{-3}$ mol L^{-1} (*e*). MeCN—Bu_4NBF_4 (0.1 mol L^{-1}), glassy carbon electrode, $\upsilon = 100$ mV s^{-1}. The potentials *E* are given *versus* Ag/$AgNO_3$ (0.01 mol L^{-1}) in MeCN.

Table 4. Reduction potentials of compound **9** on various electrodes[a,b]

Electrode	$-E_p^{red}$/V
GC	1.86, 1.99, 2.26
Pb	1.81
Ag	1.85, 1.99
Pt	1.92
Cu	1.81
Hg	1.84

[a] Potentials are given *versus* Ag/$AgNO_3$ (0.01 mol L^{-1}).

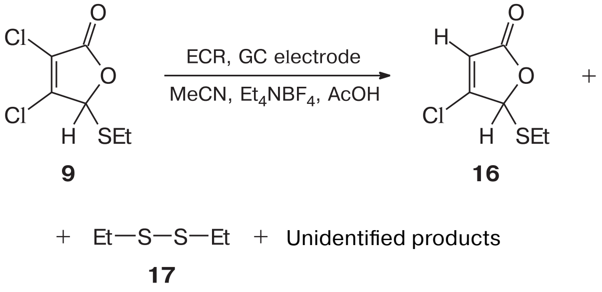
[b] $C = 3 \cdot 10^{-3}$ mol L^{-1}, MeCN—Bu_4NBF_4 (0.1 mol L^{-1}), υ = 100 mV s^{-1}.

fers somewhat by the presence of additional peaks (*cf.* Fig. 1, *e* and Fig. 5, *a*). This may indicate that reduction of compound **9** is accompanied by competitive elimination of the chloride ion and ethylthiolate ion, with the former process predominating. These preliminary conclusions are in line with virtually all of the obtained results. The reverse branch of the CV curve shows reoxidation peaks for both the ethylthiolate ion ($E_p^{reox,1}$ = –0.36 V) and chloride ion ($E_p^{reox,2}$ = +0.88 V). The addition of AcOH to the solution increases the height of both the first reduction peak and the second low-intensity peak $E_p^{red,2}$ = –1.96 V (see Fig. 5), which can be assigned, by analogy with 5-alkoxy derivatives, to the reduction of monochloro 2(5*H*)-furanone derivative. The height of this peak increases with increasing concentration of the acid, but does not reach the level of the corresponding peak of 5-alkoxy derivatives even with large excess of AcOH (see Fig. 5). This means that elimination of the chloride ion is not quantitative in this case, but competes with elimination of the ethylthiolate ion. The CV curves measured in the presence of AcOH exhibit many other peaks of different intensity, which also points to formation of several products (see Fig. 5).

Further, we carried out the preparative reduction of compound **9** in the presence of an eightfold excess of AcOH both on a lead electrode and on a GC electrode; in both cases, a complex mixture of products was obtained (Scheme 5). Using GC/MS and ^{1}H NMR spectroscopy, the major products were identified in the reaction mixture, namely, monochloro derivative **16**, diethyl disulfide **17**, and some other unidentified furanone derivatives, which could not be isolated in a pure state. This result supports the competition between elimination of chloride and ethylthiolate ions during the reduction of compound **9** at the first peak potentials.

According to the ^{1}H NMR data for the reaction mixture and some isolated fractions resulting from attempted separation of the mixtures by column chromatography, compound **16** can be presumably identified as 4-chloro-5-ethoxy-2(5*H*)-furanone. This is indicated by the presence of a triplet and a multiplet typical of ethoxy group protons and two doublets at δ 5.96 and 6.25 ($^3J_{HH}$ = 1.6 Hz) corresponding to the methine proton at the C(5) carbon atom and the vinylic proton at C(3). In our opinion, the signal at δ 6.25 corresponds to the vinylic proton at C(3) rather than at C(4), because the C(4)H proton is more deshielded and is expected to resonate at δ ≈ 7.0, which is actually observed for 3-monochloro derivatives.[25]

Scheme 5



ECR is electrochemical reduction.

Thus, the results of preparative microelectrolysis are more or less consistent with the assumed competitive elimination of the chloride ion and ethylthiolate ion in the ECR of compound **9** at the first peak potentials.

General views on the mechanism of reduction of 2(5*H*)-furanone derivatives. Application of a set of methods (quantum chemical calculations, cyclic voltammetry, and preparative microelectrolysis) gives a comprehensive view on the electrochemical behavior of 2(5*H*)-furanone derivatives at first peak potentials in acetonitrile.

The reduction of 5-alkoxy derivatives **1**—**4** on a lead and GC electrodes in the presence of AcOH as proton donor is a highly selective reaction giving 5-alkoxy-3-chloro-2(5*H*)-furanones.[25] The performed analysis of experimental data and quantum chemical calculations for the structures of possible intermediates led to the conclusion that the EE_DC mechanism comprising a tandem transfer of two electrons with chloride ion elimination in the step of second electron transfer and protonation is the most likely ECR mechanism for compounds **1**—**4**.[25]

In the ECR of mucochloric acid **5** and 5-arylsulfanyl- and 5-arylsulfonyl-3,4-dichloro-2(5*H*)-furanones, anionoid elimination of the substituent from position 5 of the lactone ring is the predominant process. The contribution of the competing elimination of the chloride ion increases on going to 3,4-dichloro-5-ethylsulfanyl-2(5*H*)-furanone (**9**).

Thus, on the basis of our results, it is possible to propose a simple experimental criterion for one or another pathway of electrochemical reduction using only CV data without resorting to the whole set of studies. For 3,4-dichloro-2(5*H*)-furanone derivatives reduced with selective elimination of 4-substituent, the CV curves measured in a MeCN—Bu_4NBF_4 (0.1 mol L^{-1}) solution exhibit one intense reduction peak, while for derivatives that are reduced with elimination of the 5-substituent, three peaks of comparable intensity are present. Therefore, there is no need to record the complete CV curve; it is sufficient to measure only the forward branch and determine the number of reduction peaks. If the forward branch exhibits one intense peak, elimination of the chloride ion takes place; if three peaks are present, elimination of the 5-substituent occurs. The presence of some other peaks of a different morphology attests to a different ECR mechanism.

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