Mechanistic Aspects and Synthetic Applications of the Electrochemical and Iodobenzene Bis(trifluoroacetate) Oxidative 1,3-Cycloadditions of Phenols and Electron-Rich Styrene Derivatives

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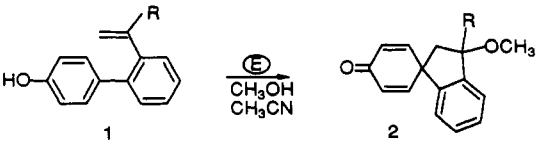
Anodic oxidation of *p*-methoxy-substituted phenols and electron-rich styrene or propenylbenzene derivatives affords in good yield *trans*-dihydrobenzofurans derived from a formal 1,3-oxidative cycloaddition of the phenol to the styrene derivative. The yield of product in this electrochemical oxidation depends upon the ratio of phenol to styrene derivative, current density, and to a lesser extent the amount of supporting electrolyte. While *p*-methoxyphenol and 4-methoxy-3-methylphenol give good yields of the dihydrobenzofurans using 1:1 molar ratio of reactants, 3,4-dimethoxyphenol requires a 3–4 molar excess of the styrene derivative for a comparable yield of product. Although 4-methoxy-1-naphthol shows yields comparable to *p*-methoxyphenol in the anodic cycloaddition reaction, 1- and 2-naphthol gave very low yields of product. Qualitatively, *trans*- and *cis*-1,2-dimethoxy-4-propenylbenzene show similar yields in the cycloaddition reaction. Many of these same substrates were examined using iodobenzene bis(trifluoroacetate) as oxidant, and the same products were formed as in the electrochemical oxidations noted above. However, for the reaction of 2-naphthol and 1,2-dimethoxy-4-propenylbenzene the iodobenzene bis(trifluoroacetate) oxidation gave a much better yield of the product. A mechanism involving reaction of a phenoxy radical–styrene radical cation pair is considered and discussed.

Introduction

The widespread availability and ease of oxidation of phenolic compounds in the presence of other functionalities makes these moieties attractive substrates for oxidative functionalization reactions. Oxidative phenolic coupling reactions and reactions of oxidized phenol intermediates with oxygen nucleophiles[1,2] are well-known and often comprise useful synthetic processes. Less common are carbon–carbon bond-forming reactions arising from addition of carbon nucleophiles to oxidized phenols.[3,4] Such reactions have great synthetic potential since they can be performed electrochemically with no spent oxidant produced in the process. We have been interested in understanding and exploiting oxidative carbon–carbon bond-forming reactions of phenolic substrates. Earlier work has dealt with reactions wherein olefinic side chains underwent oxidative cyclization reactions to furnish spiro-2,5-cyclohexadienones as illustrated in Scheme I.[4] Of more general interest are bimolecular reactions of oxidized phenol intermediates leading to carbon–carbon bond-forming products. This paper details the bimolecular reaction of electron-rich styrene derivatives and phenols under oxidative conditions resulting in an efficient synthesis of substituted dihydrobenzofuran derivatives.[5]

Scheme I. Anodic Cyclizations of 4-(2′-Alkenylphenyl)-phenols



1 2

Anodic Cycloaddition Studies. Our work on the intramolecular olefinic cyclization reactions of 4-(2′-alkenylphenyl)phenols demonstrated that only vinyl derivatives having nucleophilic double bonds give good yields of cyclization products.[4] Thus, the olefinic substrates chosen for our exploratory studies were commercially available methoxy-substituted propenylbenzene derivatives having electron-rich double bonds. A second consideration in our choice of reagents was the synthetic interest in neolignan natural products possessing the dihydrobenzofuran ring system[6,7] which dictated the choice of phenols to be investigated. Initially, anodic oxidation studies of *p*-methoxyphenol and 1,2-dimethoxy-4-propenylbenzene proved disappointing as complex reaction mixtures with low yields of product were observed. In fact, the anodic oxidation approach was abandoned in favor of iodobenzene diacetate oxidation of the phenol.[5] This chemistry is described later in this paper, and the results are compared with the electrochemical oxidations. Although the reason for these initial failures is not entirely clear, the studies discussed below establish the dependence of the yield of these anodic oxidations on reaction conditions.

Our first successful anodic oxidations were conducted using a platinum mesh anode and platinum sheet cathode

(1) For leading references to phenol oxidations leading to quinone monoketals, see the following: Swenton, J. S. Chemistry of Quinone Bis- and Monoketals. In *The Chemistry of Quinonoid Compounds*; Patai, S., Rappoport, Z., Eds.; John Wiley & Sons: New York, 1988; pp 918–925.

(2) For extensive discussions of electrochemical phenol oxidations, see the following: (a) Yoshida, K. *Electrooxidation in Organic Synthesis*; John Wiley and Sons: New York, 1984; pp 126–151. (b) Torii, S. *Electroorganic Synthesis, Methods and Applications*; VCH Monographs in Modern Chemistry; Deerfield Beach, FL, 1984. (c) Nilsson, A.; Palmquist, U.; Pettersson, T.; Ronlân, A. *J. Chem. Soc., Perkin Trans. 1* **1978**, 696. (d) Reiker, A.; Beisswenger, R.; Regier, K. *Tetrahedron* **1991**, *47*, 645.

(3) For leading references, see the following: Yamamura, S. *Electroorganic Synthesis*; Little, R. D., Weinberg, N. L., Eds.; Marcel Dekker: New York, 1991; pp 309–315. Yamamura, S.; Shizuri, Y.; Shigemori, H.; Okuno, Y.; Ohkubo, M. *Tetrahedron* **1991**, *47*, 635.

(4) (a) Morrow, G. W.; Swenton, J. S. *Tetrahedron Lett.* **1987**, *28*, 5445. (b) Callinan, A.; Chen, Y.; Morrow, G. W.; Swenton, J. S. *Tetrahedron Lett.* **1990**, *31*, 4551. (c) Morrow, G. W.; Chen, Y.; Swenton, J. S. *Tetrahedron* **1991**, *47*, 655.

(5) For a preliminary report of the iodobenzene bis(trifluoroacetate) oxidations, see: Wang, S.; Gates, B. D.; Swenton, J. S. *J. Org. Chem.* **1991**, *56*, 1979.

(6) (a) Lima, O. A.; Gottlieb, O. R.; Magalhaes, M. T. *Phytochemistry* **1972**, *11*, 2031. (b) von Bulow, M. V.; Franca, N. C.; Gottlieb, O. R.; Suarez, A. M. P. *Phytochemistry* **1973**, *12*, 1805. (c) Gottlieb, O. R.; da Silva, M. L.; Ferreira, Z. S. *Phytochemistry* **1975**, *14*, 1825. (d) Aiba, C. J.; Fernandes, J. B.; Gottlieb, O. R.; Sores Maia, J. G. S. *Phytochemistry* **1975**, *14*, 1597. (e) Shen, T. Y.; Hwang, S.-B.; Chang, M. N.; Doeber, T. W.; Lam, M.-H. T.; Wu, M. S.; Wang, X.; Han, G. Q.; Li, R. Z. *Proc. Natl. Acad. Sci. U.S.A.* **1985**, *82*, 672. (f) Iida, T.; Ichino, K.; Ito, K. *Phytochemistry* **1982**, *21*, 2939.

(7) For a discussion of the biosynthesis of *neolignans*, see the following: (a) Gottlieb, O. R. *Phytochemistry* **1972**, *11*, 1537. (b) Angle, S. R.; Turnbull, K. D. *J. Am. Chem. Soc.* **1990**, *112*, 3698 and references cited therein.

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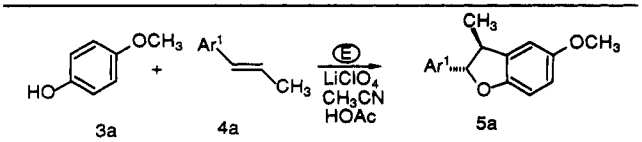
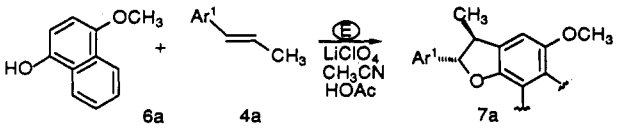
Table I. Anodic Cyclizations[a] of 4-Methoxyphenol and 4-Methoxynaphthol with 1,2-Dimethoxy-4-propenylbenzene



3a 4a 5a

entry	3a (M)	4a[b] (M)	$LiClO_4$ (wt %)	mA	time (min)	5a yield (%)
1	0.046	0.046	0.4	80	270	61
2	0.046	0.046	0.4	200	72	43
3	0.046	0.046	0.8	200	90	49
4	0.046	0.046	2.0	200	105	55
5	0.046	0.046	0.4	400	50	39
6	0.092	0.092	0.8	80	380	65
7	0.184	0.184	1.2	100	540	63



6a 4a 7a

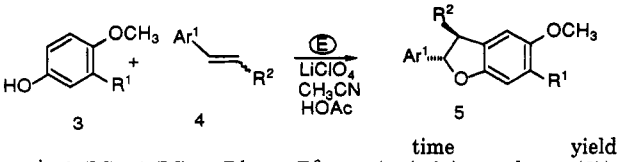
entry	6a (M)	4a[b] (M)	$LiClO_4$ (wt %)	mA	time (min)	7a yield (%)
8	0.031	0.025	0.4	80	150	76
9	0.031	0.025	0.4	200	40	55
10	0.031	0.025	0.8	200	60	69
11	0.057	0.050	1.3	200	60	68
12	0.031	0.027	0.8	400	35	--[c]

[a] Reactions were conducted in 8:1 CH_3CN/HOAc using a platinum anode and cathode (see Experimental Section for details). [b] The 1,2-dimethoxy-4-propenylbenzene was a ca. 90:10 trans–cis mixture. [c] No product could be isolated.

with *p*-methoxyphenol, **3a**, and 1,2-dimethoxy-4-propenylbenzene, **4a**, in 8:1 CH_3CN/HOAc using lithium perchlorate as supporting electrolyte. From this reaction a good yield of the dihydrobenzofuran **5a** was isolated. The structure of **5a** was supported by ^1H NMR and IR spectroscopy. For all of the adducts herein the stereochemistry of the methyl and aryl group on the furan side chain has been assigned as trans. This assignment was based on the chemical shift of the methyl group since it is known that in structures of this type the *trans*-methyl resonance in the ^1H NMR spectrum appears at $\delta \approx 1.3$ and the more shielded methyl group in the cis isomer at $\delta \approx 0.7$.[8] Later, this assignment was confirmed for two particular compounds by comparison of the ^1H NMR spectrum of the oxidative cycloaddition product with that reported.

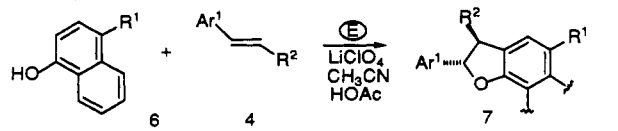
The data in Table I illustrate the effect of some of the reaction variables on the yield of dihydrobenzofurans. First, good yields of **5a** and **7a** could be obtained from reactions employing the reagents in nearly stoichiometric quantities. The few examples of bimolecular anodic carbon–carbon bond-forming reactions involving phenols and olefinic systems have employed a 10- to 20-fold excess of olefinic partner.[9] Second, the yield of **5a** and **7a** is a function of current density[4a] as illustrated by entries 1, 2, and 5 and 8, 9, and 12. For the former entries the yield of **5a** decreases from 61% to 39% as the current increases from 80 to 400 mA; for the latter series the yield is nearly zero when the reaction is performed at 400 mA. Thus, the effect of current density on yield is also a function of the phenol structure. Since the current density depends on both the area of the electrode and the current, these must be optimized for an individual experimental setup. The

Table II. Anodic Cyclizations[a] of Phenols and Styrenes



3 4 5

entry[b]	3 (M)	4 (M)	R^1	R^2	mA	time (min)	product	yield (%)
1	0.05	0.05	OCH_3	*t*-CH_3	80	110	**5b**	14
2	0.05	0.18	OCH_3	*t*-CH_3	80	120	**5b**	61
3	0.04	0.04	CH_3	*t*-CH_3	80	90	**5c**	75
4	0.05	0.05	H	H	80	120	**5d**	18
5	0.05	0.18	H	H	80	120	**5d**	40
6	0.05	0.05	H	*c*-CH_3	80	95	**5a**	50
7	0.03	0.03	H	*t*-CH_3	40	120	**5e**	80



6 4 7

entry[c]	6 (M)	4 (M)	R^1	R^2	mA	time (min)	product	yield (%)
8	0.03	0.03	OCH_3	CH_3	40	180	**7c**	64
9	0.03	0.03	OCH_3	H	40	180	**7b**	<5
10	0.03	0.08	OCH_3	H	40	180	**7b**	35
11	0.03	0.02	H	CH_3	40	180	–	<5

[a] Reactions were conducted as in Table I. Entries 1–3, 6, 11, Ar^1 = 1,2-$(OCH_3)_2C_6H_3$. Entries 4, 5, 7–10, Ar^1 = 4-$(OCH_3)C_6H_4$. [b] Wt % $LiClO_4$ 0.55–0.93. [c] Wt % $LiClO_4$ 0.5.

estimated area of the platinum mesh electrode used in this study is 40 cm^2, and under the given conditions a current density of 2–3 mA/cm^2 gave a good yield of product. Fortunately, the effect of current density on yield still allows useful preparative scale reactions to be conducted with standard size electrodes, vide infra.

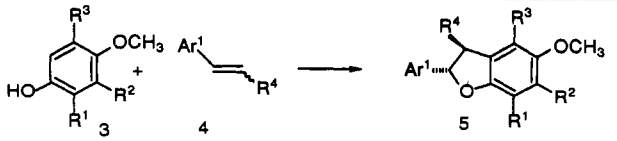
Reactions can be conducted at higher current density by increasing the amount of supporting electrolyte at a constant current. For formation of **5a** at 200 mA, entries 2–4 show a modest improvement in yield (43% to 55%) when the weight percent of $LiClO_4$ is increased from 0.4 to 2.0. A similar effect was noted for the formation of **7a** (entries 9–11). Finally, the yield of the dihydrobenzofuran is not affected by the concentration of the reactants in the range 0.046–0.184 M (entries 1, 6, 7). The preparation of 9 g of **5a** from anodic oxidation of **3a** and **4a** followed by simple extractive workup and crystallization illustrates the synthetic utility of this chemistry (see Experimental Section for details). Extraction of the reaction mixture with Claisen's alkali is an especially useful expedient in the isolation of product since any phenolic coupling products and the majority of the colored impurities are removed by this procedure.

Selected aspects of the anodic cycloaddition's yield as a function of substituents on the phenolic and styrene component were studied (Table II). We were surprised at both the efficiency of the reaction in some cases and the dramatic dependence of the reaction on substituents in other cases. First, no anodic cycloaddition products could be isolated using styrene itself as the olefinic component. Second, the additional methoxy group present in 3,4-dimethoxyphenol, **3b**, reduces the yield of **5b** in reactions with 1,2-dimethoxy-4-propenylbenzene—equimolar amounts of **3b** and **4a** gave only a 14% yield of the adduct **5b** (entry 1). However, the yield of the reaction could be increased to 61% if a 3-fold excess of **4a** was used (entry 2). Note that 4-methoxy-3-methylphenol, **3c**, affords a cycloaddition product in 75% yield employing stoichiometric amounts of reagent (entry 3). Thus, 3-substitution on the phenol is not necessarily detrimental to the yield

(8) Gregson, M.; Ollis, W. D.; Redman, B. T.; Sutherland, I. O. *J. Chem. Soc., Chem. Commun.* **1968**, 1394. See also: Engler, T. A.; Combrink, K. D.; Ray, J. E. *J. Am. Chem. Soc.* **1988**, *110*, 7931.

(9) (a) Shizuri, Y.; Nakamura, K.; Yamamura, S. *J. Chem. Soc., Chem. Commun.* **1985**, 530. (b) Shizuri, Y.; Yamamura, S. *Tetrahedron Lett.* **1983**, *24*, 5011.

Table III. Oxidative Cyclizations with Iodobenzene Bis(trifluoroacetate)[a]



entry	mole ratio 4:3	R^1	R^2	R^3	R^4	product	yield (%)
1	1.1	H	H	H	*t*-CH_3	**5a**	67
2	4.0	H	H	H	*t*-CH_3	**5a**	71
3	1.5	H	H	H	*c*-CH_3	**5a**	50
4	1.0	H	H	H	H	**5d**	57
5	1.0	H	CH_3O	H	*t*-CH_3	**5b**	26
6	1.5	H	CH_3O	H	*c*-CH_3	**5b**	23
7	3.6	H	CH_3O	H	*t*-CH_3	**5b**	64
8	4.0	H	CH_3O	H	H	**5f**	34
9	1.1	H	CH_3	H	*t*-CH_3	**5c**	81
10	3.0	allyl	H	H	*t*-CH_3	**5g**	68
11	4.0	allyl	H	Cl	*t*-CH_3	**5h**	53

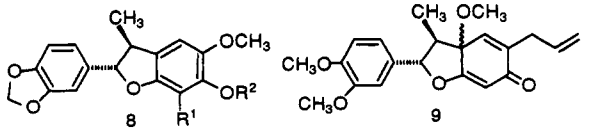
[a] Entries 1–3, 5–7, 9–11, Ar^1 = 1,2-$(OCH_3)_2C_6H_3$. Entries 4, 8, Ar^1 = 4-$OCH_3C_6H_4$.

in the reaction. No evidence was found for formation of the other regioisomeric cycloaddition product in the reactions of either **3b** or **3c**. However, the 4-methoxy group is important for good yields of cycloaddition product since neither phenol, *m*-methoxyphenol, 1-naphthol, nor 2-naphthol gave isolable amounts of product.

Substitution on the styrene component also influences the yield of the anodic cycloaddition reaction. The anodic oxidation of **3a** and *p*-methoxystyrene, **4b**, gave only an 18% yield of **5d** using equimolar quantities of reagent; however, the yield increased to 40% when a 3-fold excess of **4b** was employed (entries 4, 5). Essentially the same effect on yield was observed in the reaction of **6a** with **4b** to afford **7b** (entries 9, 10). We believe that the decreased yields in the reaction with *p*-methoxystyrene, **4b**, reflects lower reactivity due to absence of the terminal methyl group in the styrene. However, some polymerization of **4b** was noted in these reactions, and at least part of the lower yield may arise from **4b** undergoing polymerization during the reaction. The 2-methoxy group of the 1,2-dimethoxy-4-propenylbenzene has little effect on the reaction as 4-methoxy-1-propenylbenzene, **4c**, undergoes the anodic cycloaddition reaction in good yield employing equimolar amounts of reactants (entries 7 and 8). Finally, the stereochemistry of the double bond in **4a** appears to have only a small effect on the yield of the anodic cyclization product—**5a** is formed in yields of 61 and 50%, respectively (see Table I, entry 1; Table II, entry 6), in the reaction of trans and cis isomers of 1,2-dimethoxy-4-propenylbenzene.

Iodobenzene Bis(trifluoroacetate) Cycloadditions. For many electrochemical reactions there is a chemical counterpart—a noteworthy exception being the anodic 1,4-addition of methanol to 1,4-dioxygenated benzenes.[1] Iodobenzene diacetate and bis(trifluoroacetate) oxidation of phenols often give the same products as those formed in electrochemical oxidation of the phenols.[10,11] As noted earlier, our initial attempts at effecting anodic cycloaddition reactions gave low yields of products; it was at that time that we investigated iodobenzene diacetate and iodobenzene bis(trifluoroacetate) as oxidants in these systems. Since the yields of cycloaddition product with iodobenzene bis(trifluoroacetate) always equaled or exceeded those obtained with iodobenzene diacetate, only the yields with the former reagent are reported. Although iodobenzene bis(trifluoroacetate) is somewhat expensive, the reactions are easily performed except for the inconvenience of separating an equivalent of iodobenzene produced in the reaction.

Scheme II. Selected Examples of Neolignan Natural Products

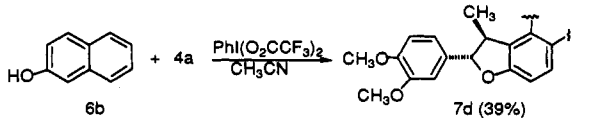


8a, R^1 = H; R^2 = $CH_2CH{=}CH_2$
b, R^1 = $CH_2CH{=}CH_2$; R^2 = H
c, R^1 = $CH_2CH{=}CH_2$; R^2 = CH_3
d, R^1 = R^2 = H

9a *Kadsurenone* α-OCH_3
b *Denudatin B* β-OCH_3

Table III summarizes the majority of our studies in this area. Except for two cases, vide infra, where direct comparisons are possible the same product was formed in very nearly the same yield from either the electrochemical or chemical oxidation. Much of this chemistry was completed before it was found that good yields of cycloadduct could be obtained from reaction of equimolar amounts of reactants in the electrochemical oxidations. Thus, it may not be necessary to employ the excess of styrene used in the reactions of Table III in all of the cases studied. Quantitatively, the same limitations on reactivity of substituted phenols and styrenes were noted as those observed for the anodic cycloaddition reactions discussed earlier: 4-methoxyphenol gives higher yields than 3,4-dimethoxyphenol; *cis*- and *trans*-1,2-dimethoxy-4-propenylbenzene give comparable yields of product; 4-methoxystyrene gives lower yields of cycloadduct than do the olefins mentioned above. The difference in reactivity noted previously between the *cis*- and *trans*-1,2-dimethoxy-4-propenylbenzene is smaller than thought previously.[5]

The two cases which yielded different results involved the oxidation of naphthalene systems. The yield for the cycloaddition product from **6a** and **4a** was 76% (Table I, entry 8) in the electrochemical reaction and 44% in the chemical oxidation. However, whereas 2-naphthol, **6b**, gave a very low yield of **7d** with **4a** in the electrochemical oxidation, a 39% yield of **7d** was obtained using iodobenzene bis-trifluoroacetate as oxidant. Unfortunately, the reason for these different results with **6a,b** is not known.



Synthetic Aspects of the Chemistry. The oxidative cycloadditions of 4-methoxyphenols with electron-rich styrene derivatives afford in one step the dihydrobenzofuran ring systems **5** and **7**—a unit present in a number of neolignan-derived natural products. The preparation of the natural product **8a** and the intermediate **15**, which has been converted to kadsurenone and denudatin B (Scheme II), is described below.

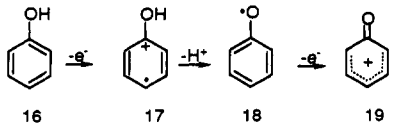
The preparation of **8a** began with the diallyl derivative of resorcinol, **10**. Anodic oxidation chemistry[12] proved especially useful in this case as oxidation of **10** formed 1,1,4-trimethoxy-2,4-bis(allyloxy)-2,5-cyclohexadiene which was then directly hydrolyzed and reduced to afford **11**

(10) For conversion of phenols to quinone monoketals, see the following: (a) Pelter, A.; Elgendy, S. *Tetrahedron Lett.* **1988**, *29*, 677. (b) Tamura, Y.; Yakura, T.; Haruta, J.; Kita, Y. *J. Org. Chem.* **1987**, *52*, 3927.

(11) For phenolic coupling reactions with positive iodine reagents, see the following: Szantay, C.; Blasko, G.; Barczai-Beke, Pechy, P.; Dornyei, G. *Tetrahedron Lett.* **1980**, *21*, 3509. Raman Krishna, K. V.; Sujatha, K.; Kapil, R. S. *Tetrahedron Lett.* **1990**, *31*, 1351. Kita, Y.; Yakura, T.; Tohma, H.; Kikuchi, K. *Tetrahedron Lett.* **1989**, *30*, 1119.

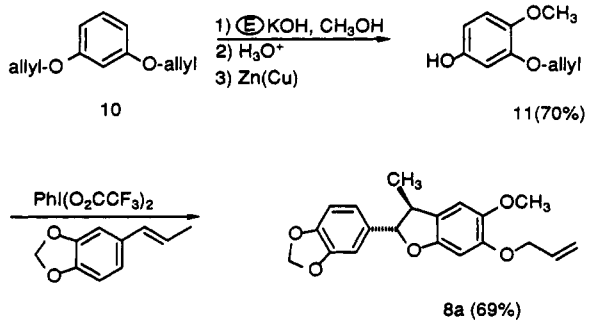
(12) (a) Weinberg, N. L.; Belleau, B. *J. Am. Chem. Soc.* **1963**, *85*, 2525. (b) Henton, D. R.; Anderson, K.; Manning, M. J.; Swenton, J. S. *J. Org. Chem.* **1980**, *45*, 3422.

Scheme III. Simplified Steps in Phenol Oxidation



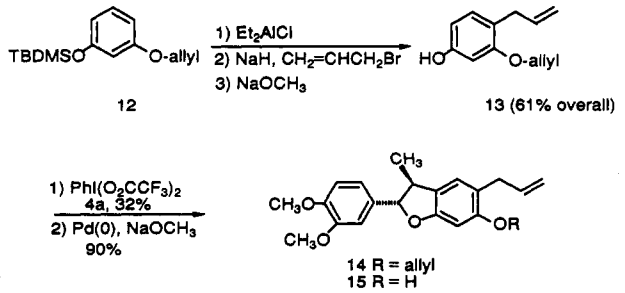
16 17 18 19

(70%). Oxidative cyclization of **11** and isosafrole gave **8a** (69%) which showed an ^{1}H NMR spectrum in good agreement with the known compound.[6c]



10 11(70%) 8a (69%)

This chemistry also permitted a facile preparation of **15**, a compound which has been converted to kadsurenone and denudatin B.[13] The required phenol for the oxidative coupling was prepared from the silyl ether of monoallyl resorcinol, **12**, as shown below. The diethylaluminum chloride catalyzed rearrangement[14] of **12** gave an 83:17 mixture of two allylated phenols (93%) which were not easily separable by chromatography. Allylation of this mixture gave an 86:14 mixture of products (83%) which again were not easily separated by chromatography. However, desilylation of this product mixture and chromatography gave **13** in 61% overall yield. Finally the coupling of **13** and **4a** gave **14** (32%). Removal of the allyl group with palladium(0)[15] gave the known **15** (90%). This compound showed a ^{1}H NMR spectrum identical with that of an authentic sample[13] and further supports the assignment of trans stereochemistry at the furan ring for all of the products reported in this paper. The oxidative cyclization illustrates again the sensitivity of the anodic cyclization reaction to phenol structure. No product could be isolated from the reaction of **4a** with *m*-methoxyphenol, yet the addition of the allyl group at the 4-position of *m*-allyloxyphenol results in a modest yield of **14**. Although this chemistry comprises a reasonably efficient route to **15**, conversion of **15** to kadsurenone and denudatin B occurs in only 10 and 15% yield, respectively.[13]

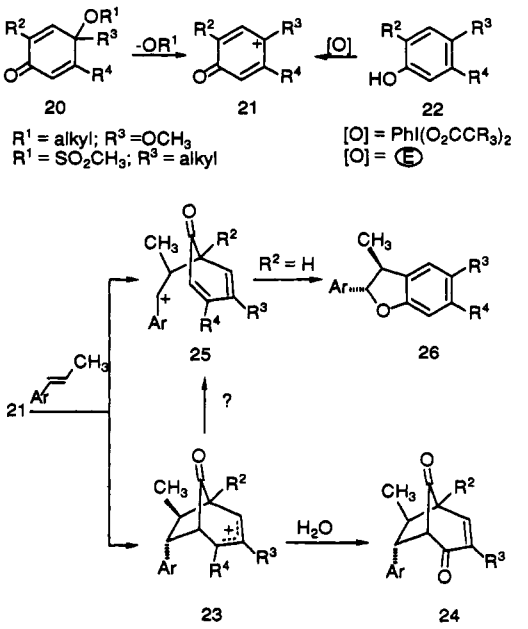


12 13 (61% overall)

14 R = allyl
15 R = H

Interpretative Discussion. There are a number of intermediates involved in the oxidation of phenols, and

Scheme IV. Generation and Mechanisms for Oxidative Phenol–Propenylbenzene Cycloadditions



20 21 22

R^1 = alkyl; R^3 = OCH_3
R^1 = SO_2CH_3; R^3 = alkyl

[O] = $PhI(O_2CCR_3)_2$
[O] = E

23 24

the situation is further complicated as proton transfer processes can generate other intermediates.[16] A simplified situation is depicted in Scheme III wherein phenol is oxidized to its radical cation **17**, a strong acid, which undergoes deprotonation to give a phenoxy radical **18**. This is followed by further oxidation to give the phenoxonium ion, **19**. Weakly acidic conditions are commonly regarded as favoring the formation of **19**. In addition, more substituted analogues of intermediate **19** have also been postulated as being formed from ionization of quinone monoketals[17] and quinols[18] (see Scheme IV).

Scheme IV summarizes the methods and generation of phenoxonium ion intermediates and their reactions with electron-rich styrenes. Earlier work postulated that **21** underwent concerted cycloaddition with the styrene derivative to afford the bicyclic ion **23** and that all of the chemistry arose from this intermediate.[7b,17,19] Hydrolysis of **23** led to bicyclic ketones such as **24**. Ring opening led to **25** which underwent ring closure and tautomerization to the thermodynamic product **26**, in cases in which R^2 = H, or led to cross-conjugated dienones via hydrolysis reactions (structure not shown). All of the earlier studies of these oxidative cycloadditions, **22** → **21**, have employed phenols having R^3 and R^4 as oxygen substituents and all of the **20** → **21** reactions have had R^4 as an oxygen substituent. Such a substitution pattern would be expected to stabilize an intermediate such as **23** since the positive charge would be conjugated with the R^4 oxygen substituent. Attempts to support the concerted and thus stereospecific cycloaddition step by studying the reaction of

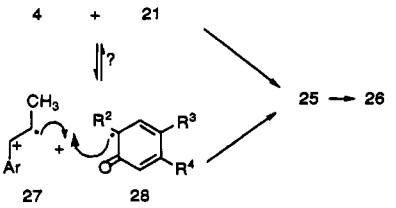
(13) Ponpipom, M. M.; Yue, B. Z.; Bugianesi, R. L.; Brooker, D. R.; Chang, M. N.; Shen, T. Y. *Tetrahedron Lett.* **1986**, *27*, 309.
(14) Sonnenberg, F. M. *J. Org. Chem.* **1970**, *35*, 3166.
(15) Takahashi, K.; Miyake, A.; Hata, G. *Bull. Chem. Soc. Jpn.* **1972**, *45*, 230.
(16) For a recent discussion of this point, see ref 2d.
(17) (a) Buchi, G.; Mak, C.-P. *J. Am. Chem. Soc.* **1977**, *99*, 8073. (b) Buchi, G.; Chu, P.-S. *J. Org. Chem.* **1978**, *43*, 3717. (c) See also ref 7b.
(18) Mortlock, S. V.; Seckington, J. K.; Thomas, E. J. *J. Chem. Soc., Perkin Trans. 1* **1988**, 2305.
(19) An intermediate similar to **23** but involving coordination of a titanium(IV)-to-oxygen substituents at R^3 and R^4 has been proposed for the reaction of quinones with styrene derivatives. However, the chemistry reported is also successful for a system in which R^4 = H, so a bicyclic intermediate akin to **23** is not required for the reaction. See the following: (a) Engler, T. A.; Combrink, K. D.; Ray, J. E. *J. Am. Chem. Soc.* **1988**, *110*, 7931. (b) Engler, T. A.; Combrink, K. D.; Takusagawa, F. *J. Chem. Soc., Chem. Commun.* **1989**, 1573. (c) Engler, T. A.; Reddy, J. P.; Combrink, K. D.; Vander Velde, D. *J. Org. Chem.* **1989**, *55*, 1248 and references cited therein.

cis-propenylbenzenes as the olefin partner have not led to the formation of cis-endo products analogous to **24**. In one case the corresponding endo adduct analogous to **24** was not formed[17a] and in another case the bicyclic ketone analogous to **24** was formed but with the substituents being cis-exo.[9b] Very recently an intramolecular cycloaddition of a *cis*-propenylbenzene side chain to an oxidized phenol giving a bicyclic product retaining the cis-exo geometry in the product has been reported.[20] Although there is no compelling evidence for a concerted bimolecular cycloaddition between **21** and *cis*-propenylbenzene derivatives to form a bicyclic ion analogous to **23**, this still remains an attractive mechanistic step, especially for simple olefins lacking a carbonium ion-stabilizing group at one terminal. The endo selectivity of the aryl substituent in these reactions does not require a concerted cycloaddition since π-stacking interactions would favor this orientation even in a nonconcerted reaction.

As noted above, the bicyclic isomer **23** would be especially favorable when R^4 is an electron-releasing group, i.e., OCH_3. Synthetic studies already had established that *p*-methoxyphenol gave better yields in the 1,3-oxidative cycloaddition than 3,4-dimethoxyphenol—could these two phenols be reacting via different intermediates? If so, then the selectivity of the oxidized phenol for a trans–cis pair of olefins could be different. Reaction of each phenol with a known mixture of *trans*- and *cis*-1,2-dimethoxy-4-propenylbenzene followed by analysis of the recovered olefin permits calculation of the relative reactivity of the olefin isomers in the reaction (see Experimental Section). These studies indicate that the relative reactivity of both *p*-methoxyphenol and 3,4-dimethoxyphenol with the *trans*- and *cis*-1,2-dimethoxy-4-propenylbenzene are similar, k(trans)/k(cis) $\simeq$ 7 and 2, respectively. The values should only be considered approximate since reaction of 2 equiv of a 52:48 trans/cis mixture of the propenylbenzene with 1 equiv of iodobenzene bis(trifluoroacetate) led to recovered propenylbenzene having a 35:65 ratio of trans to cis. Thus, some oxidation of the olefin is also occurring under the conditions of the oxidative cycloaddition reaction. However, it seems unlikely that two phenols showing similar selectivity toward trans and cis isomers would be reacting via different mechanisms. Furthermore, the selectivity between the trans and cis isomers of 1,2-dimethoxy-4-propenylbenzene as noted above is much smaller than for classical 4 + 2 additions,[21] but this could reflect the higher reactivity and thus lower selectivity of the oxidized phenol intermediate.

A further complicating aspect of the electrochemistry studied herein is that the phenols and styrenes studied have similar oxidation potentials. For example, *p*-methoxyphenol shows an $E_{p/2}$ = 1.05 V, and 1,2-dimethoxy-4-propenylbenzene has a value of $E_{p/2}$ = 1.10 V. Since these reactions were conducted without control of potential, it is likely that both the styrenes and phenols are being oxidized. In spite of this complication, good yields of cycloaddition product result using equimolar quantities of reactant at current efficiencies in the 70–90% range.

A second mechanism for the formation of dihydrobenzofuran derivatives involves an initial coupling step between the phenoxy radical and the radical cation of the styrene followed by ring closure and tautomerization, **27** + **28** → **25** → **26**. As discussed below, this process, akin to the EEC_rC_p mechanism,[22] has some attractive features. For the iodobenzene bis(trifluoroacetate) oxidations in which preferential oxidation of the phenol is more likely and for the ionization processes akin to **20** → **21**, an electron-transfer step generating **27** and **28** from **4** and **21** would be required.



An acceptable mechanism for the benzofuran formation observed herein should explain the following experimental observations. First, only the combination of an electron-rich phenol and a double bond attached to an electron-rich aromatic ring give good yields in the anodic cycloaddition reaction. Second, the stereochemistry at the olefinic center is lost in the reaction—both cis and trans isomers give the same product. Third, whereas oxygen nucleophiles react with oxidized phenols preferentially at the position para to the phenolic hydroxyl group, the oxidative cycloadditions discussed herein involve bonding at the ortho position. Note, however, that oxygen nucleophiles (CH_3OH, H_2O, etc.) would not be oxidized easily to radical cations, and a pathway analogous to **4** → **27** → **25** → **26** would not operate. Finally, anodic phenolic coupling reactions occur predominantly at the position ortho to the phenolic hydroxyl group unless these positions are substituted.[23] Perhaps a similar selectivity would be exhibited for regioselectivity in the radical coupling reaction, **27** + **28** → **25**. These observations do not provide enough evidence to distinguish between the mechanism discussed above and that outlined in Scheme IV. Both mechanisms would explain the loss of stereochemistry at the olefinic center. However, the sequence **27** + **28** → **25** → **26** more conveniently explains the dramatic dependence on substrate structure and the selectivity toward carbon–carbon bond formation at the ortho position.

Summary

The bimolecular oxidative cycloaddition between 4-methoxyphenols and electron-rich styrene and propenylbenzene derivatives serves as a one-step route to trans-substituted dihydrobenzofuran derivatives. The electrochemical version of the reaction comprises a reagentless method for preparation of these dihydrobenzofuran derivatives. The chemistry has been conducted on ca. 10-gram scale and further scaleup has no obvious problems. The mechanism of this reaction and its relation to the other reactions discussed above have not been rigorously established, but the phenolic radical/radical cation coupling is an attractive step in the chemistry. This chemistry for preparing the dihydrobenzofuran ring system[24] is a more convenient and higher yielding procedure than reported routes emanating from the quinone monoketal[17] or quinol derivative.[18] Not only is the preparation of the quinone monoketal omitted, but also the latter procedures

(20) Maki, S.; Suzuki, T.; Kosemura, S.; Shizuri, Y.; Yamamura, S. *Tetrahedron Lett.* **1991**, *32*, 4973.

(21) The trans isomer is more reactive than the cis isomer in the Diels–Alder reaction of cyclopentadiene (40 °C) with 1,2-dibenzoylethylene, 1,2-bis(phenylsulfonyl)ethylene, 1-benzoyl-2-(phenylsulfonyl)ethylene by factors of 742, 83, and 186, respectively. Sauer, J.; Lang, E.; Wiest, H. *Chem. Ber.* **1964**, *97*, 3183.

(22) Dolson, M. G.; Swenton, J. S. *J. Am. Chem. Soc.* **1981**, *103*, 2361. Swenton, J. S. In *Electroorganic Synthesis*; Little, R. D., Weinberg, N. L., Eds.; Marcel Dekker: New York, 1991; pp 145–151.

(23) Yoshida, K. *Electrooxidation in Organic Synthesis*; John Wiley and Sons: New York; 1984, pp 129–130.

(24) For a direct comparison of the quinone monoketal route versus the oxidative cyclization procedure see ref 5.

typically afford 20–40% yields of the dihydrobenzofuran. Furthermore, in some cases the strong acid employed in these latter reactions leads to side reactions.

Experimental Section[25]

Anodic Oxidation Studies. These reactions were conducted at constant current in a water-jacketed single cell at 20–25 °C using a cylindrical platinum anode (5-cm × 3.5-cm diameter, 50 mesh screen) and a rectangular platinum sheet cathode (2 × 2.5 cm). The solutions were stirred magnetically and all reactions were conducted in an atmosphere of air. Since all of the reactions were performed similarly, only the large-scale reaction is described in detail. For the remaining reactions the reagents are given in the following order: table entry, styrene or propenylbenzene (g, mmol), phenol (g, mmol), 8:1 CH_3CN/HOAc (mL), $LiClO_4$ (g), purification procedure, spectroscopic and analytical data.

(±)-*trans*-2-(3,4-Dimethoxyphenyl)-2,3-dihydro-5-methoxy-3-methylbenzofuran, 5a. An acetonitrile (160 mL) solution containing *p*-methoxyphenol (6.21 g, 50 mmol), 1,2-dimethoxy-4-propenylbenzene (9.09 g, 51 mmol), $LiClO_4$ (2.75 g), and HOAc (20 mL) was electrolyzed (100 mA, 29.5 h) at rt in a single cell using the electrodes described above. At that time TLC showed the disappearance of the propenylbenzene and appearance of a product spot at lower R_f. The reaction was diluted with water (40 mL) and neutralized with solid $NaHCO_3$. The solution was filtered, the solvent was removed in vacuo, and the resulting dark red oil was extracted with 2:1 benzene/ether (3 × 50 mL). The combined organic layers were washed with water (10 mL), Claisen's alkali[26] (3 × 25 mL), water (2 × 20 mL), and brine (2 × 30 mL) and dried over $CaSO_4$. The solvent was removed in vacuo, and the resulting yellow oil (13.13 g) was dissolved in boiling methanol (110 mL) and cooled to yield white crystals (8.96 g, 60%), mp 95–97 °C: IR (KBr) 1515, 1486, 1262, 1246, 1202, 1162, 1032, 806 cm^{-1}; ^1H NMR δ 6.6–7.0 (m, 6 H), 5.04 (d, J = 9.4 Hz, 1 H), 3.88 (s, 3 H), 3.87 (s, 3 H), 3.77 (s, 3 H), 3.5–3.4 (m, 1 H), 1.37 (d, J = 6.8 Hz, 3 H). Anal. Calcd for $C_{18}H_{20}O_4$: C, 71.98; H, 6.71. Found: C, 71.92; H, 6.71.

(±)-*trans*-2-(3,4-Dimethoxyphenyl)-2,3-dihydro-5-methoxy-3-methylnaphtho[1,2-*b*]furan, 7a. Table I, entry 8; 1,2-dimethoxy-4-propenylbenzene (0.40 g, 2.24 mmol); 4-methoxy-1-naphthol[12b] (0.50 g, 2.87 mmol); 100 mL; $LiClO_4$ (0.33 g). Chromatography on silica gel [2.5 × 25 cm column; PE (150 mL), 3:1 PE/EtOAc (300 mL) as eluant] gave an off-white solid (0.59 g, 76%), mp 119–120 °C. Recrystallization from PE afforded pale orange crystals, mp 121–123 °C: IR (KBr) 1518, 1462, 1269, 1240, 1141, 1025, 767 cm^{-1}; ^1H NMR δ 8.2–8.1 (m, 1 H), 8.0–7.9 (m, 1 H), 7.5–7.4 (m, 2 H), 7.1–7.0 (m, 2 H), 7.0–6.8 (m, 1 H), 6.7 (s, 1 H), 5.25 (d, J = 8.9 Hz, 1 H), 4.0 (s, 3 H), 3.9 (s, 3 H), 3.8 (s, 3 H), 3.7–3.6 (m, 1 H), 1.48 (d, J = 6.8 Hz, 3 H). Anal. Calcd for $C_{22}H_{22}O_4$: C, 75.41; H, 6.33. Found: C, 75.57; H, 6.44.

(±)-*trans*-2-(3,4-Dimethoxyphenyl)-2,3-dihydro-5,6-dimethoxy-3-methylbenzofuran, 5b. Table II, entry 2; 1,2-dimethoxy-4-propenylbenzene (1.46 g, 8.2 mmol), 3,4-dimethoxyphenol (0.32 g, 2.05 mmol); 45 mL; $LiClO_4$ (0.24 g). Chromatography on silica gel [2 × 15 cm column; PE (100 mL), 10% EtOAc/PE (200 mL) as eluant] gave **5b** (0.41 g, 61%) as a white solid, mp 124–125 °C: IR (KBr) 1515, 1500, 1260, 1240, 1220, 1190, 1120, 1025 cm^{-1}; ^1H NMR δ 6.97–6.84 (m, 3 H), 6.71 (s, 1 H), 6.52 (s, 1 H), 5.04 (d, J = 9.1 Hz, 1 H), 3.89 (s, 3 H), 3.88 (s, 3 H), 3.86 (s, 6 H), 3.5–3.35 (m, 1 H), 1.38 (d, J = 6.7 Hz, 3 H); HRMS calcd for $C_{19}H_{22}O_5$ m/e 330.1467, obsd m/e 330.1490.

(±)-*trans*-2-(3,4-Dimethoxyphenyl)-2,3-dihydro-5-methoxy-3,6-dimethylbenzofuran, 5c. Table II, entry 3; 1,2-dimethoxy-4-propenylbenzene (0.34 g, 1.9 mmol), 4-methoxy-3-methylphenol[27] (0.24 g, 1.7 mmol); 45 mL; $LiClO_4$ (0.2 g). Chromatography on silica [2 × 20 cm column; PE (50 mL), 10% EtOAc/PE (150 mL), 15% EtOAc/PE (200 mL) as eluant] gave **5c** (0.40 g, 75%) as a white solid, mp 85–86 °C: IR (KBr) 1516, 1490, 1463, 1265, 1234, 1201, 1160, 1144, 1023 cm^{-1}; ^1H NMR δ 7.0–6.8 (m, 3 H), 6.66, 6.64 (overlapping s, 2 H), 5.02 (d, J = 9.5 Hz, 1 H), 3.87 (s, 3 H), 3.86 (s, 3 H), 3.79 (s, 3 H), 3.5–3.3 (m, 1 H), 2.19 (s, 3 H), 1.37 (d, J = 6.8 Hz, 3 H). Anal. Calcd for $C_{19}H_{22}O_4$: C, 72.59; H, 7.05. Found: C, 72.93; H, 7.29.

(±)-2-(4-Methoxyphenyl)-2,3-dihydro-5-methoxybenzofuran, 5d. Table II, entry 5; *p*-methoxystyrene (1.1 g, 8.2 mmol), *p*-methoxyphenol (0.25 g, 2.05 mmol); 45 mL; $LiClO_4$ (0.25 g). Silica gel chromatography [2 × 15 cm column; PE (100 mL), 10% EtOAc/PE (150 mL) as eluant] gave **5d** (0.19 g, 40%) as a white solid, mp 79–80 °C: IR (KBr) 1515, 1490, 1248, 1208, 1029 cm^{-1}; ^1H NMR δ 7.32 (d, J = 8.8 Hz, 2 H), 6.88 (d, J = 8.8 Hz, 2 H), 6.8–6.6 (m, 3 H) 5.66 (t, J = 8.8 Hz, 1 H), 3.79 (s, 3 H), 3.75 (s, 3 H), 3.53 (dd, J = 5.5, 8.8 Hz, 1 H), 3.17 (dd, J = 5.5, 8.8 Hz, 1 H). Anal. Calcd for $C_{16}H_{16}O_3$: C, 74.98; H, 6.29. Found: C, 74.76; H, 6.36.

(±)-*trans*-2-(4-Methoxyphenyl)-2,3-dihydro-5-methoxy-3-methylbenzofuran, 5e. Table II, entry 7; *trans*-anethole (0.22 g, 1.48 mmol), *p*-methoxyphenol (0.19 g, 1.53 mmol); 45 mL; $LiClO_4$ (0.34 g, 3 mmol). Silica gel chromatography [2.5 × 25 cm column; 6:1 PE/EtOAc (300 mL) as eluant] yielded a blue oil which gave off-white crystals (0.32 g, 80%), mp 54–56 °C: IR (KBr) 1515, 1486, 1250, 1203, 1174 cm^{-1}; ^1H NMR δ 7.36 (d, J = 8.8 Hz, 2 H), 6.91 (d, J = 8.7 Hz, 2 H), 6.8–6.7 (m, 3 H), 5.08 (d, J = 9.1 Hz, 1 H), 3.8 (s, 3 H), 3.7 (s, 3 H), 3.5–3.3 (m, 1 H), 1.37 (d, J = 6.8 Hz, 3 H). Anal. Calcd for $C_{17}H_{18}O_3$: C, 75.53; H, 6.71. Found: C, 75.58; H, 6.75.

(±)-*trans*-2-(4-Methoxyphenyl)-2,3-dihydro-5-methoxy-3-methylnaphtho[1,2-*b*]furan, 7c. Table II, entry 8; *trans*-anethole (0.20 g, 1.35 mmol); 4-methoxy-1-naphthol (0.23 g, 1.32 mmol); 45 mL; $LiClO_4$ (0.19 g). Chromatography on silica gel [2.5 × 25 cm column; 6:1 PE/EtOAc (400 mL) as eluant] afforded a clear oil (0.30 g, 71%). Crystallization gave white crystals (0.27 g, 64%) in two crops, mp 88–89 °C: IR (KBr) 1514, 1459, 1401, 1246 cm^{-1}; ^1H NMR δ 8.2–8.1 (m, 1 H), 8.0–7.9 (m, 1 H), 7.5–7.3 (m, 4 H), 6.92 (d, J = 8.8 Hz, 2 H), 6.7 (m, 1 H), 5.27 (d, J = 8.5 Hz, 1 H), 4.0 (s, 3 H), 3.8 (s, 3 H), 3.6–3.5 (m, 1 H), 1.47 (d, J = 6.8 Hz, 3 H). Anal. Calcd for $C_{21}H_{20}O_3$: C, 78.73; H, 5.92. Found: C, 78.77; H, 6.36.

(±)-2-(4-Methoxyphenyl)-2,3-dihydro-5-methoxynaphtho[1,2-*b*]furan, 7b. Table II, entry 10; *p*-methoxystyrene (0.54 g, 4.02 mmol); 4-methoxy-1-naphthol (0.23 g, 1.32 mmol); 45 mL; $LiClO_4$ (0.17 g). Chromatography on silica gel [2.5 × 25 cm column; PE (100 mL), 3:1 PE/EtOAc (200 mL) as eluant] gave a blue semisolid which afforded white crystals (0.14 g, 35%) after filtration through alumina (CH_2Cl_2 as eluant), mp 108–110 °C: IR (KBr) 1515, 1249, 1235, 1113, 763 cm^{-1}; ^1H NMR δ 8.2–8.1 (m, 1 H), 8.0–7.9 (m, 1 H), 7.5–7.3 (m, 4 H), 6.9 (d, J = 8.8 Hz, 2 H), 6.7 (s, 1 H), 5.87 (t, J = 8.8 Hz, 1 H), 3.9 (s, 3 H), 3.8 (s, 3 H), 3.4–3.3 (m, 2 H). Anal. Calcd for $C_{20}H_{18}O_3$: C, 78.41; H, 5.92. Found: C, 78.97; H, 6.29.

Iodobenzene Bis(trifluoroacetate) Oxidations. These reactions were conducted similarly for all of the systems studied. A detailed procedure is given for preparation of **5a**, and for the remaining reactions only the following data are given: table entry; iodobenzene bis(trifluoroacetate)[28] (g, mmol), phenol (g, mmol); styrene or propenylbenzene (g, mmol); mL of acetonitrile; purification procedure and spectroscopic data (if not given earlier).

(±)-*trans*-2-(3,4-Dimethoxyphenyl)-2,3-dihydro-5-methoxy-3-methylbenzofuran, 5a. Table III, entry 1; iodobenzene

(25) **General Procedures.** Melting points were determined in capillaries and are uncorrected. Only strong absorptions are reported for IR spectra unless otherwise noted. ^1H NMR spectra were measured at 200 MHz in $CDCl_3$ unless noted otherwise. All reagents or compounds not explicitly referenced were obtained from commercial sources. The commercial 1,2-dimethoxy-4-propenylbenzene employed in this work was a ca. 95:5 mixture of the trans and cis isomers. Alumina and silica gel (Kieselgel 60 230–400 mesh) were obtained from E. Merck Co. TLC was done using Merck silica gel 60 F_{254} precoated aluminum-backed plates, 0.2-mm thickness. All organometallic reactions were done under N_2 or Ar. Visualization was by UV or by spraying with 5% ethanolic phosphomolybdic acid and then heating. THF was purified by distillation from benzophenone ketyl. Throughout the Experimental Section the following abbreviations are used: petroleum ether, bp 35–60 °C (PE), *p*-toluenesulfonic acid (*p*-TsOH). Extractive workup refers to extraction of the material into the indicated solvent, washing the organic layer with brine solution, drying over Drierite ($CaSO_4$), concentration in vacuo, and drying to constant weight under vacuum (1–2 Torr).

(26) Fieser, M.; Fieser, L. F. *Reagents for Organic Synthesis*; Wiley: New York, 1967; Vol. I, p 153.

(27) Kharasch, N.; Kalfayan, S. H.; Arterberry, J. D. *J. Org. Chem.* **1956**, *21*, 925.

(28) Loudon, G. M.; Radhakrishna, A. S.; Almond, M. R.; Blodgett, J. K.; Boutin, R. H. *J. Org. Chem.* **1984**, *49*, 4272.

bis(trifluoroacetate) (0.74 g, 1.8 mmol) was added all at once to a solution of *p*-methoxyphenol (0.20 g, 1.6 mmol) and 1,2-dimethoxy-4-propenylbenzene, **4a** (0.30 g, 1.8 mmol), in acetonitrile (5 mL). The dark purple reaction mixture was stirred at rt for 15 min, and then the solvent was removed in vacuo. The crude product was chromatographed on silica gel [2.5 × 25 cm column; PE (100 mL), 10% EtOAc/PE (300 mL), 20% EtOAc/PE (200 mL) as eluant]. The dihydrobenzofuran, **5a**, was isolated as an off-white solid (0.47 g, 98%). Recrystallization from Et_2O/PE gave pure **5a** (0.32 g, 67%).

(±)-2-(4-Methoxyphenyl)-2,3-dihydro-5-methoxybenzofuran, 5d. Table III, entry 4; iodobenzene bis(trifluoroacetate) (0.19 g, 0.44 mmol), *p*-methoxyphenol (0.05 g, 0.4 mmol), and *p*-methoxystyrene (0.054 g, 0.40 mmol); 2 mL. Chromatography on silica gel [1 × 20 cm column; PE (40 mL), 10% EtOAc/PE (150 mL) as eluant] gave **5d** (0.059 g, 57%).

(±)-*trans*-2-(3,4-Dimethoxyphenyl)-2,3-dihydro-5,6-dimethoxy-3-methylbenzofuran, 5b. Table III, entry 7; iodobenzene bis(trifluoroacetate) (1.5 g, 3.49 mmol), 3,4-dimethoxyphenyl, **3b** (0.375 g, 2.43 mmol), and 1,2-dimethoxy-4-propenylbenzene, **4a** (1.58 g, 8.89 mmol); 2 mL. Chromatography on silica gel [2.5 × 12 cm column; PE, 5% EtOAc/PE, then 10% EtOAc/PE as eluant] gave **5b** (0.512 g, 64%).

(±)-2-(4-Methoxyphenyl)-2,3-dihydro-5,6-dimethoxybenzofuran, 5f. Table III, entry 8; iodobenzene bis(trifluoroacetate) (0.84 g, 2.0 mmol); 3,4-dimethoxyphenol (0.2 g, 1.3 mmol); *p*-methoxystyrene (0.7 g, 5.2 mmol); 3 mL. Chromatography on silica gel [2 × 15 cm column; PE (75 mL), 10% EtOAc/PE (150 mL), 20% EtOAc/PE (200 mL) as eluant] gave **5f** (0.125 g, 34%) as a white solid, mp 98–99 °C: IR (KBr) 1501, 1240, 1212, 1185, 1161 cm^{-1}; ^1H NMR δ 7.31 (d, J = 8.6 Hz, 2 H), 6.87 (d, J = 8.6 Hz, 2 H), 6.75 (s, 1 H), 6.48 (s, 1 H), 5.67 (t, J = 9 Hz, 1 H), 3.82 (s, 3 H), 3.81 (s, 3 H), 3.79 (s, 3 H), 3.51 (dd, J = 9, 15 Hz, 1 H), 3.1 (dd, J = 9, 15 Hz, 1 H). Anal. Calcd for $C_{17}H_{18}O_4$: C, 71.31; H, 6.34. Found: C, 71.44; H, 6.58.

(±)-*trans*-2-(3,4-Dimethoxyphenyl)-2,3-dihydro-5-methoxy-3,6-dimethylbenzofuran, 5c. Table III, entry 9; iodobenzene bis(trifluoroacetate) (0.34 g, 0.8 mmol), 4-methoxy-3-methylphenol (0.1 g, 0.72 mmol); 1,2-dimethoxy-4-propenylbenzene (0.14 g, 0.8 mmol); 10 mL. Chromatography on silica gel [2 × 15 cm column; PE (30 mL), 15% EtOAc/PE (200 mL) as eluant] gave **5c** (0.182 g, 81%).

(±)-*trans*-2-(3,4-Dimethoxyphenyl)-2,3-dihydro-7-allyl-5-methoxy-3-methylbenzofuran, 5g. Table III, entry 10; iodobenzene bis(trifluoroacetate) (0.37 g, 0.91 mmol), 2-allyl-4-methoxyphenol[29] (100 mg, 0.61 mmol); 1,2-dimethoxy-4-propenylbenzene (430 mg, 2.42 mmol); 1 mL. Column chromatography on silica gel (12 × 2.5 cm column, 5% EtOAc/PE, 10% EtOAc/PE as eluant) gave **5g** as a colorless oil (141 mg, 68%): IR (NaCl) 1510, 1480, 1465, 1455, 1260, 1235, 1140 cm^{-1}; ^1H NMR δ 6.98–6.84 (str m, 3 H), 6.59 (s, 2 H), 6.08–5.95 (m, 1 H), 5.16–5.04 (m, 2 H), 5.06 (d, J = 9.7 Hz, 1 H), 3.89 (s, 3 H), 3.88 (s, 3 H), 3.78 (s, 3 H), 3.45–3.30 (m, 3 H), 1.39 (d, J = 6.8 Hz, 3 H); HRMS calcd for $C_{21}H_{24}O_4$ m/e 340.1675, obsd m/e 340.1696.

2-Allyl-5-chloro-4-methoxyphenol. To a solution of 3-chloro-4,4-dimethoxy-2,5-cyclohexadienone[30] (11.0 g, 58.4 mmol) in Et_2O (200 mL) was added dropwise a solution of allylmagnesium bromide [100 mL of a 2.34 M solution prepared from allyl bromide (28.0 g, 0.234 mol) with magnesium in Et_2O (100 mL)]. The reaction solution turned blue, and a white precipitate formed quickly. After being stirred at 0 °C for 0.5 h and at rt for another 0.5 h, the reaction was quenched by adding 1% HCl (50 mL). Extractive workup with Et_2O (2 × 50 mL) gave a dark oil (^1H NMR spectrum of the crude product indicates that it consists of 84% 2-allyl-5-chloro-4-methoxyphenol and 16% of an isomeric product). Flash silica gel chromatography (12 × 4 cm column 5% Et_2O/PE as eluant) gave the major phenol as a solid (8.36 g, 73%), mp 41–43 °C: IR (KBr) 3440 (br m), 1495, 1400, 1305, 1195, 1050 cm^{-1}; ^1H NMR δ 6.88 (s, 1 H), 6.69 (s, 1 H), 6.08–5.91 (m, 1 H), 5.21–5.11 (m, 2 H), 4.68 (s, 1 H), 3.85 (s, 3 H), 3.38 (pseudo d, J = 6.2 Hz, 2 H); HRMS calcd for $C_{10}H_{11}O_2Cl$ m/e 200.0428, obsd m/e 200.0454.

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(±)-*trans*-2-(3,4-Dimethoxyphenyl)-2,3-dihydro-7-allyl-4-chloro-5-methoxy-3-methylbenzofuran, 5h. Table III, entry 11; iodobenzene bis(trifluoroacetate) (0.24 g, 0.55 mmol); 2-allyl-4-methoxy-5-chlorophenol (0.1 g, 0.5 mmol); 1,2-dimethoxy-4-propenylbenzene (0.36 g, 2.0 mmol); 10 mL. Chromatography on silica gel [1 × 25 cm column; PE (25 mL), 10% EtOAc/PE (100 mL); 20% EtOAc/PE (100 mL) as eluant] gave **5h** (0.1 g, 53%) as a colorless oil: IR (melt) 1512, 1460, 1260, 1228 cm^{-1}; ^1H NMR δ 6.84–6.82 (m, 3 H), 6.59 (s, 1 H), 6.04–5.90 (m, 1 H), 5.17 (d, J = 5.8 Hz, 1 H), 5.13–5.02 (m, 2 H), 3.85 (s, 3 H), 3.82 (s, 6 H), 3.6–3.4 (m, 1 H), 3.44–3.31 (m, 2 H), 1.54 (d, J = 6.9 Hz, 3 H); HRMS calcd for $C_{21}H_{23}O_4Cl$ m/e 376.1255, obsd m/e 376.1220.

(±)-*trans*-2-(3,4-Dimethoxyphenyl)-1,2-dihydro-1-methylnaphtho[2,1-*b*]furan, 7d. Iodobenzene bis(trifluoroacetate) (1.00 g, 2.4 mmol); 2-naphthol (0.23 g, 1.6 mmol); 1,2-dimethoxy-4-propenylbenzene (1.15 g, 6.4 mmol); 5 mL. Chromatography on silica gel [2.5 × 25 cm column; PE (150 mL) 10% EtOAc/PE (300 mL), 20% EtOAc/PE (250 mL) as eluant] gave **7d** as an off-white solid (0.20 g, 39%), >98% pure, which gave white plates on recrystallization from PE (0.13 g, 25%), mp 110–111 °C: IR (KBr) 1519, 1463, 1423, 1285, 1261, 1240, 1159, 1138, 1026, 815 cm^{-1}; ^1H NMR δ 7.82 (dd, J = 1, 7.4 Hz, 1 H), 7.73 (d, J = 8.7 Hz, 2 H), 7.5–7.4 (m, 1 H), 7.3–7.2 (m, 1 H), 7.19 (d, J = 8.7 Hz, 1 H), 7.0–6.9 (m, 2 H), 6.82 (d, J = 8.0 Hz, 1 H), 5.3 (d, J = 5.7 Hz, 1 H), 3.86 (s, 3 H), 3.82 (s, 3 H), 3.5 (m, 1 H), 1.64 (d, J = 6.9 Hz, 3 H). Anal. Calcd for $C_{21}H_{20}O_3$: C, 78.73; H, 6.29. Found: C, 78.65; H, 6.40.

Di-*O*-allylresorcinol, 10. To a vigorously stirred mixture of resorcinol (45 g, 0.41 mol) and DMF (300 mL) was added freshly ground K_2CO_3 (118 g, 0.9 mol) followed by allyl bromide (75 mL, 0.87 mol). This suspension was heated at 70 °C for 72 h, and the cooled reaction mixture was vacuum-filtered, diluted with H_2O (300 mL), and then extracted with Et_2O (3 × 300 mL). The ethereal layer was washed with Claisen's alkali (3 × 100 mL washings) then with brine (100 mL), and the mixture was dried through $CaSO_4$. Removal of the solvent in vacuo gave a dark red liquid which was purified by Kugelrohr distillation (80–90 °C (1 mmHg)) to yield the di-*O*-allylresorcinol (36.9 g, 47%) as a colorless liquid. The alkaline layer was acidified, and the mono-*O*-allylresorcinol was isolated (20 g, 32%) by extractive workup [Et_2O (3 × 150 mL)]. The mono-*O*-allylresorcinol was then subjected to similar alkylation and workup conditions to those described above: K_2CO_3 (21 g, 0.16 mol), allyl bromide (22 mL, 0.26 mol), DMF (100 mL). Workup and purification gave the di-*O*-allylresorcinol (14 g, 50.9%, 65% overall) and the mono-*O*-allylresorcinol (8.66 g, 13%).

Di-*O*-allylresorcinol showed: IR (NaCl) 1595, 1490, 1180, 1145 cm^{-1}; ^1H NMR δ 7.22–7.12 (str m, 1 H), 6.55–6.45 (str m, 3 H), 6.16–5.96 (m, 2 H), 5.47–5.25 (str m, 4 H), 4.51 (d of t, J = 5.3, 1.5 Hz, 4 H); HRMS calcd for $C_{12}H_{14}O_2$ m/e 190.0993, obsd m/e 190.0978.

Mono-*O*-allylresorcinol showed: IR (NaCl) 3350 (br s), 1595, 1490, 1170, 1140 cm^{-1}; ^1H NMR δ 7.17–7.08 (str m, 1 H), 6.54–6.41 (str m, 3 H), 6.10–5.95 (m, 1 H), 5.45–5.25 (str m, 2 H), 4.87 (s, 1 H), 4.50 (d of t, J = 5.3, 1.5 Hz, 2 H); HRMS calcd for $C_9H_{10}O_2$ m/e 150.0681, obsd m/e 150.0688.

3-(Allyloxy)-4-methoxyphenol, 11. A solution of 1,3-bis(allyloxy)benzene (5.0 g, 26 mmol) and KOH (1 g) in CH_3OH (100 mL) was electrolyzed in an undivided cell using a circular platinum mesh anode (3.5-cm diameter × 5.0-cm high) and a platinum sheet cathode (2.0 cm × 2.0 cm) at a constant current of 3 A at 25 °C for 200 min (14.3 F/mol). The mixture was concentrated in vacuo, and the resulting residue was diluted with H_2O (100 mL). Extractive workup [CH_2Cl_2 (3 × 50 mL)] gave the crude product bisketal as a yellow oil which was dissolved in THF (100 mL). After addition of 5% HOAc (20 mL) to the solution [pH ≈ 5, Zn–Cu couple (3.4 g, 2 equiv) was added, and the resulting mixture was heated at reflux for 2 h. The reaction mixture was cooled to rt and vacuum filtered to remove the solid. Extractive workup with Et_2O (3 × 70 mL) and purification by column chromatography on silica gel (2.5 × 14 cm column, 10% Et_2O/PE as eluant) gave 11 (3.3 g, 70%) as a white solid. A small portion of the product was recrystallized from Et_2O/PE to give 11 as a white needle-like crystalline solid, mp 83–84.5 °C: IR (KBr) 3520, 3012 (br, m), 1510, 1225, 1125 cm^{-1}; ^1H NMR δ 6.74 (d, J = 8.6 Hz,

1 H), 6.46 (d, J = 2.8 Hz, 1 H), 6.33 (dd, J = 8.6, 2.8 Hz, 1 H), 6.12–5.95 (m, 1 H), 5.43–5.24 (str m, 2 H), 5.14 (s, 1 H), 4.55 (d of t, J = 5.4, 1.5 Hz, 2 H), 3.81 (s, 3 H); HRMS calcd for $C_{10}H_{12}O_3$ m/e 180.0786, obsd m/e 180.0785.

(±)-*trans*-2-[3,4-(Methylenedioxy)phenyl]-2,3-dihydro-6-(allyloxy)-5-methoxy-3-methylbenzofuran, 8a. To a solution of the phenol from above (500 mg, 2.78 mmol) and (*E*)-isosafrole (1.98 g, 11.1 mmol) in CH_3CN (2 mL) at 0 °C was added iodobenzene bis(trifluoroacetate) (1.43 g, 3.34 mmol). The reaction was kept at 0 °C for 0.5 h and then concentrated in vacuo. Extractive workup and column chromatography on silica gel (2.5 × 14 cm column, 5% EtOAc/PE as eluant) afforded **8a** as a colorless solid (652 mg, 69%). The analytical sample was obtained by recrystallization in Et_2O/PE to give a white crystalline solid, mp 59–61 °C (lit.[6c] reports product as an oil) with identical ^1H NMR spectrum to that reported: IR (KBr) 1495, 1240, 1215, 1175, 1015 cm^{-1}; ^1H NMR δ 6.92–6.77 (str m, 3 H), 6.70 (d, J = 1 Hz, 1 H), 6.51 (s, 1 H), 6.17–5.96 (m, 1 H), 5.96 (s, 2 H), 5.46–5.25 (str m, 2 H), 5.03 (d, J = 8.7 Hz, 1 H), 4.58 (d of t, J = 5.4, 1.5 Hz, 2 H), 3.85 (s, 3 H), 3.40–3.28 (m, 1 H), 1.36 (d, J = 6.7 Hz, 3 H). Anal. Calcd for $C_{20}H_{20}O_5$: C, 70.57; H, 5.92. Found: C, 70.54; H, 6.07.

1-(Allyloxy)-3-(*tert*-butyldimethylsiloxy)benzene, 12. A solution of 3-(allyloxy)phenol (4.5 g, 30 mmol), imidazole (4.5 g, 60 mmol), and *tert*-butyldimethylsilyl chloride (4.53 g, 30 mmol) in CH_3CN (30 mL) was stirred for 2 h at rt. Extractive workup with CH_2Cl_2 (30 mL) and column chromatography on silica gel (2.4 × 14 cm column, 5% Et_2O/PE as eluant) gave **12** (7.2 g, 91%) as a colorless oil: IR (NaCl) 1600, 1180, 1150, 840 cm^{-1}; ^1H NMR δ 7.15–7.06 (m, 1 H), 6.55–6.41 (str m, 3 H), 6.12–5.95 (m, 1 H), 5.46–5.24 (m, 2 H), 4.50 (d of t, J = 5.3 Hz, 1.5 Hz, 2 H), 0.97 (s, 9 H), 0.19 (s, 6 H); HRMS calcd for $C_{15}H_{24}O_2Si$ m/e 264.1545, obsd m/e 264.1517.

4-Allyl-3-(allyloxy)phenol, 13. To a solution of 1-(allyloxy)-3-(*tert*-butyldimethylsiloxy)benzene (4.0 g, 15.2 mmol) in PE (100 mL) was added diethylaluminum chloride (23 mL of a 1.0 M solution in PE). The mixture was stirred for 1 h at rt, and then the reaction was quenched by adding 3% HCl (30 mL). Extractive workup with Et_2O (200 mL) and column chromatography on silica gel (2.5 × 12 cm column, 10% Et_2O/PE as eluant) afforded an 83:17 (^1H NMR) mixture (3.71 g, 93%). A solution of the mixture from above (2.0 g, 7.58 mmol) in THF (50 mL) was added slowly to a suspension of NaH [606 mg of a 60% mixture in mineral oil washed once with PE and once with THF (13.4 mmol)] in THF (20 mL) at rt, and the resulting mixture was stirred for 2 h. Allyl bromide (1.1 g, 9.1 mmol) was added, and the resulting mixture was stirred for 6 h at rt. Extractive workup with Et_2O (100 mL) and column chromatography on silica gel (2.5 × 12 cm column, 2% Et_2O/PE as eluant) afforded an 86:14 (^1H NMR) mixture as a colorless oil (1.92 g, 83%). To a solution of this mixture (750 mg, 2.48 mmol) in CH_3OH (20 mL) was added $NaOCH_3$ (530 mg, 9.81 mmol) at rt. The resulting solution was stirred at rt for 3 h, and the reaction was quenched by adding H_2O (50 mL). The resulting solution was acidified by adding 5% HCl (5 mL), and the aqueous phase was extracted with CH_2Cl_2 (3 × 50 mL). Column chromatography on silica gel (1 × 14 cm column, 5% Et_2O/PE as eluant) gave **13** as a colorless oil (400 mg, 61% overall): IR (NaCl) 3310 (br s), 1610, 1600, 1500, 1450, 1275 cm^{-1}; ^1H NMR δ 6.97 (dd, J = 7.8, 0.5 Hz, 1 H), 6.40–6.30 (m, 2 H), 6.10–5.89 (m, 2 H), 5.47–5.23 (m, 2 H), 5.10–5.00 (m, 2 H), 4.61 (s, 1 H), 4.5 (d of t, J = 4.9 Hz, 1.6 Hz, 2 H), 3.33 (d, J = 6.6 Hz, 2 H); HRMS calcd for $C_{12}H_{14}O_2$ m/e 190.0993, obsd m/e 190.1000.

(±)-*trans*-2-(3,4-Dimethoxyphenyl)-2,3-dihydro-5-allyl-6-(allyloxy)-3-methylbenzofuran, 14. To a solution of **13** (450 mg, 2.37 mmol) and commercial 1,2-dimethoxy-4-propenylbenzene (3.0 g, 16.9 mmol) in CH_3CN (2 mL) at 0 °C was added iodobenzene *bis*-trifluoroacetate (1.53 g, 3.56 mmol). The reaction mixture was stirred for 20 min at 0 °C and then at rt for 20 min. Column chromatography on silica gel (2.5 × 14 cm column, PE to remove the olefin and then 5% EtOAc/PE as eluant) afforded **14** as a colorless thick oil (280 mg, 32%). An analytical sample was obtained as a white solid via recrystallization from Et_2O/PE, mp 51.5–52.5 °C: IR (KBr) 1515, 1485, 1265, 1160 cm^{-1}; ^1H NMR δ 6.97–6.83 (m, 4 H), 6.45 (s, 1 H), 6.07–5.98 (m, 2 H), 5.48–5.11 (m, 2 H), 5.08–5.00 (m, 2 H), 5.06 (d, J = 9.0 Hz, 1 H), 4.53–4.50 (m, 2 H), 3.89 (s, 3 H), 3.88 (s, 3 H), 3.43–3.30 (m, 3 H), 1.36 (d, J = 6.7 Hz, 3 H); HRMS calcd for $C_{23}H_{26}O_4$ m/e 366.1831, obsd m/e 366.1832.

(±)-*trans*-2-(3,4-Dimethoxyphenyl)-2,3-dihydro-5-allyl-6-hydroxy-3-methylbenzofuran, 15. To a solution of **14** (200 mg, 0.546 mmol) and $NaOCH_3$ (300 mg, 5.5 mmol) in CH_3OH (20 mL) was added $Pd(PPh_3)_4$ (10 mg) under N_2. The resulting mixture was stirred for 1 h at rt. The reaction was quenched by adding 1% HCl (20 mL), and CH_3OH was removed in vacuo. Extractive workup with CH_2Cl_2 (3 × 20 mL) and column chromatography on silica gel (1.5 × 12 cm column, 30% Et_2O/PE as eluant) gave **15** (161 mg, 90%) as an oily foam with identical spectral properties to those described.

Determination of Relative Reactivity of *trans*- and *cis*-1,2-Dimethoxy-4-propenylbenzene in the Oxidative Cyclization. The procedure is described for the reaction of *p*-methoxyphenol. The details for the other procedures are given in the supplementary material. The relative reactivities reported in the text are the average of two determinations.

***p*-Methoxyphenol.** To a CH_3CN (5 mL) solution of *p*-methoxyphenol (0.26 g, 2.09 mmol) and 48:52 *cis,trans*-propenylbenzene (0.73 g, 4.10 mmol) mixture was added iodobenzene–bis(trifluoroacetate) (1.00 g, 2.33 mmol), and stirring was continued for 20 min. The ratio of the propenylbenzenes was determined by VPC [20- × $^1/_8$-in. column, 3% OV-17 on Chromosorb G-HP, 100/120 mesh; 134 °C column temperature]. A 1-μL sample was taken directly from the reaction mixture after 20 min and injected to give a cis/trans ratio of 90:10. The solvent was removed in vacuo, and the resulting oil was chromatographed on flash silica gel [2- × 15-cm column; PE (200 mL), 9:1 PE/EtOAc (200 mL) as eluant] to yield the propenylbenzene (0.26 g, 1.46 mmol). The relative reactivities were calculated from the equation:[31]

$$\frac{k_{trans}}{k_{cis}} = \frac{\log\left[\dfrac{[trans]_0 - [trans]_{reacted}}{[trans]_0}\right]}{\log\left[\dfrac{[cis]_0 - [cis]_{reacted}}{[cis]_0}\right]}$$

***cis*-1,2-Dimethoxy-4-propenylbenzene.** A solution of *trans*-1,2-dimethoxy-4-propenylbenzene (2.0 g, 11.2 mmol) and 1-acetonaphthone (0.2 g, 1.2 mmol) in CH_3CN (450 mL) was irradiated using Corex-filtered light from a Hanovia 450-W medium-pressure source for 3.5 h. The progress of the isomerization was monitored by VPC (3% OV-17 on chromosorb G-HP, 100/120 mesh, 20- × $^1/_8$-in. column). Irradiation was stopped when the cis/trans ratio no longer changed (approximately 85:15 cis/trans). Careful chromatography on flash silica gel [4 × 35 cm column, PE (600 mL), 1% Et_2O/PE (300 mL) as eluant] gave the pure cis isomer (0.75g): IR (melt) 1508, 1250, 1230, 1135 cm^{-1}; ^1H NMR δ 6.88–6.79 (m, 3 H), 6.39–6.30 (m, 1 H), 5.77–5.61 (m, 1 H), 3.86 (s, 6 H), 1.89 (dd, J = 7.2, 1.8 Hz, 3 H); UV (PE) 288.0 (ϵ 10531), 258.0 (40101), 230.0 (92760), 215 (10531), 202.5 (9519).

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Registry No. **3a**, 150-76-5; **3b**, 2033-89-8; **3c**, 14786-82-4; *cis*-**4a**, 6380-24-1; *trans*-**4a**, 6379-72-2; **5a**, 132802-66-5; **5b**, 104832-93-1; **5c**, 139016-11-8; **5d**, 139016-12-9; **5e**, 139016-13-0; **5f**, 132802-69-8; **5g**, 132802-69-8; **5h**, 132802-68-7; **6a**, 84-85-5; **7a**, 139016-14-1; **7b**, 139016-15-2; **7c**, 139016-16-3; **7d**, 139016-17-4; **8a**, 132881-71-1; **10**, 13594-95-1; **11**, 132802-70-1; **12**, 132802-62-1; **13**, 132802-71-2; **14**, 132802-72-3; **15**, 104265-73-8; 1-naphthol, 90-15-3; *p*-methoxystyrene, 637-69-4; amethole, 104-46-1; isosafrole, 120-58-1; iodobenzene bis(trifluoroacetate), 2712-78-9; 2-allyl-4-methoxyphenol, 584-82-7; 2-allyl-5-chloro-4-methoxyphenol, 132802-65-4; 3-chloro-4,4-dimethoxy-2,5-cyclohexadienone, 119927-90-1; 2-

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naphthol, 135-19-3; resorcinol, 108-46-3; allyl bromide, 590-14-7; 3-(allyloxy)phenol, 1616-51-9.

Supplementary Material Available: Relative reactivity studies of *trans*- and *cis*-1,2-dimethoxy-4-propenylbenzene with phenols using iodobenzene bis(trifluoroacetate) and NMR spectra of selected compounds (23 pages). This material is contained in many libraries on microfiche, immediately follows this article in the microfilm version of the journal, and can be ordered from the ACS; see any current masthead page for ordering information.

Reductive Deoxygenation of Ketones and Secondary Alcohols by Organoaluminum Lewis Acids[1]

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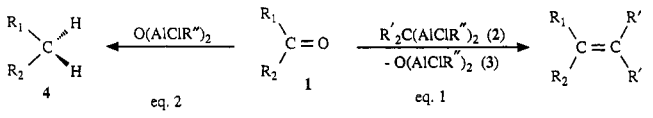
The reductive deoxygenation of ketones and secondary alcohols to the corresponding methylene hydrocarbons has been achieved in good to excellent yield by the combined action of an aluminum hydride source and a strongly Lewis-acidic aluminum reagent. Such reductions were successful with diaryl ketones, alkyl aryl ketones, and dialkyl ketones, as exemplified by the reduction of benzophenone, acetophenone and 5-nonanone, respectively. The corresponding secondary alcohols of these ketones, namely benzhydrol, 1-phenyl-1-ethanol, and 5-nonanol, could also be converted into their respective methylene hydrocarbons by Lewis-acidic sources of aluminum hydride. All such reductions of ketones could be conducted in a single reaction flask in a one-, two-, or three-step process. In the one-step process, which is most suitable for diaryl ketones, i-$BuAlCl_2$ may be employed as both the hydride source and the Lewis acid. For alkyl aryl ketones a two-step process, consisting first of reduction with i-Bu_2AlH and then treatment with $AlBr_3$ (with or without catalysis by Cp_2TiCl_2), leads to better yields. Finally, for dialkyl ketones a three-step process proved to be preferred, wherein a sequential treatment with i-Bu_2AlH, $AlBr_3$ and then additional i-Bu_2AlH (with a $Ni(acac)_2$ catalyst) gives the highest conversion to alkane. If required, residual alkene may be removed by a brief catalytic hydrogenation or treatment with BH_3·THF. The ease of deoxygenating the foregoing ketones and secondary alcohols appears to be governed by the ease of forming, and the relative stability of, the corresponding carbenium ion intermediates, namely $Ar_2HC^+ > ArRHC^+ > R_2HC^+$. The driving force for such deoxygenations by these aluminum reagents undoubtedly is the exothermic formation of the dialuminoxane system, $R_2Al-O-AlR_2$.

Introduction

During a recent study of the alkylenating action of geminal dialuminoalkanes (2) upon ketones (1),[2a] two of us[2b] made the serendipitous observation that the dialuminoxane byproduct 3 (a, R″ = Et; b, R″ = i-Bu) had been able to reduce a small portion of the ketone to the corresponding methylene derivative 4, especially in those cases where diaryl or aryl alkyl ketones were employed (eq 2; R_1, R_2 = Ar or R_1 = Ar; R_2 = R). Although the reduction of ketones to secondary alcohols by aluminum alkyls or hydrides is rich in precedent,[3] this type of reductive deoxygenation is not. Only a limited study of the reducing action of combinations of $LiAlH_4$ and AlX_3 in diethyl ether has been made, in which alkyl aryl and diaryl ketones were shown to be similarly reduced in yields ranging between 20% and 90%.[4] However, the reduction of ketones to methylene derivatives has been achieved by a number of other reagents,[5] prominent among which are zinc with acid as in the Clemmensen reduction,[6a] sodium borohydride with trifluoroacetic acid, as found by Gribble and co-workers,[6b] and hydrazine with base as in the Wolff-Kishner reduction.[7] Unfortunately, the most versatile of these reduction methods necessitate the use of strongly acidic or basic reagents with polar solvents, and such conditions can lead to undesired side reactions. The great advantage that aluminum reagents like 3 would offer for such reductive deoxygenations is that they can react in hydrocarbon media and the methylene derivative can be isolated from the aluminoxane byproduct without hy-



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