SUBSTITUENT EFFECT IN ELECTROCHEMICAL AND FERRICYANIDE OXIDATIONS OF *para*-SUBSTITUTED 1-BENZYL-3-CARBAMOYL-1,4-DIHYDROPYRIDINES*

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Half-wave potentials $E_{1/2}$ of electrochemical oxidation of the title 1,4-dihydropyridine derivatives with the substituents $N(CH_3)_2$, OCH_3, CH_3, H, F, Cl, $COOCH_3$, and CN have been measured on platinum rotating disc electrode in aqueous and anhydrous dimethylformamide, and apparent rate constants k_2 of their oxidation with potassium ferricyanide have been measured in water at 298 K. The two quantities ($E_{1/2}$ and k_2) have been correlated both mutually and with empirical σ_p constants of the substituents. The found correlation relations have been discussed with respect to mechanism of the two transformations investigated.

Electrochemical oxidation of reduced form of NAD(P)H coenzyme and its bio-organic models type *I* can proceed by a mechanism more or less similar to the initial step of enzymatic process. From the point of view of coenzyme component, the two processes can be summarily expressed by Eq. (*A*) indicating that anode or the substrate reduced biochemically take two electrons from 1,4-dihydropyridine derivative *I* with simultaneous deprotonation giving pyridinium ion *II* or the oxidized form of NAD coenzyme, respectively[1-4].

$$+ 2e^- + H^+ \qquad (A)$$

$$I \qquad\qquad II$$
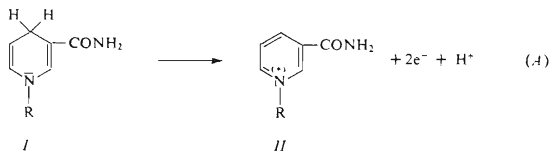
Polarograms of aqueous[4] and anhydrous[5] solutions of the depolarizers type *I* exhibit one two-electron anodic wave corresponding to overal irreversible process[4], its half-wave potential $E_{1/2}$ being independent of the proton concentration within the pH range 7 to 13. The consumption of two electrons was verified independently[3,5] by chronometry and coulometry, the formation of products *II* was proved[3,4] by macro-

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electrolysis with controlled potential. The studies by Blaedel and Haas[3,6] and Leduc and Thevenot[4,7] revealed that the whole electrochemical process involves at least two steps. In the first step one electron is abstracted to give radical cation III, in the second step which is not well-understood yet the intermediate III is further transformed to quaternary ion II according to Eq. (B).

$$I \xrightarrow{-e^-} \underset{III}{\underset{R}{\overset{H\ H}{\left\|\ \right\|}}\text{—CONH}_2} \xrightarrow{-e^-\ -H^+} II \qquad (B)$$
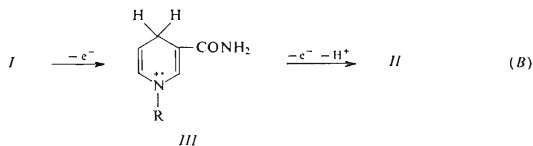
Obviously similar mechanism also applies to the ferricyanide oxidation[1,2] of 1,4-di-hydro derivatives I. Grishin and Yasnikov arrived at a conclusion[1,8] that the first two steps in the process (C) are rate-limiting (within one single charge–transfer complex with the oxidizing agent), oxidation of radical IV being thus very rapid. The same conclusion was arrived at independently by Okamoto and coworkers[2] who found the oxidation rate of the 1,4-dihydro derivative I ($R = n\text{-}C_3H_7$) to be increased with basicity of medium. The further kinetic studies[9–11], too, can be interpreted in accordance with the two first reaction steps $I \to III$ and $III \to IV$ playing decisive role.

The processes (B) and (C) show thus obvious mechanistic similarity, although the former takes place at the surface of an electrode, and the latter is realized probably in ligand sphere of iron ions.

$$I \xrightarrow{-e^-} III \xrightarrow{-H^+} \underset{IV}{\underset{R}{\overset{H}{\left\|\ \right\|}}\text{—CONH}_2} \xrightarrow{-e^-} II \qquad (C)$$
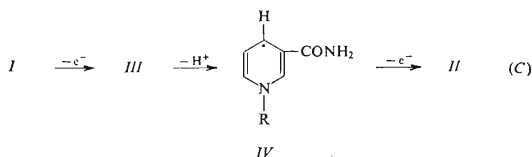
The aim of the present communication is to bring further information about character of the said processes on the basis of confrontation of reactivity–structure relations. For this purpose we have chosen quantitative evaluation of substituent effects in a series of 1-(para-substituted benzyl)-3-carbamoyl-1,4-dihydropyridines Ia ($X = N(CH_3)_2$, OCH_3, CH_3, H, F, Cl, $COOCH_3$, and CN) based on correlations of half-wave potentials $E_{1/2}$ of oxidation and apparent rate constants $\log k_2$ of ferricyanide oxidation. Available literature data[3,4,6,7] give the $E_{1/2}$ values of the

compounds I with R = CH_3, n-C_3H_7, i-C_3H_7, $C_6H_5CH_2$, and 2,6-$Cl_2C_6H_3CH_2$ but without evaluation of the substituent effects. The substituent effects in the ferri-cyanide oxidation of compounds Ia have not been studied yet. Another reaction series of compounds I (R = CH_3, CH_2CH_2OH, CH_2CONH_2, CH_2COCH_3, $CH_2CO_2CH_3$, CH_2OCH_3, and CH_2CN) was used[12] in a study of oxidation kinetics of flavine. The substituent effects exhibited the Taft relation except for the data for R = CH_2OCH_3.

EXPERIMENTAL

The melting points are not corrected and were measured with a Boetius apparatus (GDR). The UV spectra were measured with a Spekord UV-VIS apparatus (GDR), and the ^{1}H NMR spectra were measured with a Varian XL-100 (100 MHz, tetramethylsilane as internal standard, $\delta = 0$ ppm). The elemental analyses were carried out in Central Laboratories of our Institute.

TABLE I

Physico-chemical characteristics of the compounds Ia

Substituent X (yield, %)	M.p.$_{exp}$, °C (m.p. (ref.))	Formula (mol.mass)	Calculated/Found		
			% C	% H	% N
N(CH_3)$_2$ (58)	109—112 —	$C_{15}H_{19}N_3O$ (257·3)	70·29 69·98	7·08 7·37	16·39 16·18
OCH_3 (68)	109—112 —	$C_{14}H_{16}N_2O_2$ (244·3)	68·33 68·36	6·60 6·58	11·47 11·09
CH_3 (59)	81—85 —	$C_{14}H_{16}N_2O$ (228·3)	73·66 73·43	7·06 6·73	12·27 11·90
H (48)	114·5—116 (120 (19))	$C_{13}H_{14}N_2O$ (214·3)	— —	— —	— —
F (41)	112—114 (112—114·5 (20))	$C_{13}H_{13}FN_2O$ (232·3)	— —	— —	— —
Cl (64)	128—130 (130—131 (21))	$C_{13}H_{13}ClN_2O$ (248·7)	— —	— —	— —
$COOCH_3$ (39)	107—110 —	$C_{15}H_{16}N_2O_3$ (272·3)	66·16 66·21	5·92 5·95	10·29 10·43
CN (88)	^{a} —	$C_{14}H_{13}N_3O$ (239·3)	70·28 70·33	5·48 5·45	17·56 17·60

^{a} The substance melts in a broad temperature interval at $t > 80°C$.

Preparation of the Starting Substances

1,4-Dihydropyridines *Ia* were prepared by reduction of chlorides of ions *IIa* with dithionite, synthesis of *IIa* was described in the previous communication[13]. The reduction was carried out in the standard way[14] with sodium dithionite and carbonate in water. The precipitated raw product *Ia* crystallized on cooling and mechanical initiation. The compounds *Ia* were recrystallized from ethanol (1 : 1) and characterized by their melting points, elemental analyses, UV and ^{1}H NMR spectra (Table I and II). The attempts to prepare the derivative *Ia* with X = = NO$_2$ failed due probably to rapid reduction of nitro group with dithionite and subsequent decomposition of the *p*-amino derivative of *IIa* formed in aqueous medium (see the analogous finding[13] with the compound *IIa*, X = N(CH$_3$)$_2$).

Electrochemical Measurements

The electrochemical oxidation of compounds *Ia* was carried out in a three-electrode connection with a platinum rotating disc as indication electrode, saturated calomel reference electrode, and platinum working electrode with a Radelkis OH 102 apparatus (Hungary). The platinum rotating electrode and its adjustment for measurements in inert atmosphere were carried out in Central workshop of J. Heyrovský Institute of Physical Chemistry and Electrochemistry, Czechoslovak Academy of Sciences; revolutions per minute were measured with a RE-01 apparatus for regulation and stabilization of rotation of sample electrode (VPZ Běchovice). The electrochemical characteristics were measured in 0·05M phosphate buffer (containing 20% dimethylformamide) of pH > 7 and in anhydrous dimethylformamide containing 0·045 mol l^{-1} (C$_2$H$_5$)$_4$NClO$_4^{(-)}$ as the basic electrolyte in nitrogen atmosphere. The cross section of the working electrode measured 7·07 mm^2. pH Values of the solutions investigated were measured with a pH-Meter PAK 1 (ČSSR) after each recording of polarographic curve. The logarithmic analyses of the polarographic curves were carried out with the use of available program[15]. For the electrochemical oxidations of compounds *Ia* on the "pure" surface of platinum rotating electrode, the electrode was purified before each measurement with fine abrasive paper, washed with water and ethanol, and dried with filter paper. Then the electrode was left to rotate 2 min at 0 V. In other cases, the surface of the electrode was modified according to Blaedel and Jenkins[16]. The rate of potential change during recording of the polarographic curves was 2 mV s^{-1} from 0 V to positive potentials. The resulting oxidation curves were obtained by correction with respect to the current of the basic solution. The obtained electrochemical data are given in Table III.

Kinetic Measurements

Oxidation of compounds *Ia* with ferricyanide was followed spectrophotometrically with a Spekord UV-VIS (Zeiss, Jena) in a thermostatted cell at 298 ± 0·1 K. All the reactions of compounds *Ia* with K$_3$Fe(CN)$_6$ were carried out in aqueous solutions containing 20% ethanol at pH 11·1 (adjusted by addition of K$_2$CO$_3$) at ionic strength $\bar{\mu}$ = 0·1 (adjusted by addition of KCl). The reaction was started by addition of 40 μl solution of compound *Ia* in ethanol to 2 ml solution of K$_2$Fe(CN)$_6$, and its course was followed (as in refs[1,2]) by recording time dependence of absorbance of the solution at the long-wave absorption maximum of the respective 1,4-dihydro derivative *Ia*. The oxidation of compounds *Ia* is known[1,2] to obey well the kinetic equation

$$-\mathrm{d}c/\mathrm{d}t = k_2[\mathrm{I}][\mathrm{Fe(CN)}_6^{3-}] \, . \tag{1}$$

TABLE II
^{1}H NMR spectra of the compounds Ia and characteristic absorption bands of Ia in UV spectra

Substituent X	λ_{max}, nm (log ε)		δ, ppm						
	ethanol	CH_3CN	H-4[a]	—CH_2—	H-5[a]	$CONH_2$	H-6[a]	H-2[a]	—C_6H_4—
$N(CH_3)_2$	222 (3·97) 360 (3·69)	307 (4·15) 376 (3·28)	3·1[b]	4·12 s	4·66 m	5·3[c]	5·7 d[d]		6·86 dd[e,f]
OCH_3	225 (4·18) 354 (3·85)	308 (4·44) 377 (3·4)	3·14[b]	4·18 s	4·69 m	5·3[c]	5·68 d[d]		6·99 dd[e,g]
CH_3	220 (4·28) 355 (3·64)	308 (3·81) 373 (3·09)	3·15[b]	4·21 s	4·73 m	5·35[c]	4·7 d[d]		7·21 dd[e]
H	215 (4·22) 354 (3·83)	308 (4·51) 373 (3·25)	3·15[b]	4·25 s	4·71 m	5·48[c]	5·69[d]	7·12 s	7·25 s
F	218 (4·19) 353 (3·79)	307 (4·43) 374 (3·39)	3·14[b]	4·22 s	4·51 m	5·62[i]		7·1 m[e]	
Cl	221 (4·19) 357 (3·19)	307 (3·93) 374 (3·1)	3·15[b]	4·22 s	4·72 m	5·43[c]	5·68 d[d]		7·22 dd[e]
$COOCH_3$	234 (4·29) 354 (3·83)	307 (4·49) 374 (3·43)	3·15[b]	4·21 s	4·73 m	5·66[i]		7·09 s	7·64 dd[d,j]
CN	224 (4·46) 355 (3·77)	308 (4·4) 375 (3·37)	3·17[b]	4·33 s	4·76 m	5·43[c]	5·68 d[a]	7·08 s	7·48 dd[d]

[a] The protons at the pyridine nucleus; [b] broadened singlet; [c] broadened signal; [d] $^3J_{HH} = 8$ Hz; [e] overlapping signals; $^3J_{HH} = 8 - 9$ Hz; [i] overlapping signals; [j] $COOCH_3$; $\delta = 3·88$ ppm (s).
[f] $N(CH_3)_2$; $\delta = 2·95$ ppm (s); [g] OCH_3; $\delta = 3·76$ ppm (s); [h] CH_3; $\delta = 2·33$ ppm (s);

TABLE III
Electrochemical oxidation of the compounds Ia on platinum rotating electrode. Composition of the solution measured: solution A: $5 . 10^{-4}$ mol . l^{-1} compound Ia, phosphate buffer, pH 7·6, 10% dimethylformamide; solution B: solution A + $5 . 10^{-4}$ mol . l^{-1} compound IIa; solution: $5 . 10^{-4}$ mol . l^{-1} compound Ia, 0·045 mol l^{-1} $(C_2H_5)_4 N ClO_4^{(+)(-)}$, anhydrous dimethylformamide, speed of the platinum rotating electrode 1 500 r.p.m.

Substituent X	Solution A/solution B			Solution A^a/solution B^b		Solution C		
	$E_{1/2}$, V	$\bar{I}_d . 10^5$, A	$RT/\alpha n F$, mV^c	$E_{1/2}$, V	$\bar{I}_d . 10^5$, A	$E_{1/2}$, V	$\bar{I}_d . 10^5$, A	$RT/\alpha n F$, mV^c
N(CH$_3$)$_2$	0·400	1·90	119·8	0·507	0·84	0·613	3·23	157·3
	—	—	—	—	—			
OCH$_3$	0·459	2·30	122·7	0·470	1·8	0·642	3·42	164·9
	0·470	2·26	—	0·490	1·9			
CH$_3$	0·470	2·14	116·1	0·500	1·8	0·643	3·21	135·1
	0·480	2·04	—	0·507	1·8			
H	0·505	2·49	124·5	0·507	2·0	0·658	3·22	145·2
	0·506	2·45	—	0·518	2·1			
F	0·516	2·28	129·1	0·518	1·9	0·676	2·86	156·5
	0·478	2·21	—	0·490	1·9			
Cl	0·490	2·26	121·8	0·529	1·8	0·655	3·11	150·3
	0·522	2·16	—	0·569	2·0			
COOCH$_3$	0·475	2·30	113·8	0·487	1·9	0·677	3·10	154·3
	0·493	2·30	—	0·514	2·2			
CN	0·492	1·78	121·0	0·159	1·5	0·680	2·56	153·5
	0·510	1·73	—	0·524	1·6			

^{a} After 1 h electrolysis at 0·7 V; ^{b} after 0·5 h electrolysis at 0·7 V; ^{c} the values calculated from logarithmic analyses of the polarographic curves.

In our case the concentrations [I] and $[Fe(CN)_6^{3-}]$ were always $1 . 10^{-4}$ mol l^{-1} and 0·980 to $5·88 . 10^{-3}$ mol l^{-1}, respectively, so the oxidation course could have pseudomonomolecular nature. The relation (*1*) was simplified to

$$-dc/dt = k_{obs}[I] ,$$

and the apparent oxidation rate constant was evaluated as the slope of the dependence $\ln A_t = k_{obs}(t_0 - t_t) + \text{const.}$, where A_t means the absorbance of the reaction mixture at the time *t*. The apparent second order rate constant k_2 was calculated from the found k_{obs} value according to the relation $k_2 = k_{obs}/[Fe(CN)_6^{3-}]$. It was shown[1,2,8-12] that the reaction rate of (*C*) is also affected by concentration of base and by the presence of alkali metals, which made us to consider the k_2 values of the simplified expression (*1*) as apparent. With respect to these circumstances the aqueous solutions of compounds *Ia* used in the kinetic runs had constant pH and K$^+$ ion concentration in all cases. The k_{obs} values were obtained by submitting the experimental data to the least squares treatment using a Hewlett–Packard 21 MX computer (the correlation coefficient $r \geqq 0·999$). Accuracy of determination of the k_2 constants is assessed at $\geqq 95\%$ (Table IV).

RESULTS AND DISCUSSION

Electrochemical Oxidation

First of all, behaviour of compounds *Ia* was examined in solutions in anhydrous dimethylformamide. Table III shows that the oxidation proceeds in wave which, according to dependence of the current on the depolarizer concentration and r.p.m. of the electrode, has diffusion character. As two-electron mechanism was verified[4]

TABLE IV

Rate constants of oxidation of the compounds *Ia* with ferricyanide in aqueous medium. Composition of the solution measured: $1 . 10^{-4}$ mol l^{-1} compound *Ia*, 20% ethanol, pH 11·1, ionic strength $\mu = 0·1$, $t = 298·15 \pm 0·1$ K

Substituent X	$c_{Fe(CN)_6^{3-}}$ $. 10^{-3}$ mol l^{-1}	k_2 1 mol^{-1} s^{-1}
N(CH$_3$)$_2$	0·98—1·96	28·90 $\pm$ 1·09
OCH$_3$	1·96—3·92	13·13 $\pm$ 0·10
CH$_3$	1·96—3·92	10·49 $\pm$ 0·12
H	1·96—3·92	8·89 $\pm$ 0·58
F	1·96—3·92	6·52 $\pm$ 0·25
Cl	1·96—3·92	4·13 $\pm$ 0·17
COOCH$_3$	2·94—4·90	2·37 $\pm$ 0·19
CN	3·92—5·88	1·53 $\pm$ 0·10

for the derivative Ia with X = H, and also the other derivatives show waves of similar height, this feature of the electrode process can be considered identical in the whole series. Also the irreversible character of the process (B) was verified for the whole series of compounds Ia by logarithmic analysis of the polarographic curves whose values $RT/\alpha n F$ vary within the limits from 135 to 164 mV. In Fig. 1 the $E_{1/2}$ values are plotted against the Hammett σ_p constants of the substituents X. It can be seen that *para*-fluoro derivative Ia deviates distinctly from the correlation[17]

$$E_{1/2} = \varrho_{\pi,R}\sigma_p + const. ,\qquad (2)$$

its electrooxidation taking place at potentials by about 0·02 V more positive than those corresponding to the found reaction constant $\varrho_{\pi,R} = 0\cdot045\ (r = 0\cdot980)$. It can be presumed that the electrical process can, in this case, be expressed by scheme

$$Ia\ +\ HCON(CH_3)_2\ \xrightarrow{-e^-}\ [IIa.HCON(CH_3)_2]^{\overset{+}{\cdot}}\ \rightarrow$$

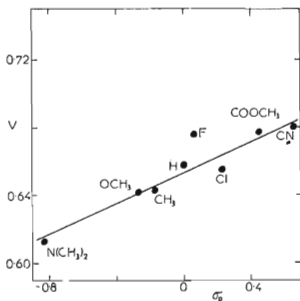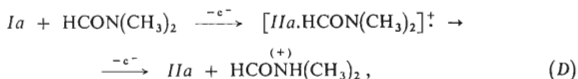$$\xrightarrow{-e^-}\ IIa\ +\ \overset{(+)}{HCONH}(CH_3)_2 ,\qquad (D)$$

Fig. 1

Correlation of the $E_{1/2}$ values of oxidation of the compounds Ia on platinum rotating electrode in anhydrous dimethylformamide with the σ_p constants of the substituents X
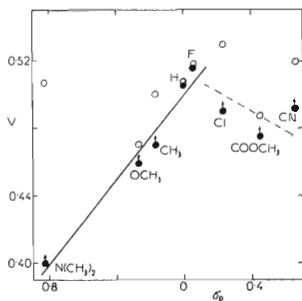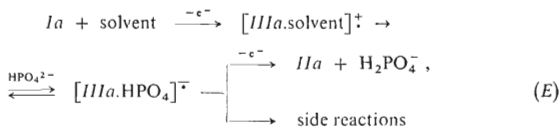
Fig. 2

Correlation of the $E_{1/2}$ values of oxidation of the compounds Ia on platinum rotating electrode in aqueous medium (10% dimethylformamide) with the σ_p constants of the substituents X. ● Oxidation at "pure" surface of the platinum rotating electrode; ○ oxidation on the surface of platinum rotating electrode modified according to ref.[16]

in which the intermediate with solvent (*i.e.* dimethylformamide) has identical charge with the rotating platinum electrode and, therefore, is adsorbed only slightly at its surface. As the substituents X with more positive σ_p value should stabilize the 1,4-dihydro derivatives *Ia* by polar effects, and, on the contrary, they should destabilize the radical cations *IIIa*, the positive sign of reaction constant indicates that the first

Ia   *IIa*   *IIIa*
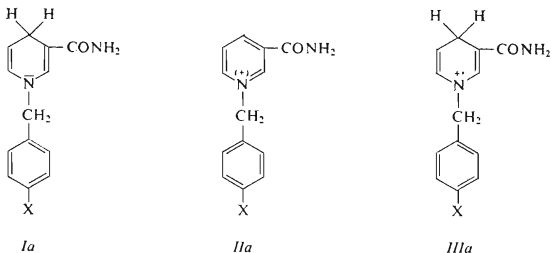
step of the process (*D*) is dominant. The above-mentioned deviation for X = F could be explained by retardation of the second step of the sequence (*F*) due to formation of hydrogen bond C—F...H$^+$ whose dissociation energy would be surmounted by increased potential at the electrode or by formation of a firmer associate with participation of water molecules (traces of humidity in solvent). Electrochemical behaviour of compounds *Ia* in aqueous solutions (10% dimethylformamide and phosphate buffer) appeared more complex and less easily interpretable (Table III). Although the oxidation of all the studied depolarizers *Ia* takes place in a single wave of diffusion character and irreversibly (the values $RT/\alpha nF$ within the limits from 114 to 129 mV), the average value of the diffusion current $\bar{I}_d$ is lower (*i.e.* $2.2 \cdot 10^{-5}$ A) as compared with the value $3.1 \cdot 10^{-5}$ A for the above-mentioned solutions in net dimethylformamide. The last finding suggests a possibility of side non-electrochemical reactions of intermediates *IIIa*. However, a much more important finding was that reproducible $E_{1/2}$ values can only be obtained under suitably adjusted reaction conditions, which signalizes undoubted participation of adsorption effect in the polarographic process. Figure 2 presents the half-wave potentials $E_{1/2}$ obtained by measurement at the "pure" surface of platinum rotating electrode (full circles) and those obtained after one hour electrolysis at 0·7 V according to Blaedel and Jenkins[16] (empty circles) plotted against the σ_p constants of the substituents X. In the former case the data for the substituents with $\sigma_p < +0.1$ (*i.e.* X = N(CH$_3$)$_2$, OCH$_3$, CH$_3$, H, F) obey the Hammett correlation (2) with the reaction constant $\varrho_{\pi,R} = = 0.127$ ($r = 0.985$), whereas the points belonging to more electron-acceptor substituents (X = Cl, COOCH$_3$, and CN) deviate distinctly towards less positive potentials.

In the latter case the $E_{1/2}$ potentials assume considerably positive values and do not show any clear substituent effect. These findings were interpreted on the basis of the following scheme of electrochemical process:

$$Ia + \text{solvent} \xrightarrow{-e^-} [IIIa.\text{solvent}]^{\ddagger} \rightarrow$$

$$\xrightleftharpoons{\text{HPO}_4{}^{2-}} [IIIa.\text{HPO}_4]^{\ddagger} \begin{array}{c} \xrightarrow{-e^-} IIa + H_2PO_4^-, \\[4pt] \\ \longrightarrow \text{side reactions} \end{array} \qquad (E)$$

which involves a transformation of the positively charged and little adsorbed intermediate into the negatively charged and, hence, strongly adsorbed complex of radical cations $IIIa$ with the buffer anion, the complex being further oxidized or submitted to side non-electrochemical reactions. In the reaction at the "pure" surface of platinum rotating electrode the process (E) is controlled by the said formation
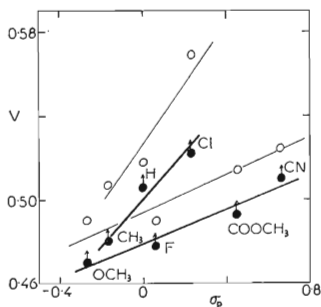

Fig. 3

Correlation of the $E_{1/2}$ values of oxidation of the compounds Ia on platinum rotating electrode in aqueous medium (10% dimethylformamide) in the presence of equimolar amounts of the compounds IIa with the σ_p constants of the substituents X. ● Oxidation on "pure" surface of the platinum rotating electrode; ○ oxidation on the surface of platinum rotating electrode modified according to ref.[16]
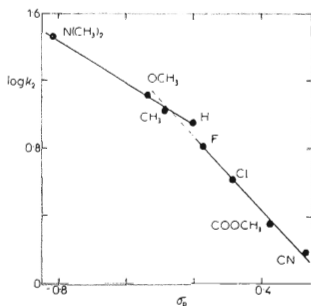
Fig. 4

Correlation of log k_2 values of oxidation of the compounds Ia with ferricyanide *versus* the σ_p constants of the substituents X

of the slightly adsorbed complex, and the $E_{1/2}$ values are affected by electronic effects of the substituents X. After 1 h electrolysis, the equilibria between the both complexes of the process (E) are obviously established at the surface of the platinum rotating electrode, so due to adsorption and desorption phenomena the $E_{1/2}$ values cease to be affected by substituent effect. Furthermore, we modified the electrochemical chemical experiments according to ref.[16], *i.e.*, we analyzed aqueous solutions of equimolar mixtures of the starting 1,4-dihydro derivative *Ia* and the corresponding product (ion *IIa* in the form of the respective quaternary chloride[13]). In this approach we had to exclude *o*-dimethylamino derivative *Ia* because of insufficient stability of the corresponding quaternary ion *IIa* $(X = N(CH_3)_2)$ in aqueous medium[13]. In Fig. 3 the $E_{1/2}$ values (Table III) measured in fresh solutions (full circles) and in the solutions electrolyzed at 0·7 V for 30 min (empty circles) are plotted against σ_p constants of the substituents X. Obviously, in both cases the field of points is divided (from the point of view of the Hammett correlation (2)) into two correlation straight lines *A* and *B* with $\varrho_{\pi,R}^A = 0.103$ $(r = 0.975)$ and 0.159 $(r = 0.962)$, respectively, and $\varrho_{\pi,R}^B = 0.042$ $(r = 0.973)$ and 0.039 $(r = 0.945)$, respectively, the set *A* involving the substituents $X = CH_3$, H, and Cl unable of formation of effective hydrogen bonds, whereas the set *B* involves the substituents $X = OCH_3$ F, $COOCH_3$, and CN able of formation of the bonds type $X \cdots H$. This finding is interpreted on the basis of the presumption that the electrochemical process follows the scheme (F).
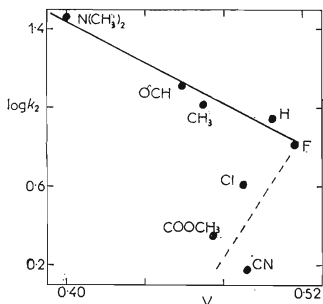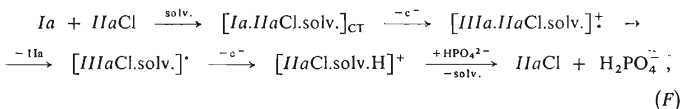
$$Ia + IIaCl \xrightarrow{\text{solv.}} [Ia.IIaCl.\text{solv.}]_{CT} \xrightarrow{-e^-} [IIIa.IIaCl.\text{solv.}]^{\ddagger} \rightarrow$$

$$\xrightarrow{-IIa} [IIIaCl.\text{solv.}]^{\cdot} \xrightarrow{-e^-} [IIaCl.\text{solv.H}]^+ \xrightarrow[-\text{solv.}]{+HPO_4^{2-}} IIaCl + H_2PO_4^{-};$$

$$(F)$$

Fig. 5

Correlation of $\log k_2$ values of oxidation of the compounds *Ia* with ferricyanide with the $E_{1/2}$ values of oxidation of the same compounds on platinum rotating electrode in aqueous medium

where the symbol solv. denotes a certain number of molecules of the solvating solvent (predominantly water), and CT means charge-transfer complex between the π-donor 1,4-dihydro derivative Ia and π-acceptor pyridinium ion IIa. The splitting of correlation in Fig. 3 can be explained by different extent of solvation by means of hydrogen bridges in the individual complexes and/or by the therewith connected typical orientation of the Ia and $IIIa$ depolarizers in electrode double layer. The shift of $E_{1/2}$ values towards more positive potentials after 30 min electrolysis is perhaps connected with formation of a layer of adsorbed complexes of Scheme (F) at the surface of platinum rotating electrode.

Ferricyanide Oxidation

From Table IV it follows that values of the apparent rate constants k_2 are strongly affected by substituent effects; among the derivatives Ia they are decreased 19 times on going from $X = N(CH_3)_2$ to $X = CN$. Figure 4 presents the kinetic characteristics $\log k_2$ plotted against σ_p constants of substituents X. Obviously, the Hammett correlation (3) can be interpreted in two ways in this case, *viz.* (i)

$$\log k_2 = \varrho\sigma_p + \text{const.} \qquad (3)$$

as a close correlation with $\varrho = -1.04$ ($r = 0.994$) for all the substituents X except for $X = N(CH_3)_2$ or (ii) as splitting of the correlation field into two parts: one for electron-donor substituents X ($\sigma_p \leqq 0$) with $\varrho' = -0.629$ ($r = 0.997$) and the other for the electron-acceptor X's ($\sigma_p > 0$) with $\varrho'' = -1.054$ ($r = 0.998$). The former interpretation must presume in the whole series Ia that for the reaction constants of the first two steps of the process (C) it is $\varrho \simeq \varrho_{I-III} \gg \gg \varrho_{III-IV}$ and/or $\varrho \simeq \varrho_{III-IV} \gg \varrho_{I-III}$. The exceptional behaviour of the p-dimethylamino derivative Ia could be explained by unusually efficient stabilization of the intermediate $IIIa$ ($X = N(CH_3)_2$) or, perhaps, by inhibition effects of the nicotinamide which is formed by decomposition of the quaternary ion IIa ($X = N(CH_3)_2$) in aqueous medium[13]. It is, of course, difficult to explain why some of the compounds Ia or $IIIa$ should be practically unaffected by substituent effect, and, therefore, this interpretation of situation in Fig. 4 is considered little justified. If we admit the second interpretation version, *i.e.*, operation of substituent effect in the both first steps of the process (C), then, obviously, the correlation Eq. (3) must be considered in the form

$$\log k_2 = (\varrho_{I-III} + \varrho_{III-IV})\,\sigma_p + \text{const.}$$

As already mentioned the electronic effect of substituents R on reactivity of the molecules I and III should by just opposite, because electron-donor substituents X ($\sigma_p \leqq 0$) will destabilize the π-donor 1,4-dihydro derivatives Ia and stabilize the

π-acceptor radical cations *IIIa*, whereas electron-acceptor substituents X $(\sigma_p > 0)$ will have opposite effects. The observed values $\varrho' = \varrho'_{I-III} + \varrho'_{III-IV}$ for electron-donor substituents and $\varrho'' = \varrho''_{I-III} + \varrho''_{III-IV}$ for electron-acceptor substituents should thus be generally different, *i.e.*, in accordance with the second interpretation version of the situation in Fig. 4. With respect to character of the process (C) and to structure of compounds *Ia* it can be expected that it will be always $\varrho_{I-III} < 0$ and $\varrho_{III-IV} > 0$, the absolute values being $|\varrho'_{I-III}| \geqq |\varrho''_{I-III}|$ and $|\varrho'_{III-IV}| > |\varrho''_{III-IV}|$. As Fig. 4 shows that $\varrho'' < \varrho' < 0$, this presumption can further mean that the splitting of the correlation dependence is due to a more distinct stabilization of radical cations *IIIa* by electron-donor substituents X. This means that these intermediates will undergo most likely subsequent transformations in the sense of scheme (C) just in the cases of these substituents, whereas in the case of electron-acceptor substituents the destabilization of intermediates *IIIa* can lead to their decomposition by other (*e.g.* disproportionation) reactions[18]. As a consequence thereof it can be expected that similarly of the reaction processes (B) and (C) will be more likely fulfilled for electron-donor substituents. To verify this presumption, we plotted the kinetic characteristics $\log k_2$ against the $E_{1/2}$ potentials. From 5 it is obvious that there really exists a correlation for substituents with $\sigma_p \leqq 0$ (X = $N(CH_3)_2$, OCH_2, CH_3, H and F)

$$\log k_2 = -5{\cdot}25 E_{1/2} + 3{\cdot}54 \quad (r = 0{\cdot}985),$$

whereas the points for the substituents with $\sigma_p > 0$ are distinctly deviated. This finding seems to support our hypothesis.

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