

Concurrent Anodic Cyanation and Methoxylation of Methylated Furans. Oxidation Potential and Reactivity, and Stereochemical Control of Addition

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(Received June 23, 1986)

The potentiostatic electrooxidation of a series of methyl-substituted furans was performed in MeOH that contains NaCN at a Pt anode in a divided cell. In all instances, the 1,4-additions of cyano and/or methoxyl group(s) across the furan ring were achieved. Replacement of an aromatic hydrogen by a cyano group occurred concurrently in some cases. The relative rates of cation radicals toward two different nucleophiles (CN^- ion and the solvent MeOH (or the MeO^- ion as a result of the equilibrium between CN^- ion and the solvent MeOH)) at the electrode surface were determined from the yields of products by using the rate expressions of competitive reactions. There is a linear correlation between the relative reactivity of the furans (on a log scale) and their oxidation potential. The ratio of stereoisomers formed in an electrooxidation of 2,5-dimethylfuran (2,5-DMF) changes with addition of adsorbable compound as well as substrate concentration and this is thought to be due to the influence of concentration (or coadsorbate) on substrate orientation in the adsorption layer.

Previously we reported the electrooxidation of 2,5-dimethylfuran (2,5-DMF) in MeOH that contains NaCN.^{1–4)} Stereoselective 1,4-addition of cyano and/or methoxyl group(s) to the furan ring occurred. The process consists of two successive competitive reactions; the first one is addition of two different nucleophiles, CN^- ion and the solvent MeOH (or the MeO^- ion as a result of the equilibrium between CN^- and MeOH), to the 2,5-DMF cation radical and the second one is to the benzenium-type ion formed by means of an ECE process. If this system is applied to a series of sequentially substituted furans, the mode and yields of products may well reflect the competitive reactions toward each cationic intermediate. It should provide information on the relative reactivity of a series of related cations toward two competing nucleophiles at the electrode.

In an attempt to determine the relative concentrations of those two nucleophiles at the electrode from oxidation products of 1,4-dimethoxybenzene (1,4-DMB) in the same solvent–electrolyte system using a competitive technique, Weinberg and co-workers assumed that the relative rates of 1,4-DMB cation radical and of substituted benzenium ions toward two nucleophiles would be both equal to those of relatively stable carbenium ions such as triarylmethyl cations, arenediazonium ions, and tropylium ions.⁵⁾ There is, however, no foundation for such a hypothesis. The idea that the relative (if not absolute) reactivity changes with the structure is rather natural.

The present paper describes the competitive anodic cyanation and methoxylation of a series of sequentially methyl-substituted furans. The relative reactivity of furans cation radicals toward two competing nucleophiles at the electrode has been estimated by studying the products. The relative reactivity changes widely with the substrate structure, and correlates with the oxidation potential at that. Addition to the furan

ring, especially the second nucleophilic addition, is sterically controlled by the electrode. The influence of substrate concentration, aromatic additive, and electrode material on the ratio of stereoisomeric products has been investigated.⁶⁾

Results

Cyclic Voltammetry (CV). Cyclic voltammograms were recorded for each compound using a solution of 0.4 M[†] NaCN in MeOH. The background current with this system began to increase at potentials more anodic than 1.60 V. The E_p values are collected in Table 2. 2,5-DMF gave a single anodic peak. The electrochemical data revealed that the height of the peak varied linearly with concentration, and there was no evidence of a reversible cathodic peak for any of the furans. The current function, $i_p/v^{1/2}$, where i_p is the peak current and v is the sweep rate, decreased, and E_p shifted more positive with increasing sweep rate. Similar voltammetric data were noted for other substituted furans (Table 1). All of the preceding data are consistent with a fast chemical reaction following the electron transfer.

Product Studies. The reactions were performed potentiostatically in a divided cell with a Pt anode at room temperature. The reference electrode was an SCE. The electroreaction medium was MeOH–0.4 M NaCN. The products were isolated by preparative GLC and were identified by the elemental and ^1H NMR, IR, and mass spectroscopic analyses.

The 1,4-addition of cyano and/or methoxyl group(s) across the diene system of a furan took place for all of the molecules investigated, and besides the replacement of an aromatic hydrogen by a cyano group at a free 2 (or 5) position occurred concurrently

[†] 1 M=1 mol dm^{−3}.

for furans lacking the substituent on either 2 or 5 (or both) position(s). Nuclear cyanation at the 3 position also occurred slightly for 2,5-DMF. In some cases,

Table 1. Cyclic Voltammetric Data for the Electro-oxidation of Methylated Furans in 0.4 NaCN-MeOH^{a)}

Compd	Sweep rate, mV/s	i_p , mA	$i_p/v^{1/2}$, mA s ^{1/2} /V ^{1/2}	E_p , V vs. SCE
2,5-DMF	10	1.3	13.0	1.28
	50	2.4	10.7	1.33
	100	3.1	9.8	1.35
	300	5.2	9.5	1.42
2,3,4-TMF	30	1.9	11.0	1.33
	100	2.9	9.2	1.37
	300	4.3	7.8	1.48
2,3,5-TMF	10	1.1	11.0	1.16
	100	2.8	8.9	1.25
	300	4.4	8.0	1.32
TetMF	10	1.0	10.0	1.06
	100	2.8	8.9	1.13
	300	4.2	7.7	1.24

a) Pt wire electrode, 0.322 cm². 2×10^{-2} M substrate.

small amounts of side-chain-methoxylation products were produced. Some of cyanation products undergo base-catalyzed reaction^{5,7)} in the reaction medium, yielding methyl imidates. Small amounts of 1,4-dicarbonyl compounds and their monoacetals were occasionally obtained. Structural formulas of products are shown below and the results of preparative electroreduction are given in Table 2. The Table also contains the results of both the electro-oxidation of 2,5-diethylfuran (2,5-DEF) in the same solvent-electrolyte system and the electroreduction of 2,5-DMF in EtOH that contains NaCN.

Structure of Isomeric Pairs. The extensive and detailed studies on geometrical isomerism in 2,5-dihydro-2,5-dimethoxyfurans⁸⁻¹¹⁾ make possible the structural assignments to isomeric pairs of the relevant 1,4-mixed addition products. The basis for the structural assignments resides in the fact that the chemical shift of a group in the 2 position of the furan ring is affected both by the other group at the 2 position and the magnetic influence exerted by the group at the 5 position that is cis to it. Thus, if a 2-methyl is cis to a 5-methoxyl (or a 5-cyano) it will resonate at lower field and raise the δ value than if it is

Table 2. Electrooxidation of Furans. Voltammetric Data and Products^{a)}

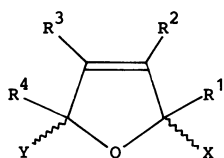
Compd	E_p , V ^{b)}	Product	Isomer ratio (cis/trans)	CE ^{c)} %	Compd	E_p , V ^{b)}	Product	Isomer ratio (cis/trans)	CE ^{c)} %
Unsubstituted	≈ 2.0	1a	1.7	27 ^{d)}	2,5-DMF ^{f)}		1y^{g)}	3.4	53
		3a		0.5			1z	0.4	5
2-MF	1.61	1b	0.8	10			2m		Trace
		1c	1.6	32	3,4-DMF	1.61	2h		3
		2a		5			2i		1
3-MF	1.78	2b		0.5			1m		3
		1d	1.3	63			1n	1.5	60
		3b		0.5	2,3,4-TMF	1.37	1o	1.2	22
2,3-DMF	1.51	1e	2.0	27			1p		7
		1f	1.1	17			1q	1.2	13
		3c		2			2j		11
2,4-DMF	1.55	1g	1.3	10			2k		9
		1h		1	2,3,5-TMF	1.25	1r		5
		1i		2			1s	2.7	71
		1j	1.0	28			1t	2.5	7
		2c		21			1u	0.5	1.5
		2d		7	TetMF	1.13	1v	1.0	14
		3d		2			1w	3.2	75
2,5-DMF	1.35	1k	2.5	69			1x		Trace
		1l	0.5	3			2l		Trace
		2e		2	2,5-DEF	1.36	1aa^{h)}	3.0	58
		2f		e)			1bb	1.0	2
		2g		e)					

a) Oxidation in MeOH solvent, unless otherwise stated. The potential was set at the peak potential of the substrate. b) Peak potential from CV; Pt anode, MeOH, 0.4 M NaCN, SCE reference. Sweep rate is 0.1 V/s. Substrate concentration is 2×10^{-2} M. All voltammograms showed no cathodic peak corresponding to reversible reduction of a cation radical. c) Current efficiency. d) The remainder of the current is consumed by concurrent discharge of the solvent-electrolyte system. e) A small amount. f) Oxidation in EtOH. g) Equilibrium mixture at room temperature: cis/trans=1.5. h) Equilibrium mixture at room temperature: cis/trans=1.7.

cis to another 5-methyl (or 5-protio) group (Table 3). The same reasoning can be applied to the methoxyl peaks and permits the indicated structural assignments for the two isomers.

Stereochemical Experiments. Table 4 summarizes the isomer compositions of the products of electro-oxidative cyanomethoxylation of 2,5-DMF conducted under various experimental conditions. The product mixture was analyzed in very early stages of the run to avoid the shift of the substrate concentration. Consequently, samples were withdrawn and analyzed after passage of 1 to 5% of the charge calculated for a two-electron transfer process, and the average of two or more runs was then taken to be the isomer ratio.

The reaction is sterically controlled by a Pt electrode. The ratio of the resultant stereoisomers depends on the concentration of the substrate, the highest value (3.1:1) being obtained in the most dilute solution. The ratio also changed with the type and concentration of aromatic additives. Among aromatic additives, 1,4-DMB and pyridine cause greater changes in the cis-to-trans ratio. On the contrary, addition of aromatic molecules such as bis(*p*-methoxyphenyl)-amine, triphenylamine, tris(*p*-bromophenyl)amine,

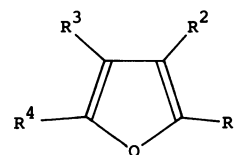


- 1a**, $R^1=R^2=R^3=R^4=H$; $X=Y=OMe$
1b, $R^1=Me$; $R^2=R^3=R^4=H$; $X=CN$; $Y=OMe$
1c, $R^1=Me$; $R^2=R^3=R^4=H$; $X=Y=OMe$
1d, $R^1=R^3=R^4=H$; $R^2=Me$; $X=Y=OMe$
1e, $R^1=R^2=Me$; $R^3=R^4=H$; $X=CN$; $Y=OMe$
1f, $R^1=R^2=Me$; $R^3=R^4=H$; $X=Y=OMe$
1g, $R^1=R^3=Me$; $R^2=R^4=H$; $X=CN$; $Y=OMe$
1h, $R^1=R^3=Me$; $R^2=R^4=H$; $X=C(OMe)=NH$; $Y=OMe$
1i, $R^1=R^3=Me$; $R^2=R^4=H$; $X=OMe$; $Y=CN$
1j, $R^1=R^3=Me$; $R^2=R^4=H$; $X=Y=OMe$
1k, $R^1=R^4=Me$; $R^2=R^3=H$; $X=CN$; $Y=OMe$
1l, $R^1=R^4=Me$; $R^2=R^3=H$; $X=Y=OMe$
1m, $R^1=R^4=H$; $R^2=R^3=Me$; $X=CN$; $Y=OMe$
1n, $R^1=R^4=H$; $R^2=R^3=Me$; $X=Y=OMe$
1o, $R^1=R^2=R^3=Me$; $R^4=H$; $X=CN$; $Y=OMe$
1p, $R^1=R^2=R^3=Me$; $R^4=H$; $X=OMe$; $Y=C(OMe)=NH$
1q, $R^1=R^2=R^3=Me$; $R^4=H$; $X=Y=OMe$
1r, $R^1=R^2=R^4=Me$; $R^3=H$; $X, Y=CN$, $C(OMe)=NH$
1s, $R^1=R^2=R^4=Me$; $R^3=H$; $X=CN$; $Y=OMe$
1t, $R^1=R^2=R^4=Me$; $R^3=H$; $X=OMe$; $Y=CN$
1u, $R^1=R^2=R^4=Me$; $R^3=H$; $X=Y=OMe$
1v, $R^1=R^2=R^3=R^4=Me$; $X=CN$
1w, $R^1=R^2=R^3=R^4=Me$; $X=CN$; $Y=OMe$
1x, $R^1=R^2=R^3=R^4=Me$; $X=Y=OMe$
1y, $R^1=R^4=Me$; $R^2=R^3=H$; $X=CN$; $Y=OEt$
1z, $R^1=R^4=Me$; $R^2=R^3=H$; $X=Y=OEt$
1aa, $R^1=R^4=Et$; $R^2=R^3=H$; $X=CN$; $Y=OMe$
1bb, $R^1=R^4=Et$; $R^2=R^3=H$; $X=Y=OMe$

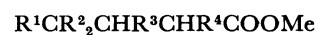
and tri-*p*-tolylamine, of which oxidation potentials are lower than that of the substrate, prevented the reaction. These aromatic compounds are apparently inert under the present conditions even though they discharge practically. The current is consumed by the regeneration of the additive as a consequence of homogeneous electron transfer between the electro-generated cation radical and CN^- ion.

In contrast to the Pt electrode, a vitreous C anode gives an isomer ratio approaching that of the equilibrium mixture.

Acid-Catalyzed Reactions of 1,4-Mixed Addition Products. It was confirmed that neither of the isomers *cis*-**1k** and *trans*-**1k** undergoes interconversion under the reaction conditions. Both of them also remained intact on GLC. However, a trace of a strong acid converted either isomer into an equilibrium mixture of the two isomers. To obtain a value for the equilibrium isomer composition, *cis*-*trans* isomerization was carried out in MeOH in the presence of 1% CF_3COOH at 25.0 °C. The equilibrium was reached within 1 h. The equilibrium value for the ratio *cis*-**1k**:*trans*-**1k** was 1.5:1. Moreover, a temperature change had a negligible effect on the K value at 0 to 100 °C. The acid-catalyzed isomerization also occurs in other solvents such as $CHCl_3$ and CCl_4 , but in EtOH it gives place to the alcohol exchange accompanying the isomerization equilibrium.



- 2a**, $R^1=Me$; $R^2=R^3=H$; $R^4=C(OMe)=NH$
2b, $R^1=C(OMe)=NH$; $R^2=Me$; $R^3=R^4=H$
2c, $R^1=R^3=Me$; $R^2=H$; $R^4=CN$
2d, $R^1=R^3=Me$; $R^2=H$; $R^4=C(OMe)=NH$
2e, $R^1=R^4=Me$; $R^2=CN$; $R^3=H$
2f, $R^1=CH_2OMe$; $R^2=R^3=H$; $R^4=Me$
2g, $R^1=CH_2OMe$; $R^2=R^3=H$; $R^4=CH_2OMe$
2h, $R^1=CN$; $R^2=R^3=Me$; $R^4=H$
2i, $R^1=C(OMe)=NH$; $R^2=R^3=Me$; $R^4=H$
2j, $R^1=R^2=R^3=Me$; $R^4=CN$
2k, $R^1=R^2=R^3=Me$; $R^4=C(OMe)=NH$
2l, $R^1=CH_2OMe$; $R^2=R^3=R^4=Me$
2m, $R^1=CH_2OEt$; $R^2=R^3=H$; $R^4=Me$



- 3a**, $R^1=R^3=R^4=H$; $R^2=OMe$
3b, $R^1=R^3=H$; $R^2=OMe$; $R^4=Me$
3c, $R^1=R^3=Me$; $R^2=1/2O$; $R^4=H$
3d, $R^1=R^4=Me$; $R^2=1/2O$; $R^3=H$

Table 3. Spectroscopic Data of Electrooxidation Products

Product	¹ H NMR, ^{a)} δ , ppm (J in Hz)	MS m/z (M^+)	IR ν , cm^{-1}
<i>cis</i> -1a	3.40 (6 H, s), 5.60 (2 H, s), 6.04 (2 H, s)		
<i>trans</i> -1a	3.40 (6 H, s), 5.88 (2 H, s), 6.04 (2 H, s)		
3a	1.76–2.04 (2 H, m), 2.20–2.48 (2 H, m), 3.32 (6 H, s), 3.67 (3 H, s), 4.38 (1 H, t, $J=6.0$)	161 ^{b)}	1740 (C=O), 2840 ($\text{H}_3\text{=CO}$)
<i>cis</i> -1b	1.47 (3 H, s), 3.49 (3 H, s), 5.70 (1 H, dd, $J=5.7, 1.1$), 5.72 (1 H, m), 6.19 (1 H, dd, $J=5.7, 1.1$)		
<i>trans</i> -1b	1.67 (3 H, s), 3.43 (3 H, s), 5.78 (1 H, m), 5.99 (1 H, dd, $J=5.7, 0.9$), 6.06 (1 H, dd, $J=5.7, 0.9$)		
<i>cis</i> -1c	1.52 (3 H, s), 3.20 (3 H, s), 3.50 (3 H, s), 5.47 (1 H, m), 5.90 (1 H, dd, $J=6.0, 0.9$), 5.96 (1 H, dd, $J=6.0, 0.9$)		
<i>trans</i> -1c	1.57 (3 H, s), 3.12 (3 H, s), 3.42 (3 H, s), 5.75 (1 H, m), 5.90–5.98 ^{e)}		
	1.48 (3 H, s), 2.99 (3 H, s), 3.30 (3 H, s), 5.56 (1 H, m), 5.71 (1 H, dd, $J=5.7, 1.0$), 5.79 (1 H, dd, $J=5.7, 1.0$) ^{d)}		
2a	2.34 (3 H, m), 3.89 (3 H, s), 6.02 (1 H, m), 6.2–6.9 (1 H, b), 6.63 (1 H, d, $J=3.6$)	139	3320 (NH), 1655 (C=N)
2b	2.24 (3 H, s), 3.90 (3 H, s), 6.0–6.5 (1 H, b), 6.26 (1 H, $d, J=1.9$), 7.33 (1 H, m)	139	3320 (NH), 1650 (C=N)
<i>cis</i> -1d	1.80 (3 H, m), 3.38 (3 H, s), 3.40 (3 H, s), 5.35 (1 H, m), 5.50 (1 H, m), 5.64 (1 H, m)		
<i>trans</i> -1d	1.78 (3 H, m), 3.34 (3 H, s), 3.38 (3 H, s), 5.60–5.68 (2 H, m), 5.70–5.80 (1 H, m)		
3b	1.18 (3 H, d, $J=7.0$), 1.65–2.20 (2 H, m), 2.36–2.72 (1 H, m), 3.32 (6 H, s), 3.67 (3 H, s), 4.38 (1 H, t, $J=6.0$)	175 ^{b)}	1740 (C=O), 2840 ($\text{H}_3\text{=CO}$)
<i>cis</i> -1e	1.63 (3 H, s), 1.92 (3 H, s), 3.42 (3 H, s), 5.68 (2 H, m)		
<i>trans</i> -1e	1.70 (3 H, s), 1.92 (3 H, m), 3.39 (3 H, s), 5.60 (1 H, m), 5.71 (1 H, m)		
<i>cis</i> -1f	1.44 (3 H, s), 1.72 (3 H, m), 3.14 (3 H, s), 3.47 (3 H, s), 5.34 (1 H, m), 5.60 (1 H, m)		
<i>trans</i> -1f	1.51 (3 H, s), 1.72 (3 H, m), 3.05 (3 H, s), 3.40 (3 H, s), 5.62 (2 H, m)		
3c	1.15 (3 H, d, $J=7.0$), 2.21 (3 H, s), 2.3–2.8 (2 H, m), 2.8–3.2 (1 H, m), 3.65 (3 H, s)	144	1715 (C=O), 1730 (C=O)
<i>cis</i> -1g	1.62 (3 H, s), 1.80 (3 H, m), 3.40 (3 H, s), 5.54 (1 H, m), 5.70 (1 H, m)		
<i>trans</i> -1g	1.69 (3 H, s), 1.80 (3 H, m), 3.40 (3 H, s), 5.60 (1 H, m), 5.70 (1 H, m)		
<i>cis(or trans)</i> -1h	1.48 (3 H, s), 1.71 (3 H, s), 3.38 (3 H, s), 3.72 (3 H, s), 5.57 (1 H, m), 5.75 (1 H, s), 7.3–7.9 (1 H, b)		3320 (NH), 1655 (C=N)
<i>cis(or trans)</i> -1i	1.56 (3 H, s), 1.90 (3 H, m), 3.30 (3 H, s), 5.4–5.8 ^{e)}		
<i>cis</i> -1j	1.38 (3 H, s), 1.70 (3 H, s), 3.06 (3 H, s), 3.37 (3 H, s), 5.04 (1 H, m), 5.32 (1 H, m) ^{d)}		
<i>trans</i> -1j	1.44 (3 H, s), 1.70 (3 H, s), 2.99 (3 H, s), 3.30 (3 H, s), 5.32 (2 H, m) ^{d)}		
2c	2.16 (3 H, s), 2.30 (3 H, d, $J=0.9$), 5.98 (1 H, m)	121	2260 (C $\equiv$ N)
2d	2.18 (3 H, s), 2.27 (3 H, d, $J=0.9$), 3.90 (3 H, s) 4.4–5.2 (1 H, b), 5.88 (1 H, m)	153	3320 (NH), 1645 (C=N)
3d	1.17 (3 H, d, $J=6.3$), 2.14 (3 H, s), 2.25–3.1 (3 H, m), 3.66 (3 H, s)	144	1720 (C=O), 1735 (C=O)
<i>cis</i> -1k	1.54 (3 H, s), 1.68 (3 H, s), 3.28 (3 H, s), 5.87 (1 H, d, $J=5.7$), 6.08 (1 H, d, $J=5.7$)		
<i>trans</i> -1k	1.60 (3 H, s), 1.74 (3 H, s), 3.16 (3 H, s), 5.93 (1 H, d, $J=5.7$), 6.03 (1 H, d, $J=5.7$)		
<i>cis</i> -1l	1.48 (6 H, s), 3.30 (6 H, s), 5.86 (2 H, s)		

Table 3. (Continued)

Product	^1H NMR, ^a δ , ppm (J in Hz)	MS m/z (M^+)	IR ν , cm^{-1}
<i>trans</i> - 1l	1.58 (6 H, s), 3.20 (6 H, s), 5.88 (2 H, s)	121	2240 ($\text{C}\equiv\text{N}$)
2e	2.25 (3 H, m), 2.42 (3 H, s), 6.02 (1 H, s)		
2f	2.27 (3 H, m), 3.34 (3 H, s), 4.31 (2 H, s), 5.82—5.92 (1 H, m), 6.10—6.20 (1 H, m)		
2g	3.34 (3 H, s), 4.36 (2 H, s), 6.25 (1 H, s)	121	2245 ($\text{C}\equiv\text{N}$)
2h	1.98 (3 H, d, $J=1.0$), 2.12 (3 H, s), 7.23 (1 H, m)		
2i	1.93 (3 H, d, $J=1.1$), 2.15 (3 H, s), 3.89 (3 H, s), 7.16 (1 H, m), 7.3—7.9 (1 H, b)	153	3300 (NH), 1650 ($\text{C}=\text{N}$)
<i>cis</i> (or <i>trans</i>)- 1m	1.70 (3 H, s), 1.82 (3 H, s), 3.38 (3 H, s), 5.05 (1 H, m), 5.56 (1 H, m)	135	1650 ($\text{C}=\text{N}$)
<i>cis</i> - 1n	1.66 (6 H, s), 3.34 (6 H, s), 5.31 (2 H, s)		
<i>trans</i> - 1n	1.66 (6 H, s), 3.34 (6 H, s), 5.59 (2 H, s)		
<i>cis</i> - 1o	1.60 (3 H, s), 1.68 (3 H, m), 1.78 (3 H, m), 3.37 (3 H, s), 5.50 (1 H, m)		
<i>trans</i> - 1o	1.66 (3 H, s), 1.68 (3 H, m), 1.78 (3 H, m), 3.37 (3 H, s), 5.53 (1 H, m)		
<i>cis</i> (or <i>trans</i>)- 1p	1.44 (3 H, s), 1.60 (3 H, m), 1.74 (3 H, m), 3.19 (3 H, s), 3.79 (3 H, s), 4.68 (1 H, m), 7.5—7.9 (1 H, b)		
<i>cis</i> - 1q	1.42 (3 H, s), 1.61 (3 H, m), 1.67 (3 H, m), 3.08 (3 H, s), 3.48 (3 H, s), 5.16 (1 H, m)		
<i>trans</i> - 1q	1.48 (3 H, s), 1.61 (3 H, m), 1.67 (3 H, m), 3.00 (3 H, s), 3.36 (3 H, s), 5.46 (1 H, m)		
2j	1.88 (3 H, m), 2.08 (3 H, s), 2.23 (3 H, m)		
2k	1.85 (3 H, m), 2.12 (3 H, s), 2.22 (3 H, m), 3.92 (3 H, s), 5.5—6.2 (1 H, b)	167	2230 ($\text{C}\equiv\text{N}$) 3330 (NH), 1650 ($\text{C}=\text{N}$)
<i>cis</i> (or <i>trans</i>)- 1r	1.52 (3 H, s), 1.68 (3 H, s), 1.82 (3 H, d, $J=1.4$), 3.75 (3 H, s), 5.74 (1 H, m), 7.3—8.0 (1 H, b)	176	3320 (NH), 1655 ($\text{C}=\text{N}$)
<i>cis</i> - 1s	1.48 (3 H, s), 1.63 (3 H, s), 1.90 (3 H, d, $J=1.6$), 3.25 (3 H, s), 5.48 (1 H, m)		
<i>trans</i> - 1s	1.56 (3 H, s), 1.69 (3 H, s), 1.90 (3 H, d, $J=1.6$), 3.14 (3 H, s), 5.54 (1 H, m)		
<i>cis</i> - 1t	1.46 (3 H, s), 1.62 (3 H, s), 1.74 (3 H, d, $J=1.6$), 3.22 (3 H, s), 5.69 (1 H, m)		
<i>trans</i> - 1t	1.53 (3 H, s), 1.68 (3 H, s), 1.74 (3 H, d, $J=1.6$), 3.10 (3 H, s), 5.65 (1 H, m)		
<i>cis</i> - 1u	1.44 (3 H, s), 1.47 (3 H, s), 1.75 (3 H, d, $J=1.6$), 3.26 (3 H, s), 3.32 (3 H, s), 5.54 (1 H, m)		
<i>trans</i> - 1u	1.54 (3 H, s), 1.58 (3 H, s), 1.75 (3 H, d, $J=1.6$), 3.18 (3 H, s), 3.22 (3 H, s), 5.54 (1 H, m)		
<i>cis</i> - 1v	1.64 (6 H, s), 1.79 (6 H, s)		
<i>trans</i> - 1v	1.68 (6 H, s), 1.79 (6 H, s)		
<i>cis</i> - 1w	1.42 (3 H, s), 1.58 (3 H, s), 1.62 (3 H, s), 1.79 (3 H, s), 3.14 (3 H, s)		
<i>trans</i> - 1w	1.49 (3 H, s), 1.62 (3 H, s), 1.64 (3 H, s), 1.79 (3 H, s), 3.02 (3 H, s)	181	2245 ($\text{C}\equiv\text{N}$)
<i>cis</i> - 1x	1.39 (6 H, s), 1.62 (6 H, s), 3.23 (6 H, s)	176	2245 ($\text{C}\equiv\text{N}$)
<i>trans</i> - 1x	1.49 (6 H, s), 1.62 (6 H, s), 3.10 (6 H, s)		
2l	1.84 (3 H, s), 1.92 (3 H, s), 2.16 (3 H, s), 3.32 (3 H, s), 4.28 (2 H, s)		
<i>cis</i> - 1y	1.21 (3 H, t, $J=7.0$), 1.61 (3 H, s), 1.66 (3 H, s), 3.24—3.76 (2 H, m), 5.89 (1 H, d, $J=5.6$), 6.03 (1 H, d, $J=5.6$)		
<i>trans</i> - 1y	1.17 (3 H, t, $J=7.0$), 1.59 (3 H, s), 1.71 (3 H, s), 3.12—3.74 (2 H, m), 5.93 (1 H, d, $J=5.6$), 5.97 (1 H, d, $J=5.6$)		

Table 3. (Continued)

Product	¹ H NMR, ^{a)} δ , ppm (J in Hz)	MS m/z (M^+)	IR ν , cm^{-1}
<i>cis</i> - 1z	1.17 (6 H, t, $J=7.2$), 1.48 (6 H, s), 3.16—3.84 (4 H, m), 5.86 (2 H, s)		
<i>trans</i> - 1z	1.17 (6 H, t, $J=7.0$), 1.57 (6 H, s), 3.18—3.82 (4 H, m), 5.87 (2 H, s)		
2m	1.21 (3 H, t, $J=7.0$), 2.28 (3 H, m), 3.51 (2 H, q, $J=7.0$), 4.36 (2 H, s), 5.82—5.92 (1 H, m), 6.08—6.18 (1 H, m)		
<i>cis</i> - 1aa	0.90 (3 H, t, $J=7.6$), 1.14 (3 H, t, $J=7.4$), 1.50—2.00 (4 H, m), 3.29 (3 H, s), 5.87 (1 H, d, $J=6.0$), 6.11 (1 H, d, $J=6.0$)		
<i>trans</i> - 1aa	0.98 (3 H, t, $J=7.6$), 1.20 (3 H, t, $J=7.2$), 1.64—2.10 (4 H, m), 3.18 (3 H, s), 5.91 (1 H, d, $J=6.0$), 6.09 (1 H, d, $J=6.0$)		
<i>cis</i> - 1bb	0.91 (6 H, t, $J=7.6$), 1.52—2.06 (4 H, m), 3.29 (6 H, s), 5.93 (2 H, s)		
<i>trans</i> - 1bb	0.96 (6 H, t, $J=7.6$), 1.60—2.16 (4 H, m), 3.20 (6 H, s), 5.95 (2 H, s)		

a) 100 MHz, CDCl_3 solution unless otherwise noted. b) $M-1$ peak. c) Unresolved. d) CCl_4 solution.

Table 4. Isomer Ratio of the Products of Cyano-methoxylation of 2,5-DMF^{a)}

Concn of 2,5-DMF, M	Additive ^{b)} (E_p , V ^{c)})	E , V ^{d)}	Isomer ratio (<i>cis</i> / <i>trans</i>) ^{e)}
0.02	None	1.30	3.1
0.10	None	1.30	3.0
0.20	None	1.30	2.9
0.20 ^{f)}	None	1.30	1.8
0.20	None	1.40	2.8
0.20	None	1.50	2.8
0.20	None	1.70	2.7
2.00	None	1.30	2.2
0.20	Benzene ^{g)}	1.30	3.0
0.20	Anisole ^{g)}	1.30	2.9
0.20	1,3,5-TMB ^{h)} (1.44)	1.30	2.5
0.20	1,3,5-TMB	1.44	2.6
0.20	1,2-DMB (1.38)	1.30	2.2
0.20	1,2-DMB	1.38	2.1
0.20	1,3-DMB (1.50)	1.30	2.1
0.20	1,3-DMB	1.50	2.0
0.20	Pyridine ^{g)}	1.30	1.8
0.20	1,4-DMB (1.24)	1.30	1.6

a) Pt anode unless otherwise stated. SCE reference. 0.4 M NaCN. b) [Additive]=0.20 M. c) Peak potential from CV. 0.02 M substrate. Scan rate is 0.1 V s⁻¹. Values are obtained on first scan. d) Potential for preparative electroreduction. e) Equilibrium value is 1.5. f) Vitreous C electrode. g) In these cases the oxidation wave was not observed due to the large background current from the concurrent electrolysis of the solvent-electrolyte system, i.e. >1.6. h) Trimethoxybenzene.

The adduct **1m**, which has a hydrogen on the 2 position geminate to a cyano group, differs in behavior. It smoothly loses MeOH to afford **2h** with a trace of CF_3COOH in CHCl_3 .



Discussion

Mechanism. Both addition to and substitution on the furan ring are formally a 2-equiv change. Coulometry supports this experimentally. The voltammetric characteristics (Table 1) indicate that oxidation is initiated by electron transfer from the substrate molecule, followed by a fast chemical reaction. By analogy with anodic cyanation and methoxylation of other aromatic compounds,⁹⁾ the ECEC mechanism involving a cation-radical intermediate would be reasonable. The ionization potential of furan and the methylated derivatives is relatively low,¹²⁻¹⁴⁾ and the existence of their cation radicals has clearly been recognized in mass spectrometry¹⁵⁾ and studied by ESR.^{16,17)}

The cation radical mechanism is given in Scheme 1, illustrated for 2,3,4-trimethylfuran (2,3,4-TMF). The first step is the electron-transfer step which involves the direct discharge of the substrate. The cation radical **4** and the benzenium-type ions **5**—**8** react competitively with CN^- ion and the solvent MeOH (or the MeO^- ion as a result of the equilibrium between CN^- and MeOH). Part of **7** could undergo deprotonation to afford **2j**. We may denote rate constants as k_1 , k_2 , ..., and k_{13} , and CEs as **1ox**, **1oy**, **1px**, **1py**, **1qx**, **1qy**, **2j**, **9x**, and **9y**. Thus **9x** and **9y**

represent the CE of product **9** formed in the first and third branches of Scheme 1, respectively. Treating the reactions in Scheme 1 as a system of competitive reactions^{5,18)} one can derive the following relationships.

$$\frac{k'_1}{k'_2} = \left(\frac{k_1}{k_2} \right) \left(\frac{\text{CN}^-}{\text{MeOH}} \right) = \frac{\mathbf{1ox} + \mathbf{9x}}{\mathbf{1px} + \mathbf{1qx}} \quad (3)$$

$$\frac{k'_3}{k'_4} = \left(\frac{k_3}{k_4} \right) \left(\frac{\text{CN}^-}{\text{MeOH}} \right) = \frac{\mathbf{1py} + \mathbf{2j} + \mathbf{9y}}{\mathbf{1oy} + \mathbf{1qy}} \quad (4)$$

$$\frac{k'_5}{k'_6} = \left(\frac{k_5}{k_6} \right) \left(\frac{\text{CN}^-}{\text{MeOH}} \right) = \frac{\mathbf{9x}}{\mathbf{1ox}} \quad (5)$$

$$\frac{k'_7}{k'_8} = \left(\frac{k_7}{k_8} \right) \left(\frac{\text{CN}^-}{\text{MeOH}} \right) = \frac{\mathbf{1px}}{\mathbf{1qx}} \quad (6)$$

$$\frac{k'_{10}}{k'_{11}} = \left(\frac{k_{10}}{k_{11}} \right) \left(\frac{\text{CN}^-}{\text{MeOH}} \right) = \frac{\mathbf{9y}}{\mathbf{1py}} \quad (7)$$

$$\frac{k'_{12}}{k'_{13}} = \left(\frac{k_{12}}{k_{13}} \right) \left(\frac{\text{CN}^-}{\text{MeOH}} \right) = \frac{\mathbf{1oy}}{\mathbf{1qy}} \quad (8)$$

where

$$\mathbf{9x} + \mathbf{9y} = \mathbf{9} = 0.1 \quad (9)$$

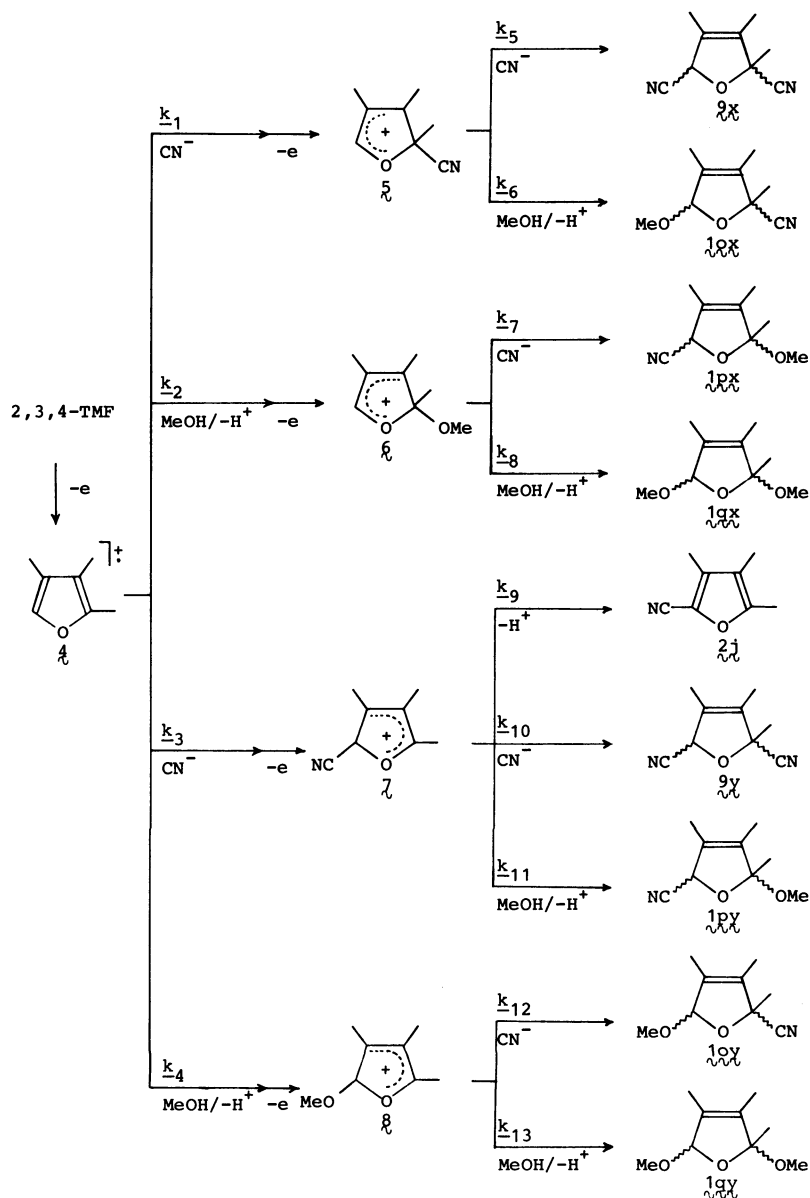
$$\mathbf{1ox} + \mathbf{1oy} = \mathbf{1o} = 22 \quad (10)$$

$$\mathbf{1px} + \mathbf{1py} = \mathbf{1p} = 7 \quad (11)$$

$$\mathbf{1qx} + \mathbf{1qy} = \mathbf{1q} = 13 \quad (12)$$

Here $k'_1 = k_1(\text{CN}^-)$, $k'_2 = k_2(\text{MeOH})$, ..., $k'_{13} = k_{13}(\text{MeOH})$.

We would like to evaluate the relative magnitudes of k_1 and k_2 . In order to solve Eqs. 3–12, it is necessary to obtain information on the relative concentration of nucleophiles in the vicinity of the electrode. In the reactions containing a fast chemical step following the electron transfer, the concentration distribution of available, i.e., physisorbed, nucleo-



Scheme 1.

philes in the electrical double layer would be kept steadily constant by the competition¹⁹⁾ between mass transfer and chemical reaction. Prior to this, adsorption saturation of nucleophiles at the electrode surface may bear a part in duration of the spatially constant concentration. The observed independence of the product distribution obtained on competitive anodic cyanation and methoxylation of 2,5-DMF on the bulk concentration of CN^- ion or potential²⁾ supports this. Accordingly, the quantity $(\text{CN}^-/\text{MeOH})$ should actually be designated as $(\text{CN}^-/\text{MeOH})_E$, i.e., referring to relative steady-state concentrations of these nucleophiles in the region of solution adjacent to the anode as compared to the bulk. Furthermore, it is assumed that $k_1/k_2 = k_3/k_4$, $k_5 \cong k_7$, $k_6 \cong k_8$, $k_{10} \cong k_{12}$, and $k_{11} \cong k_{13}$. These assumptions would be reasonable since the electronically significant part of the structures of the corresponding cationic species are identical. The 2,5-dicyano adduct **9** was not detected and thus the lowest limit (0.1% CE) of product analysis in the present experiments was allotted to **9**. Substituting the assumed values for the relative quantities k_1/k_3 , we can solve Eqs. 3–12.

Likewise, the relative rate constants of the cation radicals of other methylated furans toward two different nucleophiles have been evaluated. The results obtained are shown in Table 5, together with the observed anodic peak potential. As can be seen from Table 5, methyl substitution lowers the oxidation potential of the neutral substrate while it raises the relative reactivity k'_1/k'_2 of its cation radical. A plot of log relative rate constant versus anodic peak potential gives a linear relationship (Fig. 1). The cation-radical intermediates derived from compounds having lower oxidation potentials would be less reactive and hence more discriminating than the cation radicals of substrates having higher oxidation potentials. Thus, the cation radical of 2,3,4,5-tetramethylfuran (TetMF) is highly selective for nucleophiles and preferentially combines with a powerful nucleophile, that is, the CN^- ion, whereas the cation radical of 3-methylfuran (3-MF) preferen-

tially combines with an abundant nucleophile, namely, the solvent MeOH.

The mechanism presented in Scheme 2 can also account for the electrooxidation of 2-methylated furans. The cation radical **10** could undergo deprotonation to afford an analogue of a benzylic radical intermediate, which would subsequently undergo anodic oxidation (or homogeneous electron-transfer oxidation by the cation radical **10**) to give a cation **11**, followed by nucleophilic attack by CN^- ion (or MeOH) to give a 2,5-dihydro-5-methylenefuran **12**, which should be eventually transferred to **13**. Indeed, a compound of the type of **12** is probable as a reaction intermediate: e.g., 2,5-dihydro-5-methylene-2-furancarbonitrile and its homologues are the primary products of abnormal product formation in the reaction of 2-(chloromethyl)furans with aqueous cyanide solution.²⁰⁾ The final step is the homogeneous chemical reaction. If the anodic reaction followed this reaction path, the observed cis-to-trans isomer ratio in the products would be consistent with the isomer composition for the homogeneous equilibrium. However, the anodic reaction of 2,5-DMF gives a high cis-to-trans reaction compared with the equilibrium value. Thus this pathway is not important in the

Table 5. Relative Reactivity of Methylated Furans Toward Two Different Nucleophiles

Compd	E_p , V	$(k_1/k_3)^{-1}$ a)	k'_1/k'_2 b)
3-MF	1.78	0.2	0.01
3,4-DMF	1.61		0.1
2-MF	1.60	0.5–1.0	0.4 ^{b)}
2,4-DMF	1.55	2.7–3.0	1.4 ^{b)}
2,3-DMF	1.51	0	1.6
2,3,4-TMF	1.37	1.23	3.8
2,5-DMF	1.35		23
2,3,5-TMF	1.25	0.1–0.16	52
TetMF	1.13		742

a) Assumed values. b) Average values.

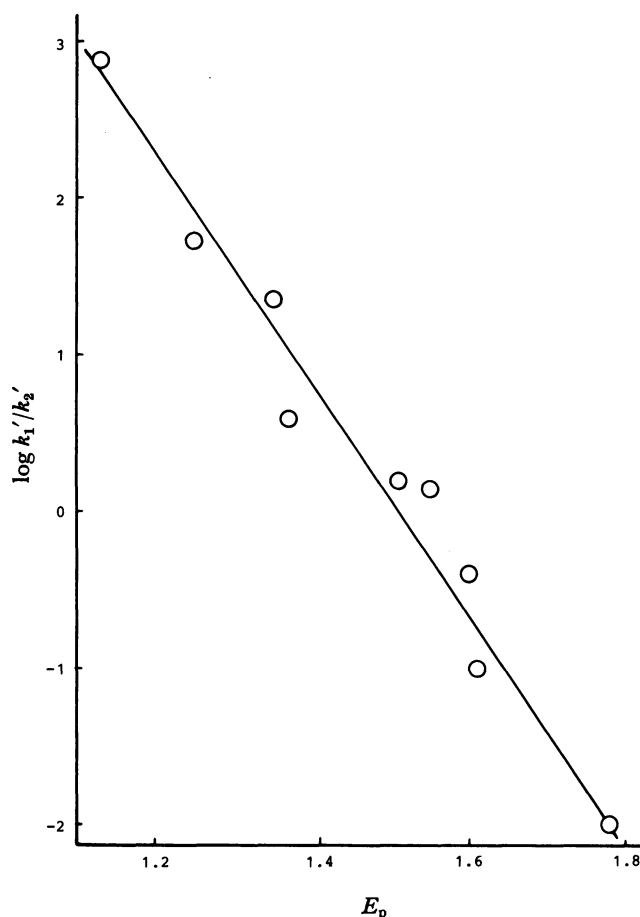


Fig. 1. Plot of log relative rate constant vs. E_p .

anodic reaction. Alternatively, the compound **12** could be aromatized in protic solvents for furans lacking the substituent on the 5 position ($R_3=H$). This mechanism was previously discussed in anodic nuclear substitution of 1,2-dimethylpyrrole and has been precluded on the basis of no incorporation of deuterium in the 2-methyl group upon the reaction in methanol- d_2 .²¹⁾

1,4-Dicarbonyl derivatives (**3**) would be formed in the acid-catalyzed ring fission^{22,23)} of 2-methoxyfurans obtained by either anodic nuclear methoxylation or 1,4-elimination^{24,25)} of MeOH element from the primary 2,5-dihydro-2,5-dimethoxyfurans.

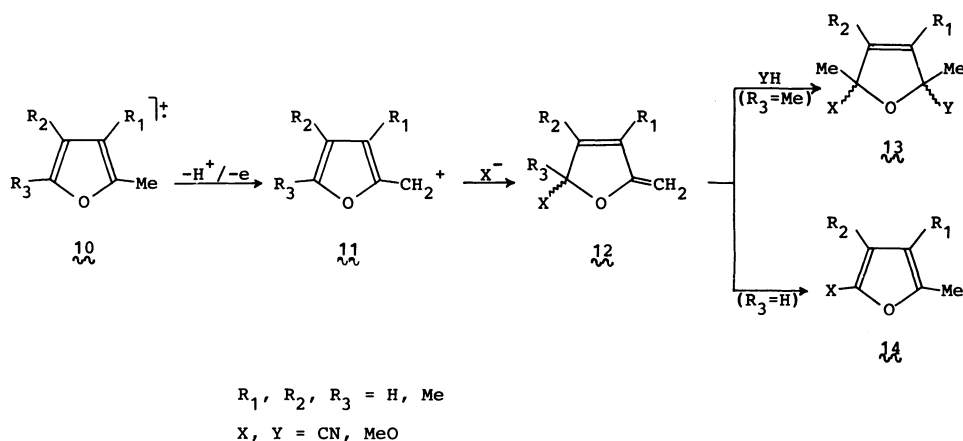
Positional Reactivity. The values of k_1/k_3 given in Table 5 reveal the relative regioreactivity of the initial nucleophilic attack to the cation radicals of unsymmetrical methylfurans. The reaction occurs preferentially at the 2 (and 5) position. When a methyl group is attached at the 2 position, the initial nucleophilic attack occurs comparably at both 2 (ipso) and 5 (para) positions. The introduction of the methyl substituent in the 3 position activates dominantly the 2 (ortho) position.

Comparison with Electrooxidation of 1,4-DMB.

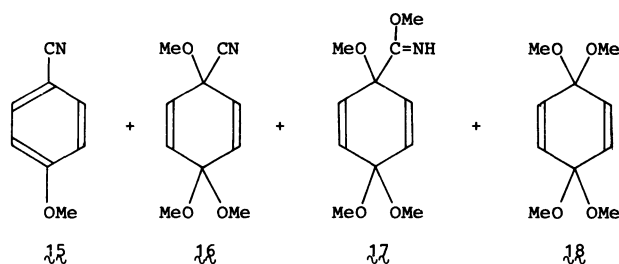
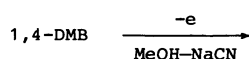
Weinberg and co-workers investigated the electrooxidation of 1,4-DMB at a Pt electrode in MeOH that contains NaCN.⁵⁾ 1,4-DMB undergoes the additions of cyano and/or methoxyl group(s) across the aromatic nucleus in competition with methoxyl

displacement. The CEs of *p*-methoxybenzonitrile **15** and of *p*-benzoquinone bis(dimethyl acetal) **18** are highly potential dependent, whereas the CE of 3-cyano-3,6,6-trimethoxy-1,4-cyclohexadiene **16** taken together with its base-catalyzed methanolysis product **17** is found to be independent of potential. A similar trend appears on changing the concentration of CN^- ion in the bulk solution. Curiously enough, there are discrepancies between their observations on 1,4-DMB and our previous results²⁾ on 2,5-DMF at the same material electrode. In the latter case, the product distribution was independent of anode potential or the bulk concentration of CN^- ion. Apparent potential dependency of the CEs of **15** and **18** in the former case may be ascribable to that, the 1,4-DMB cation radical is not adsorbed as strongly as is 2,5-DMF cation radical (or, the 1,4-DMB cation radical that reacts really with two competing nucleophiles may be formed by the homogeneous electron-transfer reaction between the primary product in the inner region and the parent uncharged molecule in the outer region), diffuses into the bulk solution which contains a greater relative concentration of MeO^- ion, and consequently produces a greater part of **18** with the decreasing in NaCN or with the lowering in anode potential.

An attempt by Weinberg and co-workers⁵⁾ to determine the relative concentrations of two nucleophiles at the electrode from electrooxidation products



Scheme 2.



(13)

by using the rate expressions of competitive reactions met with failure. Their assumptions and results are not reasonable as mentioned previously.²⁶⁾

Stereochemical Control of Addition. The stereochemistry of electrochemical incremental reactions could be brought about by the orientation of the substrate molecule on the electrode surface during the reaction, especially in a *final* bond-formation step. The present anodic mixed 1,4-addition to 2,5-DMF is sterically controlled by the Pt electrode. The dependence observed of the ratio of the stereoisomeric products on the concentration of the substrate would be ascribable to the orientational transition which occurs as the substrate concentration is changed. The orientation of adsorbed aromatic molecules has been studied as a function of adsorbate molecular structure and its concentration.²⁷⁻²⁹⁾ At low concentrations, aromatic molecules generally adopt a flat orientation on the Pt surface in which the ring is more or less parallel to the electrode surface plane. Cis addition to the adsorbed furan ring would dominate. Transitions from flat to vertical (endwise or edgewise) orientations occur at higher concentrations. In the endwise orientation a C-H bond (or other substituent) of the ring is perpendicular to the surface, and in the edgewise orientation one edge is parallel and the ring is perpendicular to the surface. The ratio of isomeric products should reflect thermodynamic control.

The ratio of the stereoisomeric products also varies significantly with the addition of adsorbable compounds. Deviations from the ratio obtained in the blank experiment are explicable in terms of the changes in orientation. The changes in orientation of aromatic molecules under the influence of a surface-active anion, iodide, have recently been detected in aqueous solutions.³⁰⁾ When a layer of molecules adsorbed in the planar orientation to the surface is exposed to a solution of a coadsorbate such as iodide, reorientation to an edgewise orientation occurs for most of the compounds. A similar phenomenon, that is, change of positional reactivity under aromatic additives, has been detected in other electrode reactions, for example, anodic nuclear acetoxylation of anisole.³¹⁾

Infrared and Mass Spectral Intensity. 2-Furonitriles have a strong band in the region of the C≡N stretching vibration in IR spectra, whilst the intensity of the nitrile absorption band in nonaromatic 2,5-dihydro-2-furonitriles is very weak or undetectable. Marked declines in C≡N intensities are commonly observed when the oxygen-containing group is attached to the same carbon atom as the cyano group.³²⁾

The parent peaks are very weak or cannot be detected at all in the mass spectra of 2,5-dihydro-5-methoxy-2-furonitriles and of 2,5-dihydro-2,5-dimethoxyfurans. The absence of a parent peak in the mass

spectrum of ethers is usually observed.³³⁾

Other Synthetic Method. The synthesis of a pertinent 2-cyano-5-methoxy compound by nonelectrochemical reaction of a 2,5-dimethoxy adduct (**1a**) and cyanotrimethylsilane has recently been reported.³⁴⁾

Experimental

Equipment. A JEOL FX-100 NMR spectrometer, a JASCO Model IR-E IR spectrophotometer, and a Hitachi Model RMS-4 mass spectrometer were used for structure determination.

CV was performed in a two-compartment cell in which the calomel reference electrode with an agar bridge was separated from the Pt anode and the cathode by a glass frit. The working electrode was a 1-cm Pt wire sealed in glass, and the auxiliary electrode was a Pt sheet. A Hokuto Denko HB-107A voltage scanner, HA-104 potentiostat, and Yokogawa Type 3083 XY recorder were used. All measurements were carried out at room temperature.

Controlled-potential electroreactions were performed by using a three-compartment cell (which separated the anode, cathode, and reference electrode solutions by glass frits). The anode compartment held 50 ml of anolyte, the cathode held 20 ml of catholyte, and the reference held 5 ml of an electrolyte solution. A Pt sheet (2×2 cm) anode was employed. A Pt wire was used as the cathode, and an SCE with an agar bridge as the reference. Anode potential was controlled by means of the potentiostat mentioned above.

Coulometry was carried out with a Hokuto Denko Model HF-108 A current integrator.

Materials. MeOH and NaCN were used without purification. Furan and 2-MF were obtained commercially and were purified by distillation.

3-MF was prepared by a three-step method starting with

Table 6. ¹H NMR Data of Alkylfurans^{a)}

Compd	Chemical shift δ, ppm
Furan	6.40 (2 H, m), 7.47 (2 H, m)
2-MF	2.29 (3 H, s), 6.00 (1 H, m), 6.28 (1 H, m), 7.30 (1 H, m)
3-MF	2.03 (3 H, m), 6.22 (1 H, m), 7.16 (1 H, m), 7.29 (1 H, m)
2,3-DMF	1.93 (3 H, m), 2.19 (3 H, m), 6.12 (1 H, m), 7.16 (1 H, m)
2,4-DMF	1.96 (3 H, s), 2.22 (3 H, s), 5.80 (1 H, m), 6.99 (1 H, m)
2,5-DMF	2.24 (3 H, m), 5.80 (1 H, m)
3,4-DMF	1.95 (3 H, m), 7.11 (1 H, m)
2,3,4-TMF	1.85 (3 H, m), 1.90 (3 H, m), 2.16 (3 H, s), 6.99 (1 H, m)
2,3,5-TMF	1.87 (3 H, m), 2.14 (3 H, s), 2.19 (3 H, s), 5.70 (1 H, s)
TetMF	1.84 (3 H, s), 2.16 (3 H, s)
2,5-DEF	1.21 (3 H, t), 2.60 (2 H, q), 5.83 (1 H, s)

a) 100 MHz, CDCl₃ solution.

2-methylallyl chloride and ethyl orthoformate.³⁵⁻³⁷⁾

2,3-DMF was prepared by lithium aluminum hydride reduction of 3-chloromethyl-2-methylfuran,³⁸⁾ which was obtained in 3 steps from chloroacetaldehyde and ethyl acetoacetate.³⁹⁾

2,4-DMF⁴⁰⁾ was obtained by thermal decomposition of the δ -sultone⁴¹⁾ which was prepared by sulfonation of mesityl oxide.

2,5-DMF was prepared by dehydration of acetonylacetone according to the method of Gaertner and Tonkyn.⁴²⁾

3,4-DMF was synthesized by the hydrogenation of 3,4-bis(chloromethyl)furan⁴³⁾ in the presence of Pd in barium sulfate.⁴⁴⁾

2,3,4-TMF was made from 3-hydroxymethyl-2,4-dimethylfuran, which was obtained by reduction of 2,4-dimethyl-3-furancarboxylic acid⁴⁵⁾ with lithium aluminum hydride, using the procedure of Winberg, Fawcett, Mochel, and Theobald.³⁸⁾

2,3,5-TMF was prepared by a four-step procedure starting with ethyl acetoacetate and 3-chloro-2-butanone.⁴⁶⁾

TetMF was obtained by the dehydration of 3,4-dimethyl-2,5-hexanedione with acetic anhydride and zinc chloride.⁴²⁾ 3,4-Dimethyl-2,5-hexanedione was prepared by the reaction of 2-butanone and di-*t*-butyl peroxide by a modification of the procedure of Moore.⁴⁷⁾ Decomposition of the peroxide was accomplished by photodissociation instead of thermal decomposition. A solution of 2-butanone (250 ml) and di-*t*-butyl peroxide (25 g) was irradiated through a Pyrex filter by a 450-W high-pressure Hg vapor lamp at room temperature for 40 h. Colorless 3,4-dimethyl-2,5-hexanedione was collected at 94 °C/16 mmHg (1 mmHg=133.322 Pa), 8 g. No attempt was made to optimize the yield.

2,5-DEF was prepared by the reaction of 2,5-bis(chloromethyl)furan⁴⁸⁾ and methylmagnesium bromide.⁴⁹⁾

NMR data of furans were given in Table 6.

Authentic samples of *cis*- and *trans*-2,5-dihydro-2,5-dimethoxy-2,5-dimethylfuran were prepared by anodic methoxylation of 2,5-DMF.^{11,50)}

2,5-Bis(methoxymethyl)furan was prepared by the bromination of 2,5-DMF with *N*-bromosuccinimide, followed by treatment with NaOMe.¹¹⁾

2-Methoxymethyl-5-methylfuran was obtained according to the same method as above except that 1 equiv of *N*-bromosuccinimide was used.

2,5-Dimethyl-3-furancarbonitrile was prepared by reaction of 2,5-DMF and chlorosulfonyl isocyanate followed by treatment of the intermediate with *N,N*-dimethylformamide.⁵¹⁾

General Electrooxidation Procedure. The anolyte (50 ml) was made up of the organic substrate (5 mmol) in a methanolic solution of NaCN (0.4 M). The catholyte was the same medium in the absence of the substrate. The anode and cathode compartments were kept under an atmosphere of nitrogen and the anolyte was stirred magnetically. The reaction was carried out at a controlled anode potential at room temperature. The potential was set at the peak potential of the substrate. During the run the current dropped with time and was discontinued when either 2 faradays/mol of furan added was passed or the current dropped to some low value near the original background level. To the product mixture were added internal standards for GLC analyses, the mixture was treated with water, and

the organic material was extracted with ether. The ethereal solution was concentrated and analyzed by GLC using a PEG 6000 column at 65 °C. Each isomeric product was separated in pure form by preparative GLC. They were identified by the elemental and ¹H NMR, IR, and mass spectroscopic analyses (Table 3). The intensity of the C $\equiv$ N stretching vibration in IR spectra varied with structure. Methyl imidates showed characteristic bands at the region of 3320 (NH) and 1650 cm⁻¹ (C=N). *Caution:* a cyanide salt in MeOH must be handled in a fume hood, as it contains HCN as a result of the equilibrium between CN⁻ and the solvent MeOH.

Isomerization Equilibrium. Isomerization was carried out in MeOH (1 ml) containing either of the two isomers *cis*-1k and *trans*-1k (0.01 g) and 1% CF₃COOH as catalyst. The reaction mixture was kept at 25.0 °C by a thermostat. At specified intervals, samples were withdrawn and analyzed by GLC after neutralization with sodium carbonate.

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