Anodic Oxidation of Unsymmetrically Substituted Diarylalkanes. Multiplicity of Mechanisms for Intramolecular Cyclization

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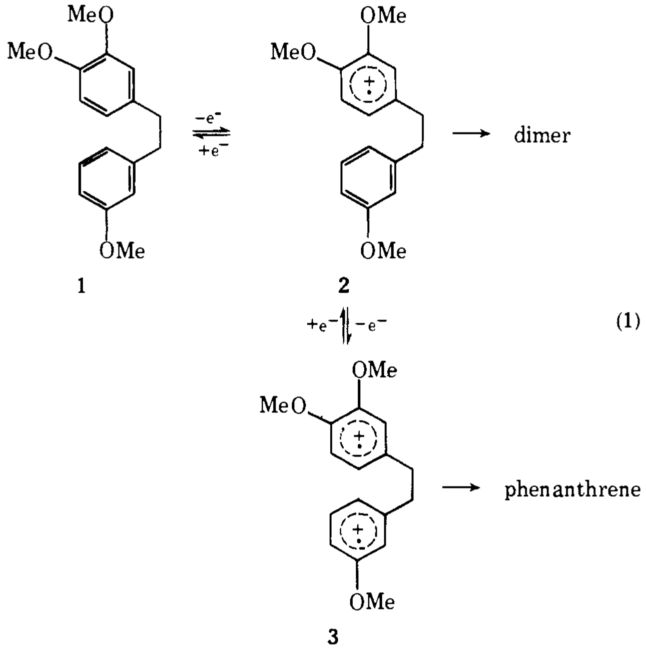
Abstract: Straight-chain alkanes substituted with a 3- or 4-anisyl group at one end and a 3,4-dimethoxyphenyl group at the other terminal carbon were found to undergo coupling reactions, either intra- or intermolecular depending on the number of carbons in the aliphatic chain and the anode potential, when subjected to anodic oxidation in dichloromethane-trifluoroacetic acid. Independent of the anode potential, both of the diarylpropanes investigated and the diarylbutane containing a 4-anisyl group gave intramolecular coupling exclusively. For the rest of the diarylalkanes studied, a marked potential dependence of the course of the coupling reaction was observed. Low anode potentials favored intermolecular coupling between the 3,4-dimethoxyphenyl rings, and high potentials favored intramolecular coupling. Voltammetric and product studies were carried out to establish the scope and mechanisms of the reactions. Both cation radical coupling and electrophilic attack of a cation radical on unoxidized rings were observed. An intermediate was detected during cyclization of the 4-anisyl substituted propane.

In a previous paper,[2] we have shown that the use of unsymmetrically substituted methoxybibenzyl as substrate for anodic coupling allowed for the distinction between the cation radical combination and the electrophilic cation radical attack on unoxidized aromatic ring mechanisms for anodic coupling. It was observed that **1** undergoes two consecutive electron transfers to give first the cation radical at +1.21 and the dication at +1.62 V (eq 1).[3] Oxidation at potentials where only the first electron transfer takes place led to the formation of a dimer, while oxidation at higher potentials resulted in formation of the corresponding phenanthrene formed by intramolecular cyclization followed by oxidative dehydrogenation.



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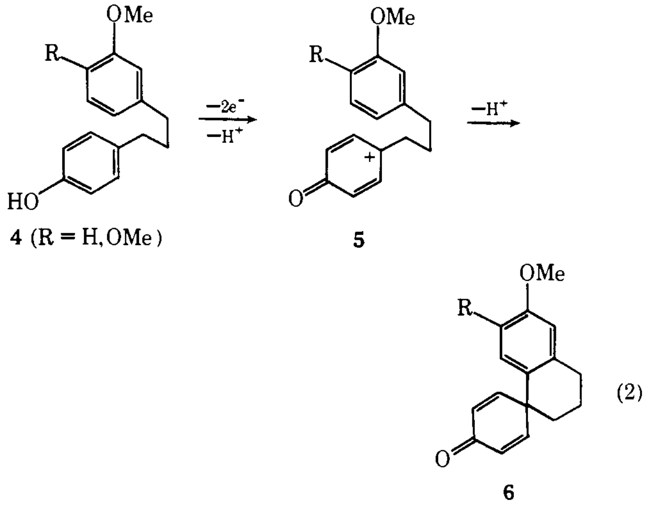
Diarylpropanes substituted with a phenolic moiety at one terminal carbon and a methoxyphenyl group at the other have been shown to undergo intramolecular cyclization to give the corresponding spirodienone during either chemical[4] or anodic[5] oxidation. The mechanism of the latter transformation was shown to be oxidation of the phenolic group to the phenoxonium ion which then undergoes electrophilic attack upon the unoxidized methoxylated ring.[5] The latter results prompted us to examine the behavior of unsymmetrically substituted diarylalkanes in which both of the aryl groups contained only ether substituents in order to assess the generality of the earlier mechanism[2] which predicts that only radical cation combination occurs during coupling of aromatic ethers.



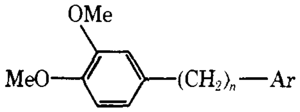
4 (R = H,OMe) 5 6 (2)

Results

The compounds studied had the general structures **7** and **8** where *n* refers to the number of CH_2 units in the saturated chain.

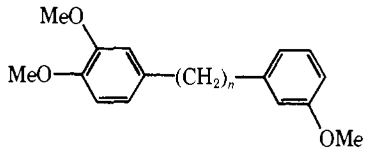
Anodic Oxidations. The reactions were investigated in two different ways. In the first method, exhaustive electrolyses were carried out on 5-10 mmol of substrate, and the products were isolated and purified using conventional organic chemical techniques. The other method involved analysis by cyclic voltammetry of the substrates in the solvent system followed by constant current coulometry[6] with voltammetric analysis of the resulting solution of products.

Table I. Results of Preparative Anodic Oxidation of



Substrate	Ar	Q, F/mol	Conversion, %	Product (%)	Principal reaction
7 (n = 1)	*m*-Methoxyphenyl	2.0^a	93	**11** (16); **9** (10); **13** (16)	D
7 (n = 1)	*m*-Methoxyphenyl	2.0^b	86	**11** (6); **9** (33); **13** (6)	C
7 (n = 2)	*m*-Methoxyphenyl	1.5^{a,c}	74	**11** (61)	D
7 (n = 2)	*m*-Methoxyphenyl	3.0^{b,c}	79	**11** (12); **14a** (3)	D + C
7 (n = 3)	*m*-Methoxyphenyl	3.0^a	89	**9** (72)	C
7 (n = 3)	*m*-Methoxyphenyl	3.0^b	79	**9** (55)	C
7 (n = 4)	*m*-Methoxyphenyl	3.0^a	92	**11** (33)	D
7 (n = 4)	*m*-Methoxyphenyl	3.0^b	98	**11** (22)	D
8 (n = 1)	*p*-Methoxyphenyl	1.5^a	35	**12** (11)	D
8 (n = 1)	*p*-Methoxyphenyl	1.5^b	20	**12** (5)	D
8 (n = 2)	*p*-Methoxyphenyl	1.5^a	75	**12** (31)	D
8 (n = 2)	*p*-Methoxyphenyl	3.0^b	78	**12** (14); **14b** (20)	D + C
8 (n = 3)	*p*-Methoxyphenyl	1.5^a	74	**10** (71)	C
8 (n = 3)	*p*-Methoxyphenyl	3.0^b	75	**10** (30); **15** (32)	C
8 (n = 4)	*p*-Methoxyphenyl	3.0^a	79	**10** (33); **16** (33)	C
8 (n = 4)	*p*-Methoxyphenyl	3.0^b	71	**10** (14); **16** (14)	C
17	Phenyl	1.5^a	90	**18** (50)	D
17	Phenyl	1.5^b	86	**18** (33)	D

[a] Carried out at constant current with current density (D_A) 0.13 mA/cm². [b] Carried out at constant current with D_A = 2.66 mA/cm². [c] From ref 2.



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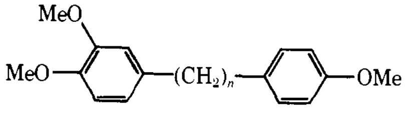

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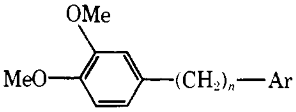
Table II. Voltammetric Data[a] for Oxidation of



Substrate	Ar	E_p^{b,c}	$E_{1/2}$^{b,c}	S_1^{e}	S_2^{f}
7 (n = 1)	*m*-Methoxyphenyl	1.49	1.47	1.34	0.94
7 (n = 2)	*m*-Methoxyphenyl	1.47	1.42	1.32	1.01
7 (n = 3)	*m*-Methoxyphenyl	1.47	1.42	1.15	1.13
7 (n = 4)	*m*-Methoxyphenyl	1.44	1.41	1.29	1.24
8 (n = 1)	*p*-Methoxyphenyl	1.46	1.43	1.34	1.34
8 (n = 2)	*p*-Methoxyphenyl	1.49	1.43		1.29
8 (n = 3)	*p*-Methoxyphenyl	1.44	1.42	1.24	1.24
8 (n = 4)	*p*-Methoxyphenyl	1.46	1.41	1.25	1.27
17	Phenyl	1.42	1.41	1.30	1.23

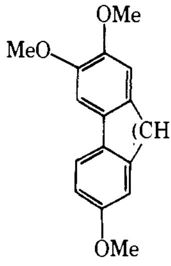
[a] Solvent dichloromethane: TFA 3:1 with n-Bu_4NBF_4 (0.2 *M*). [b] In *V* vs. saturated aqueous calomel electrode. [c] Peak potential at a stationary platinum electrode. Sweep rate 156 mV/sec. [d] Half-wave potential at a rotating platinum disk electrode. [e] Reduction peak potential after potential step to E_p, holding for 15 sec before cathodic sweep. [f] Reduction peak potential after potential step to the second oxidation peak, holding for 15 sec before cathodic sweep.

The products isolated from the preparative scale experiments were used to establish the identity of the products obtained under voltammetric conditions by comparison. Results of the preparative experiments are summarized in Table I, and the voltammetric data for substrates and products are collected in Table II.

As indicated in Table I, two different modes of initial reaction were observed, intramolecular cyclization (C) to give **9** or **10**, and dimerization (D) to give **11** or **12**. In addition, further oxidation products were sometimes obtained. For example, the cyclized dimer **13** was obtained from **7** (n = 1), and the initial cyclized product **10** (n = 2) from **8** (n = 2) underwent oxidative dehydrogenation to form **14b**. Likewise, the further oxidation products **15** and **16** were formed during oxidation of **8** (n = 3) and **8** (n = 4), respectively. The structures of the compounds are shown.

The voltammetric results (Table II) indicate that the oxidation potentials, either E_p for cyclic voltammetry or $E_{1/2}$ for rotating disk electrode voltammetry, are independent of the total structure of the compounds and are a reflection of the fact that the most easily oxidized portions of the molecules are the rings containing two methoxy groups. The potential step data show that in some cases the nature of the product is determined by the electrode potential at which oxidation takes place. Two specific examples of the voltammetric behavior are given in the following paragraphs to exemplify the data.

Voltammetry of (3,4-Dimethoxyphenyl)(3-methoxyphenyl)methane (7, *n* = 1). Cyclic and potential step sweep[7] voltammograms for **7** (n = 1) are illustrated in Figure 1. The cyclic voltammogram consists of two oxidation peaks, O_1 and O_2, and three reduction peaks, R_3, R_4, and R_5. A potential step to a potential in the vicinity of O_1, followed by a 15-sec hold before initiating a cathodic sweep, resulted in a voltammogram (1*) in which R_4 was the only significant peak.[10] The same procedure, this time with the step to a potential near O_2, gave an entirely different result. The voltammogram (3*) in the latter case showed only R_3 and R_5 with a shoulder at about the potential of R_4. These results show that the cation radical of **7** (n = 1) reacts to give a product which reduces at R_4, while the corresponding dication produces a product which undergoes two consecutive reductions at R_3 and R_5. Voltammetric analysis of the products isolated from the preparative electrolysis of **7** (n =



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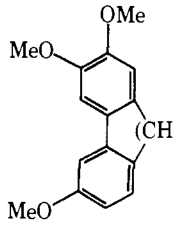

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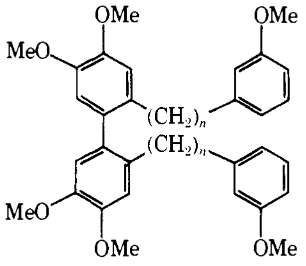

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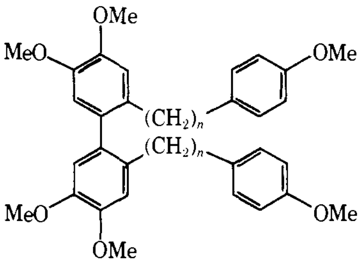

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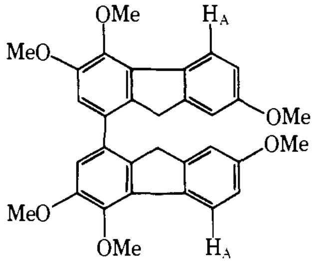

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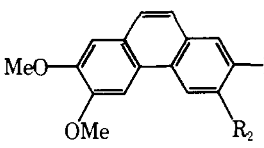
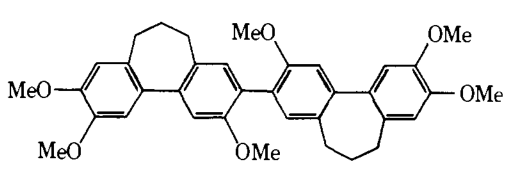


14a, $R_1 = MeO; R_2 = H$
b, $R_1 = H; R_2 = MeO$



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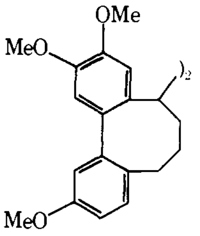

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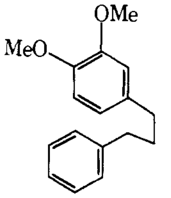

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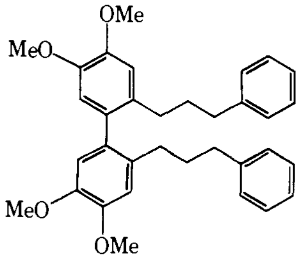

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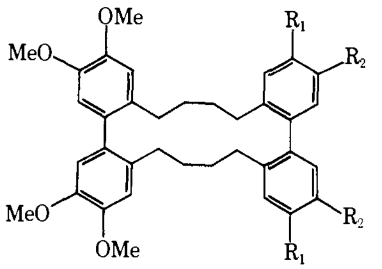


19a, $R_1 = OMe; R_2 = H$
b, $R_1 = H; R_2 = OMe$

1), **9** ($n = 1$), and **11** ($n = 1$) showed that the product formed at O_1 is the cation radical of **11** ($n = 1$), and that formed at O_2 is the dication of **9** ($n = 1$).

Voltammetry of 1-(3,4-Dimethoxyphenyl)-3-(4-methoxyphenyl)propane (8, *n* = 3). The cyclic voltammogram of **8** ($n = 3$) is shown in Figure 2a. At a voltage sweep rate of 31 mV/sec (Figure 2a), an initial oxidation peak (O_1), small peaks for a reversible redox couple (O_2-R_2), an irreversible oxidation peak (O_3), and a reduction peak (R_4) were observed on a complete cycle. The peaks O_3 and R_4 matched those observed during cyclic voltammetry of the product, **10** ($n = 3$). The height of O_3 indicated that substrate was being oxidized nearly quantitatively to **10** ($n = 3$) at that voltage sweep rate. The effect of increasing the sweep rate is illustrated in Figures 2a and 2b. The redox couple (O_2-R_2) became more pronounced with increasing sweep rate, while the relative current at O_3 was diminished. A reduction peak (R_3) corresponding to O_3 was also observed. At 310 mV/sec, O_3-R_3 was very small (Figure 2c). At voltage sweep rates greater than 600 mV/sec, O_3-R_3 was not observed, and the currents at O_1 and O_2 were nearly equal and corresponded to two consecutive one-electron transfers. Thus, it is clear that O_2-R_2 is a reversible redox couple of a short-lived intermediate formed during oxidation of **8** ($n = 3$) to **10** ($n = 3$) which has a lifetime of the order of 1 sec in dichloromethane-TFA (3:1) at room temperature. The reduction peak (R_4) was observed even at high sweep rates which indicates that, under those conditions, it corresponds to a further reduction of the species formed at R_2.

Voltammetry in acetonitrile gave similar results with the height of O_2 showing a marked sweep rate dependence. On the other hand, R_2 was not observed under any conditions in acetonitrile, indicating that the intermediate formed at O_2 was consumed in a rapid chemical reaction.

Results of exhaustive electrolysis of a solution of **8** ($n = 3$) (1.0 m*M*) in dichloromethane-TFA (3:1) containing n-Bu_4NBF_4 (0.2 *M*) are illustrated in Figure 3. The cyclic voltammogram of the substrate with switching potential after O_2 is shown in Figure 3a. The voltammogram after constant current electrolysis (12.5 mA) for a duration of 1.0 Faraday/mol is illustrated in Figure 2b. The only noticeable change taking place after electrolysis is that the height of O_1 is somewhat diminished, and the peak is broader. After 2 Faradays/mol, changes are more significant (Figure 3c). The initial oxidation peak (O_1) and the reversible redox couple (O_2-R_2) because of the intermediate formed during the cyclization are no longer evident, and the voltammogram consists only of the reversible redox couple O_4-R_4. A rotating disk electrode voltammogram (O_5) shows that the species present after two-electron oxidation of **8** ($n = 3$) is in a reduced form. Further one-electron oxi-

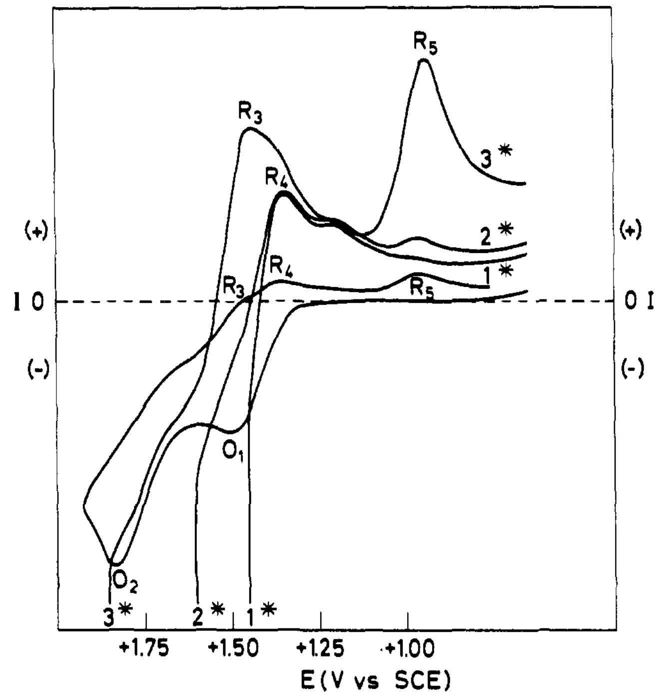


Figure 1. Cyclic and potential step sweep voltammetry of **7** ($n = 1$) in dichloromethane-TFA (3:1) containing n-Bu_4NBF_4 (0.2 M). Voltage sweep rate, 156 mV/sec. Current amplification on the potential step voltammograms is ten times that for the cyclic voltammograms. The potential was held for 15 sec at 1* (+1.45 V), 2* (+1.60 V), and 3* (+1.85 V) before initiating the cathodic sweeps.

dation (Figure 3d) gives no change in the cyclic voltammogram. However, the RDE voltammogram (R_5) now indicated that the product is in the oxidized state, and that the oxidized form is stable during the time scale of the coulometric experiment. Voltammetric analysis of the preparative scale product, **10** ($n = 3$) verified that the species undergoing oxidation at O_4 is indeed the cyclized product **10** ($n = 3$).

From these experiments we can draw the following conclusions. (1) On the coulometric time scale, the overall reaction involves three-electron oxidation of **8** ($n = 3$) to **10** ($n = 3$). (2) On the time scale of cyclic voltammetry (sweep rate 156 mV/sec), the height of O_1 (Figure 2b) as compared with that of O_4 (reversible one-electron oxidation, Figures 3c and 3d) is indicative of the transfer of slightly more than one electron. (3) An intermediate is formed during cyclic voltammetry which gives rise to O_2-R_2 but is not stable during exhaustive electrolysis. (4) The intermediate results from one-electron oxidation of **8** ($n = 3$) and undergoes reversible one-electron oxidation during cyclic voltammetry. The only other compound which showed voltammetric behavior similar to that of **8** ($n = 3$) was **8** ($n = 4$), and the nature of the intermediates formed in these reactions is taken up in the Discussion.

MTA [Manganic Tris(acetylacetonate)[11]] Oxidations. In order to assess the effect of the heterogeneous nature of the anodic reaction, the reactions were carried out with MTA as the oxidant in the same solvent system, dichloromethane-trifluoroacetic acid (TFA) (3:1).[12] The results are summarized in Table III.

Discussion

Four different mechanisms for the oxidative coupling of aromatic nuclei emerged from this work. In general, molecules containing two differently substituted aromatic rings separated by a saturated aliphatic chain undergo two consecutive electron transfers to give first the cation radical and then the dication diradical. When the oxidation of such a molecule is carried out at a potential where only the cation radical is generated, the usual reaction is intermolecular dimerization followed by loss of two protons.[14] This mechanism is well documented in Table I for the runs carried out at low current density. When the reactions of some of these molecules are carried out at a potential where the dication diradicals are generated, intramolecular cation radical coupling can occur to give bridged biphenyls. In order for the latter mechanism to be operative, two conditions must be fulfilled. A favorably sized ring must be formed, and the substituents on the aromatic ring must be suitably located so as to direct coupling between the nuclei. The former condition was satisfied when either a five-, six-, or seven-membered ring was formed [compounds **7** ($n = 1, 2, 3$) and **8** ($n = 2$)].[15] The second condition was satisfied when methoxy groups were situated para to the position of coupling on both rings. The exception in this work was the butane **7** ($n = 4$) where only dimerization was observed (in this case molecular models indicate that the transition state involved in the formation of an eight-membered ring is unfavorable because of steric hindrance). These reactions are documented in Table I and clearly illustrated by the potential sweep voltammograms of Figure 1.

The final two mechanisms involve electrophilic attack of

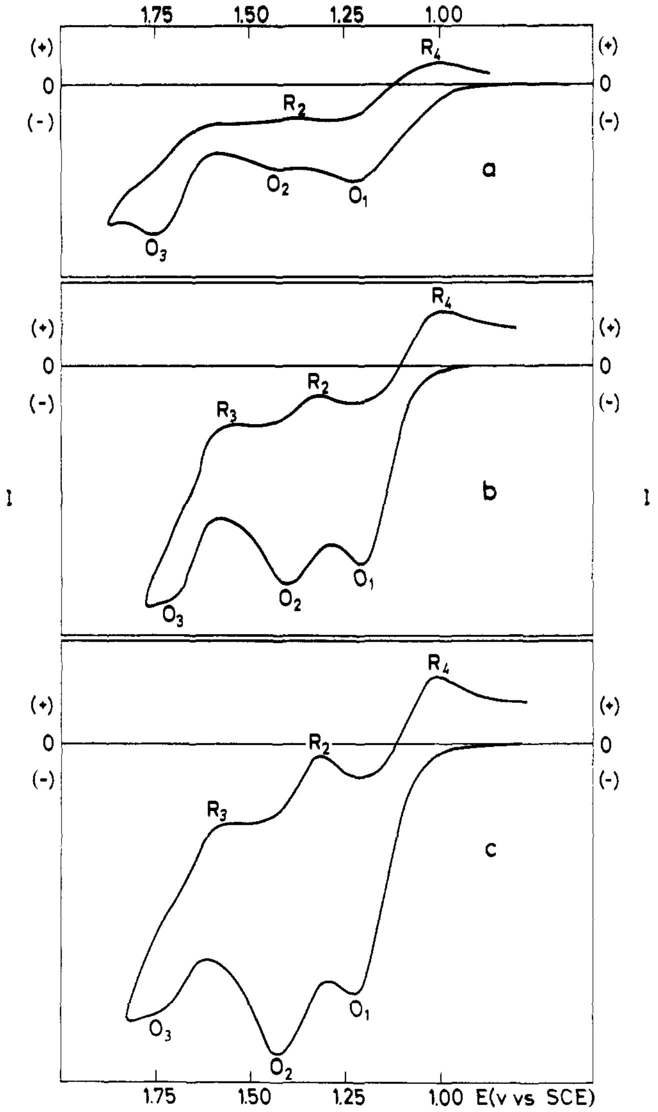


Figure 2. Cyclic voltammograms for the oxidative cyclization of **8** ($n = 3$) in dichloromethane-TFA (3:1) containing n-Bu_4NBF_4 (0.2 M). Voltage sweep rate: (a) 31; (b) 156; (c) 310 mV/sec.

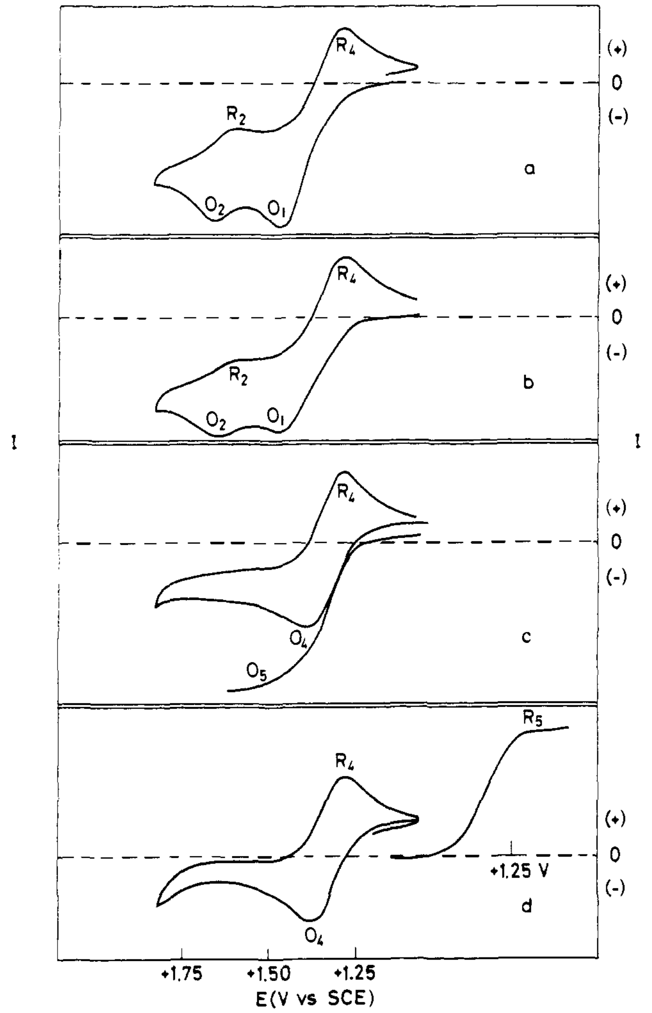
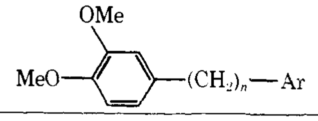


Figure 3. Cyclic and rotating disk electrode voltammograms before, during, and after exhaustive electrolysis of a solution of **8** (n = 3) (1.0 mM) in dichloromethane-TFA (3:1) containing n-Bu_4NBF_4 (0.2 M). Voltage sweep rate, 156 mV/sec. After 0 (a), 1.0 (b), 2.0 (c), and 3.0 Faradays/mol (d) at 12.5 mA.

Table III. Results of MTA Oxidations of



Substrate	Ar	Equiv of MTA	Conversion, %	Product (%)	Principal reaction
7 (n = 1)	m-Methoxyphenyl	2.0	50	**11** (31); **13** (19)	D + C
7 (n = 2)	m-Methoxyphenyl	2.0	82	**11** (8); **9** (2)[a]	D + C
7 (n = 3)	m-Methoxyphenyl	2.0	75	**9** (51)	C
7 (n = 4)	m-Methoxyphenyl	2.0	79	**11** (55); **19a** (22)	D + C
8 (n = 1)	p-Methoxyphenyl	2.0	50	**12** (8)	D
8 (n = 2)	p-Methoxyphenyl	3.0	90	**12** (75)[b]	D
8 (n = 3)	p-Methoxyphenyl	2.0	100	**10** (95)[c]	C
8 (n = 4)	p-Methoxyphenyl	2.0	85	**12** (57); **19b** (14)	D + C
17	Phenyl	1.5	91	**17** (27)	D

[a] With 2 equiv of thallium trifluoroacetate (TTFA) under the same conditions, the conversion was 65%, and the yield of **11** (n = 2) was 8% [no **9** (n = 2) was formed]. [b] In a similar oxidation with TTFA (2 equiv/mol), the conversion was 90% and the yield of **10** (n = 3) was 59%.

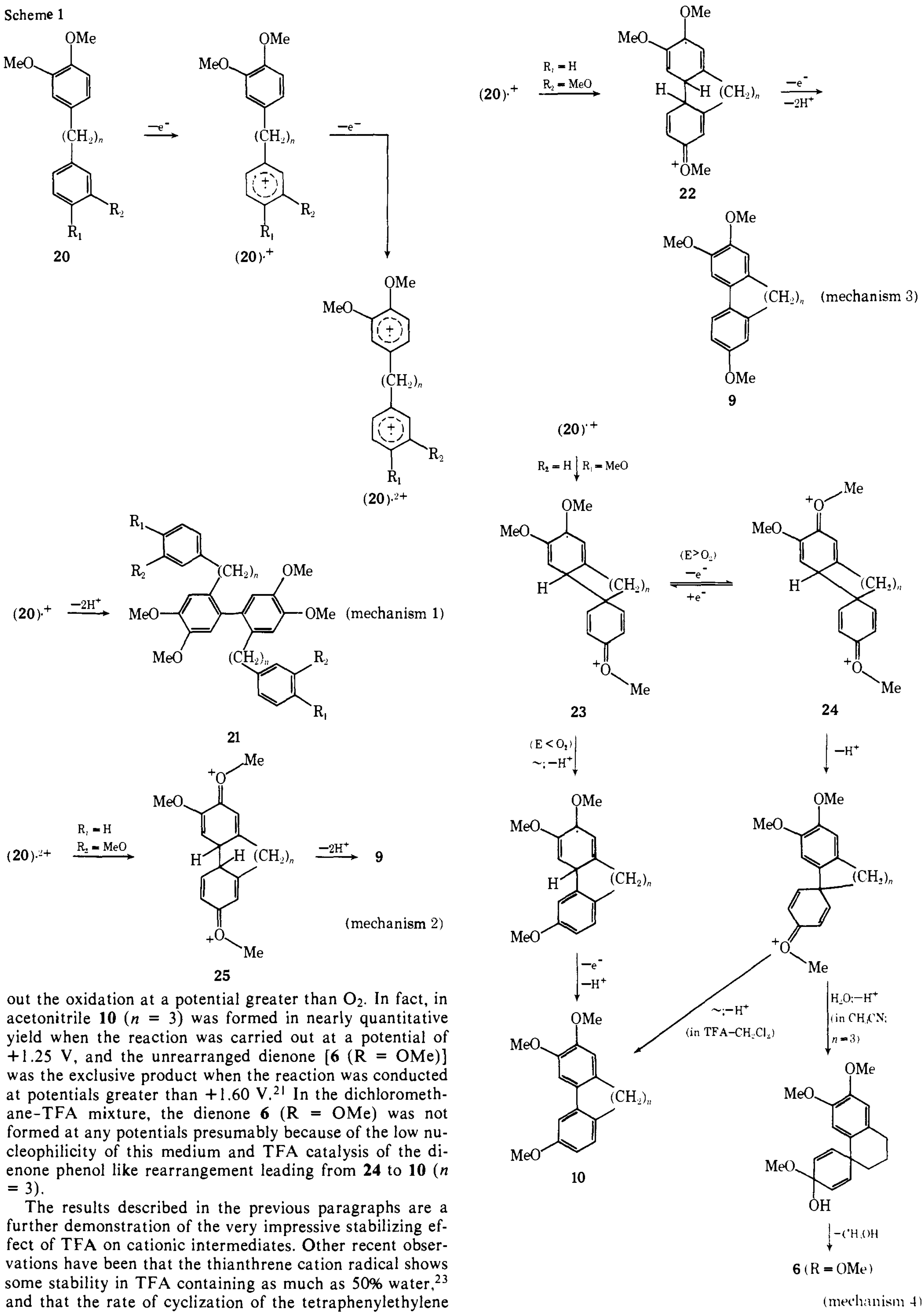
the cation radical at one end of the molecule on the unoxidized aromatic nucleus at the other end. The two mechanisms are differentiated by the position of attack. When the directing methoxy group was meta to the saturated chain, attack occurred at the unsubstituted position para to the substituent and was accompanied by rapid proton loss and further electron transfer to give the bridged biphenyl. The only example[17] of this reaction is the oxidative cyclization of **7** (n = 3). When the directing methoxy group was para to the saturated chain, electrophilic attack occurred at the substituted position to give a long-lived dienone type intermediate cation radical which could be oxidized reversibly at higher potentials. The intermediate eventually was transformed to a bridged biphenyl via a dienone phenol type rearrangement with the aryl group migrating. This reaction was observed in two cases [six- and seven-membered initial ring formation, **8** (n = 3) and **8** (n = 4), respectively] and is exemplified by voltammetric and coulometric experiments illustrated in Figures 2 and 3. The general reaction mechanisms are summarized in Scheme I.

The previous work[2] carried out on the unsymmetrical trimethoxybibenzyl **7** (n = 2) implied that the only important mechanisms for coupling of aromatic nuclei involved the combination of cation radicals. It is now obvious that the factors which control whether intramolecular cyclization and intermolecular dimerization of general structure $\mathbf{20}\cdot^+$ are both geometrical[16] and electronic in nature. The formation of a six-membered ring transition state from $[\mathbf{7}\ (n = 2)]\cdot^+$ or a five membered from $[\mathbf{8}\ (n = 2)]\cdot^+$ is not favorable enough to render the intramolecular reaction competitive with intermolecuular dimerization in spite of the fact that the meta or para methoxy group in the unoxidized ring makes the cyclization electronically favorable. For compounds **7** (n = 3) and **8** (n = 3, 4), the cyclization of the corresponding cation radicals is favorable both on geometric and electronic grounds and is the only reaction pathway observed.

From a mechanistic point of view, perhaps the most interesting observation is that of intermediates during the cyclization of **8** (n = 3 and 4). The structures of the intermediates and their corresponding oxidized forms are assigned as being **23** and **24.** The evidence supporting the structural assignment is based upon the voltammograms illustrated in Figure 2 and the fact that the dienone **6** (R = OMe) is the product observed when **8** (n = 3) is oxidized at a potential of +1.60 V in acetonitrile (vide infra). Assuming that the diffusion coefficients of **8** (n = 3) and **10** (n = 3) are very similar[18] since the oxidation of **10** (n = 3) (Figure 3c)[20] involves a reversible one-electron transfer the oxidation of **8** (n = 3) under voltammetric conditions (Figure 3a)[20] can only involve the transfer of about 1.5 electrons and that for the intermediate about 0.5 electrons. Furthermore, when the length of the time gate for observation of the intermediate was shortened by increasing the voltage sweep rate, the relative number of electrons transferred at O_1 and O_2-R_2 changed and approached one electron at each oxidation stage. Thus, the couple O_2-R_2 is due to the first product of oxidation of **8** (n = 3), and the evidence is compelling that the couple is due to **23** and **24.**

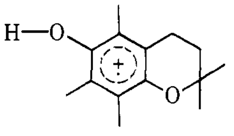
The sweep rate dependence for the observation of the reversible couple (O_2-R_2) suggested that the intermediate oxidized at O_2 undergoes a relatively slow chemical reaction which is out-run as the voltage sweep rate is increased. The latter suggested that it might be possible to observe different products if the chemical step was precluded by carrying

Scheme 1

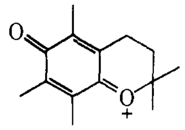


out the oxidation at a potential greater than O_2. In fact, in acetonitrile **10** (n = 3) was formed in nearly quantitative yield when the reaction was carried out at a potential of +1.25 V, and the unrearranged dienone [**6** (R = OMe)] was the exclusive product when the reaction was conducted at potentials greater than +1.60 V.[21] In the dichloromethane-TFA mixture, the dienone **6** (R = OMe) was not formed at any potentials presumably because of the low nucleophilicity of this medium and TFA catalysis of the dienone phenol like rearrangement leading from **24** to **10** (n = 3).

The results described in the previous paragraphs are a further demonstration of the very impressive stabilizing effect of TFA on cationic intermediates. Other recent observations have been that the thianthrene cation radical shows some stability in TFA containing as much as 50% water,[23] and that the rate of cyclization of the tetraphenylethylene dication decreases by a factor of about 10^6 in going from dichloromethane containing 0.1% TFA to pure TFA.[24] Perhaps observations even more pertinent to the present discussion are that both the cation radical **26** and the dienonium ion **27** from the oxidation of the corresponding α-tocopherol model compound have been found to be remarkably stable in the presence of TFA.[25]



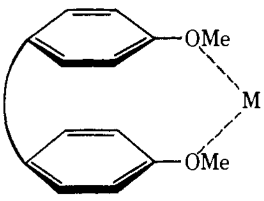
26



27

At first glance, structures **10** (n = 3 and 4) appear to be very similar, and one would expect the further oxidation products of these two compounds to be very similar. However, **10** (n = 3) undergoes dimerization at an aromatic position to form **15**, while **10** (n = 4) couples at a benzylic position producing **16**. Inspection of models of the two compounds reveals that they are indeed quite different. The compound containing the butane carbon chain **10** (n = 4) cannot assume a conformation in which both of the aromatic rings are in the same plane while the latter conformation can readily be assumed by **10** (n = 4). Thus, there is very little delocalization of charge or unshared electron to the ring containing the single methoxy group in the cation radical of **10** (n = 4), while delocalization in the case of the cation radical of **10** (n = 3) allows dimerization to take place through the unsubstituted para position of the biphenyl linkage. That delocalization is not altogether effective even in $[\mathbf{10}\ (n = 3)]^{\cdot +}$ is shown by the fact that the latter ion radical is relatively stable.[26]

In general the yields of isolated products were greater for the anodic oxidations than for the MTA oxidations. However, the most significant difference evident from comparing Tables I and III is that cyclization is a common reaction at the anode but occurred only in the case of **7** (n = 3) and **8** (n = 3) with MTA. This is probably a reflection of the one-electron oxidizing capabilities of MTA. Another outstanding difference in the two sets of data is that large ring compounds are formed after initial dimerization for both **7** (n = 4) and **8** (n = 4) during MTA oxidation but not during anodic oxidation.[28] The latter implies that the two ends of the initial dimer, for example, **11** (n = 4), are brought together by chelation to the metal atom before the final oxidation takes place as in **29**.



29

Experimental Section

Procedures and apparatus for voltammetry and coulometry have previously been described.[6,30] All melting point are uncorrected. Nmr spectra were recorded on a Varian Associates A-60A instrument with tetramethylsilane as internal standard. (The spectrum of **24** (n = 3) was recorded with CH_2Cl_2 as internal standard.) Mass spectral data were obtained with a LKB-6000 instrument. The diarylmethanes **7** (n = 1) and **8** (n = 1) were prepared by Friedel-Crafts reaction of 3- and 4-methoxybenzoyl chloride with veratrol,[31] followed by hydrogenolysis in ethanol over a palladium on carbon catalyst. The bibenzyls **7** (n = 2) and **8** (n = 2) were prepared from veratric aldehyde and 3- and 4-methoxybenzaldehyde respectively, by a route described previously. The diarylpropanes **7** (n = 3), **8** (n = 3), and **17** were prepared by condensation of veratric aldehyde with 3- or 4-methoxyacetophenone or acetophenone, respectively, followed by catalytic reduction and hydrogenolysis over a palladium on carbon catalyst in ethanol. The diarylbutanes **7** (n = 4) and **8** (n = 4) were prepared by Grignard reaction[32] of 4-(3- or 4-methoxyphenyl)bromobutane with veratric aldehyde, followed by hydrogenolysis as described above.

Preparative Electrolysis. General The compound to be oxidized (7.0 mmol) was dissolved in TFA:CH_2Cl_2 (1:3, 230 ml) containing n-Bu_4NBF_4 (3 g) and transferred to the anode chamber of a closed two-compartment cell divided by a glass frit (G-4). The anode was a platinum cylinder (area 150 cm^2) and the cathode a coil of platinum wire. The electrolysis was carried out at constant current with efficient magnetic stirring. The temperature was kept at −20° by a cryostat, and nitrogen was bubbled through the solution. When the desired amount of current had been passed through the cell, zinc dust (3 g) was added and stirring continued for 1 more hr at −20°. Water (100 ml) was added and the organic phase separated and washed with saturated bicarbonate solution (2 × 50 ml) and water (50 ml) and then evaporated to dryness. The oily residue was chromatographed on a silica gel column (200 g) with a toluene–ethyl acetate gradient. The various fractions were analyzed by TLC, NMR, and mass spectrometry. The results are summarized in Table I.

Oxidations with MTA and TTFA. General. The compound to be oxidized (2 mmol) was dissolved in TFA:CH_2Cl_2 (1:3, 50 ml), and MTA or TTFA dissolved in TFA:CH_2Cl_2 (16 ml) was added during 1 hr. The temperature was kept at −20°, and N_2 was bubbled through the solution. After addition stirring was continued for 2 hr. Zinc dust (1 g) was added and stirring continued for 1 more hr at −20°. The resulting solution was worked up as described in the preparative electrolysis.

(3,4-Dimethoxyphenyl)(3-methoxyphenyl)methane 7 (n = 1): mp (ethanol) 38–39°; NMR δ 6.63 (s, 3 H), 3.68 (s, 6 H), 3.80 (s, 2 H), 6.56–7.23 (m, 7 H); M^+ 258.

Anal. Calcd for $C_{16}H_{18}O_3$: C, 74.4; H, 7.0. Found: C, 74.7; H, 7.1.

(3,4-Dimethoxyphenyl)(4-methoxyphenyl)methane (8, n = 1): mp 30–32°; NMR δ 3.80 (s, 3 H), 3.87 (bs, 8 H), 6.78 (bs, 3 H), 6.86 (d, J = 9 Hz, 2 H), 7.14 (d, J = 9 Hz, 2 H); m/e 258 (M^+).

Anal. Calcd for $C_{16}H_{18}O_3$: C, 74.4; H, 7.0. Found: 74.5; H, 7.0.

1-(3,4-Dimethoxyphenyl)-2-(4-methoxyphenyl)ethane (8, n = 2): mp (ethanol) 72–73°; NMR δ 2.76 (s, 2 H), 3.66 (s, 3 H), 3.73 (s, 6 H), 6.66 (s, 3 H), 6.86 (q, J = 9 Hz, 4 H); m/e 272 (M^+).

Anal. Calcd for $C_{17}H_{20}O_3$:C, 75.0; H, 7.4. Found: C , 74.9; H, 7.3.

1-(3,4-Dimethoxyphenyl)-3-(3-methoxyphenyl)propane (7, n = 3): mp 46–47°; NMR δ 1.91 (m, 2 H), 2.50 (m, 4 H), 3.66 (three closely spaced singlets, 9 H), 6.61–7.33 (m, 7 H); m/e 286 (M^+).

Anal. Calcd for $C_{18}H_{22}O_3$: C, 75.5; H, 7.7. Found: C, 75.3; H, 7.7.

1-(3,4-Dimethoxyphenyl)-3-(4-methoxyphenyl)propane (8, n = 2): bp 181–182° (1 mm); NMR δ 1.90 (m, 2 H), 2.51 (m, 4 H), 3.66 (s, 3 H), 3.71 (s, 6 H), 6.63 (s, 3 H), 6.90 (q, J = 9 Hz, 4 H); m/e 286 (M^+).

Anal. Calcd for $C_{18}H_{22}O_3$: C, 75.5; H, 7.7. Found C, 75.6; H, 7.6.

1-(3,4-Dimethoxyphenyl)-4-(3-methoxyphenyl)butane (7, n = 4): mp 41–42°; NMR δ 1.67 (m, 4 H), 2.58 (m, 4 H), 3.77 (s, 3 H), 3.83 (s, 6 H), 6.78 (m, 6 H), 7.17 (m, 1 H); m/e 300 (M^+).

Anal. Calcd for $C_{19}H_{24}O_3$: C, 76.0; H, 8.0. Found: C, 75.8; H, 8.1.

1-(3,4-Dimethoxyphenyl)-4-(4-methoxyphenyl)butane (8, n = 4): mp 43–44°; NMR δ 1.60 (m, 4 H), 2.57 (m, 4 H), 3.73 (s, 3 H), 3.83 (s, 6 H), 6.70 (bs, 3 H), 6.76 (d, J = 8.5 Hz, 2 H), 7.07 (d, J = 8.5 Hz, 2 H); m/e 300 (M^+).

Anal. Calcd for $C_{19}H_{24}O_3$: C, 76.0; H, 8.0. Found: C, 76.1; H, 8.1.

1-(3,4-Dimethoxyphenyl)-3-phenylpropane (17): bp 173–174° (1 mm); NMR δ 1.95 (m, 2 H), 2.58 (m, 4 H), 3.80 (s, 6 H), 6.71 (bs, 3 H), 7.20 (bs, 5 H); m/e 256 (M^+).

Anal. Calcd for $C_{17}H_{20}O_2$: C, 79.7; H, 7.8: Found: C, 79.6; H, 7.8.

2,2′-Bis(3-methoxybenzyl)-4,4′,5,5′-tetramethoxybiphenyl (11, n = 1): mp 76–77°; NMR δ 3.68 (s, 6 H), 3.78 (s, 12 H), 3.85 (s, 4

H), 6.72 (m, 10 H), 7.12 (m, 2 H); *m/e* 514 (M^+).

Anal. Calcd for $C_{32}H_{34}O_6$: C, 74.7; H, 6.6. Found: C, 74.6; H, 6.6.

2,3,7-Trimethoxyfluorene (9, *n* = 1): mp 168–169° (sublim); NMR δ 3.72 (s, 2 H), 3.80 (s, 3 H), 3.87 (s, 3 H), 5.60 (s, 3 H), 6.92 (m, 3 H), 7.15 (s, 1 H), 7.48 (d, J = 8 Hz, 1 H); *m/e* 256 (M^+).

Anal. Calcd for $C_{16}H_{16}O_3$: C, 75.0; H, 6.3. Found: C, 74.8; H, 6.4.

1,1′-Bis(3,4,7-trimethoxyfluorene) (13): mp (EtOH) 250–251°; NMR δ 3.43 (s, 6 H), 3.62 (s, 4H), 3.98 (s, 6 H), 4.03 (s, 6 H), 6.90 (m, 6 H, arom), 7.43 (d, J = 9 Hz, 2 H, H_A); *m/e* 510 (M^+).

Anal. Calcd for $C_{32}H_{30}O_6$: C, 75.3; H, 5.9. Found: C, 75.2; H, 6.0.

2,2′-Bis(4-methoxybenzyl)4,4′,5,5′-tetramethoxybiphenyl (12, *n* = 1): mp 81–85°; NMR δ 3.77 (s, 12 H), 3.88 (bs, 10 H), 6.73 (s, 2 H), 6.92 (s, 2 H), 6.82 (d, J = 9 Hz, 4 H), 7.14 (d, J = 9 Hz, 4 H); *m/e* 514 (M^+).

Anal. Calcd for $C_{32}H_{34}O_6$: C, 74.7; H, 6.6. Found: C, 74.8; H, 6.7.

2,2′-Bis(2-(4-methoxyphenyl)ethyl)-4,4′,5,5′-tetramethoxybiphenyl (12, *n* = 2): mp 114–115° (EtOH); NMR δ 2.67 (bs, 8 H), 3.72 (s, 6 H), 3.82 (s, 6 H), 3.88 (s, 6 H), 6.65 (s, 2 H), 6.77 (s, 2 H), 6.73 (d, J = 9 Hz, 4 H), 6.93 (d, J = 9 Hz, 4 H); *m/e* 542 (M^+).

Anal. Calcd for $C_{34}H_{38}O_6$: C, 75.3; H, 7.0. Found: C, 75.4; H, 6.9.

3,6,7-Trimethoxyphenanthrene (14b): mp, 128–129° (EtOH); NMR δ 3.97 (s, 6 H), 4.03 (s, 3 H), 7.15–7.83 (m, 7 H); *m/e* 268 (M^+).

Anal. Calcd for $C_{17}H_{16}O_3$: C, 76.1, H, 6.0. Found: C, 76.1; H, 6.1.

1,2-(5-Methoxybenzo)-3,4-(4,5-dimethoxybenzo)cycloheptane (9, *n* = 3): mp 25–26°; NMR δ 2.0–2.6 (m, 6 H), 3.82 (s, 3 H), 3.89 (s, 6 H), 6.67–7.20 (m, 5 H); *m/e* 284 (M^+).

Anal. Calcd for $C_{18}H_{20}O_3$: C, 76.1; H, 7.0. Found: C, 75.9; H, 7.1.

1,2-(4-Methoxybenzo)-3,4-(4,5-dimethoxybenzo)cycloheptane (10, *n* = 3): mp (EtOH) 79–80°; NMR δ 1.86–2.73 (m, 6 H), 3.86 (s, 3 H), 6.86–7.13 (m, 5 H); *m/e* 284 (M^+).

Anal. Calcd for $C_{18}H_{20}O_3$: C, 76.1; H, 7.0. Found: C, 76.1; H, 7.0.

3,4,3′2″,3‴,4‴-Hexamethoxy-6,6′:5″,6‴-bis(trimethylene)quaterphenyl (15): mp (acetone) 269–270°; NMR δ 1.97–1.73 (m, 12 H), 3.83 (s, 6 H), 3.92 (s, 12 H), 6.75 (s, 2 H), 6.98 (s, 4 H), 7.13 (s, 2 H); *m/e* 566 (M^+).

Anal. Calcd for $C_{36}H_{38}O_6$: C, 76.3; H, 6.7. Found: C, 76.2; H, 6.7.

2,2′-Bis-(4-(3-methoxyphenyl)butyl)-4,4′,5,5′-tetramethoxybiphenyl (11, *n* = 4): mp 52–53°; NMR δ 1.47 (m, 8 H), 2.47 (m, 8 H), 3.74 (s, 12 H), 3.90 (s, 6 H), 6.67 (m, 10 H), 7.08 (m, 2 H); *m/e* 598 (M^+). .

Anal. Calcd for $C_{38}H_{46}O_6$: C, 76.3; H, 7.7. Found: C, 76.0; H. 7.9.

Compound 19a: mp 120–121°; NMR δ 1.28–3.00 (m, 16 H), 3.57 (s, 6 H), 4.07 (s, 6 H), 4.15 (s, 6 H), 6.83 (m, 8 H), 7.07 (d, J = 8.5 Hz, 2 H); *m/e* 596 (M^+).

Anal. Calcd for $C_{38}H_{44}O_6$: C, 76.5; H, 7.4. Found: C, 76.4; H, 7.3.

1,2(4-Methoxybenzo)-3,4-(4,5-dimethoxybenzo)cyclooctane (10, *n* = 4): Mp; NMR δ 1.5–2.9 (m, 8 H), 3.67 (s, 3 H), 3.80 (s, 3 H), 3.87 (s, 3 H), 6.70 (m, 2 H), 6.92 (s, 1 H), 6.97 (s, 1 H), 7.22 (d, J = 8 Hz, 1 H); *m/e* 298 (M^+).

Anal. Calcd for $C_{19}H_{22}O_3$: C, 76.5; H, 7.4. Found: C, 76.4; H, 7.4.

Compound 16: mp 202–203°; NMR δ 1.5–3.0 (m, 14 H), 3.33 (s, 6 H), 3.77 (s, 12 H), 6.7–7.1 (m, 10 H), 4.53 (m, 2 H); *m/e* 594 (M^+).

Anal. Calcd for $C_{38}H_{42}O_6$: 76.8; H, 7.1. Found: C, 76.8; H, 7.2.

Compound 19b: mp 165–167°; NMR δ 1.3–3.0 (m, 16 H), 3.83 (s, 6 H), 3.88 (s, 6 H), 3.93 (s, 6 H), 6.80 (m, 8 H), 7.20 (d, J = 8.2 Hz, 2 H); *m/e* 596 (M^+).

Anal. Calcd for $C_{38}H_{44}O_6$: C, 76.5; H, 7.4. Found: C, 76.4; H, 7.5.

2,2′-Bis(4-(4-methoxyphenyl)butyl)-4,4′,5,5′-tetramethoxybiphenyl (12, *n* = 4): mp 63–65°; NMR δ 1.50 (m, 8 H), 2.42 (m, 8 H), 3.80 (s, 12 H), 3.95 (s, 6 H), 6.63 (s, 2 H), 6.78 (s, 2 H), 6.80 (d, J = 8 Hz, 4 H), 7.03 (d, J = 8 Hz, 4 H); *m/e* 598 (M^+).

Anal. Calcd for $C_{38}H_{46}O_6$: C, 76.3; H, 7.7. Found: 76.5; H, 7.6.

References and Notes

(1) (a) University of Copenhagen; (b) The Lund Institute of Technology.

(2) A. Ronlán, O. Hammerich, and V. D. Parker, *J. Am. Chem. Soc.*, **95**, 7132 (1973).

(3) Potentials here are $E_{1/2}$ values at the rotating disk electrode, and all potentials cited in this paper are for oxidation or reduction at platinum disk electrodes and are referred to the saturated aqueous calomel electrode.

(4) M. A. Schwartz, B. F. Rose, and B. Vishnuvajjala, *J. Am. Chem. Soc.*, **95**, 612 (1973).

(5) U. Palmquist, A. Ronlán, and V. D. Parker, *Acta Chem. Scand., Ser. B*, **28**, 267 (1974).

(6) V. D. Parker, *Acta Chem. Scand.*, **24**, 2768 (1970).

(7) Potential step sweep voltammetry can be a very useful diagnostic tool in the study of electrode processes when the initial oxidation products, cation radical and dication, either react to form different products[8] or react at different rates.[9]

(8) L. Papachoudo, J. Bacon, and R. N. Adams, *J. Electroanal. Chem.*, **24**, App 1 (1970).

(9) V. D. Parker and L. Eberson, *J. Am. Chem. Soc.*, **92**, 7488 (1970).

(10) A small unidentified peak appeared about 150 mV cathodic of R_4.

(11) M. J. S. Dewar and T. Nakaya, *J. Am. Chem. Soc.*, **90**, 7134 (1968).

(12) This solvent composition has recently been observed to give the best results for coupling of simple aromatic ethers.[13]

(13) A. Ronlán, K. Bechgaard, and V. D. Parker, *Acta Chem. Scand.*, **27**, 2375 (1973).

(14) Similarly only symmetrical dimers are formed during anodic oxidation of 4-methylveratrole in the presence of anisole.

(15) In analogy with **8** (*n* = 3 and 4), the oxidation of **8** (*n* = 2) to **14b** is believed to proceed via intermediates **23** (*n* = 2), **24** (*n* = 2), and **10** (*n* = 2).

(16) Investigation of molecular models shows that only for *n* = 3, 4 are favorable orientations for intramolecular coupling of the aryl groups possible without imposing strain.

(17) Oxidation of **7** (*n* = 1) at low potential leads to formation of a small amount of the cyclized product **9** (*n* = 1), indicating that cyclization via electrophilic attack competes with dimerization in this particular case.

(18) This would appear to be a very reasonable assumption since it has been found that, even for compounds of widely differing structure, the diffusion coefficients varied only by about ±25%,[19] and very little difference would be expected for two compounds as similar as **8** (*n* = 3) and **10** (*n* = 3).

(19) J. Bacon and R. N. Adams, *Anal. Chem.*, **42**, 524 (1970).

(20) Voltage sweep rate 156 mV/sec.

(21) Compound **6** was isolated in 91% yield[22] and identified by comparison of the NMR, mass, and ir spectra with those of the authentic compound prepared by either chemical[4] or electrochemical[5] oxidation of the corresponding phenol.

(22) V. D. Parker, U. Palmquist, and A. Ronlán, *Acta Chem. Scand. Ser. A*, **28**, 1241 (1974).

(23) O. Hammerich, N. S. Moe, and V. D. Parker, *J. Chem. Soc., Chem. Commun.*, 156 (1972).

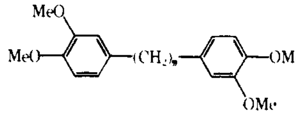
(24) U. Svanholm, A. Ronlán, and V. D. Parker, *J. Am. Chem. Soc.*, **96**, 5108 (1974).

(25) U. Svanholm, K. Bechgaard, and V. D. Parker, *J. Am. Chem. Soc.*, **96**, 2409 (1974).

(26) A recent systematic study of the effect of the biphenyl linkage on cation radical stability has shown that in general, if para positions are unsubstituted, rapid dimerization can be expected.[27] The reactions are greatly influenced also by steric factors, and the presence of the methoxy group in the meta position could also contribute to the reduced reactivity.

(27) A. Ronlán, J. Coleman, O. Hammerich, and V. D. Parker *J. Am. Chem. Soc.*, **96**, 845 (1974).

(28) Compounds similar to **19** are formed during anodic oxidation of symmetrically substitued bis(3,4-dimethoxyphenyl)alkanes **28** during anodic oxidation.[29] The latter reactions are believed to proceed via the dication diradicals oriented parallel to one another.



28 (*n* > 6)

(29) A. Ronlán and V. D. Parker, *J. Org. Chem.*, **39**, 1014 (1974).

(30) O. Hammerich and V. D. Parker, *J. Chem. Soc., Perkin Trans. 2*, 1718 (1972).

(31) C. W. Perry, M. V. Kalnius, and K. H. Deitcher, *J. Org. Chem.*, **37**, 4371 (1972).

(32) H. Gilman and S. H. Harris, *J. Am. Chem. Soc.*, **54**, 2075 (1932).