Table IV. Comparison of ρ^+ Values for Homolytic Aromatic Substitution

radical	ρ^+	ref
$C_6H_{11}\cdot$	1.1[a]	25
$CH_3\cdot$	0.1[a]	21
$C_6H_5\cdot$	0.1[a]	22
$\cdot CH_2CO_2H$	−0.6[b]	19
$\cdot CH_2COCH_3$	−1.5	this work
$\cdot CCl_3$	−1.5[b]	26
$\cdot CH_2NO_2$	−2.1	8
$C_6H_5CO_2\cdot$	−1.6	27
$i\text{-}C_3H_7OCO_2\cdot$	−2.3	28

[a] Plotted vs. ρ values, actually ρ. [b] Determined by hydrogen abstraction from substituted toluenes.

to produce a σ-radical intermediate (eq 8).[24] Many other homolytic aromatic substitutions have been nicely correlated by Hammett plots.[8,19,21,25] The large (−) ρ or ρ^+ values suggest that a fair degree of "+" charge develops on the aromatic ring during the substitution process and indicates that the acetonyl radical is electron deficient. As such it prefers attack on aromatics that have electron-donating substituents. This is evidenced by the higher yields obtained when either anisole or toluene is reacted with acetone compared to the yields obtained when either benzene or fluorobenzene is reacted (Table I).

A direct comparison of these ρ and ρ^+ values can be made to the nitromethyl radical produced from nitromethane and manganese(III), which gave values of −3.3 and −2.3, respectively.[8] For wide comparison purposes it is more informative to compare the ρ^+ values (despite the somewhat poorer correlation) with those from other electron-deficient radicals (Table IV), which generally have correlated better with σ^+ than σ. The ρ^+ values of −1.5 indicates that this radical is somewhat more electrophilic than the carboxymethyl radical,[19] despite the fact that it bears structural similarities (α-carbonyl group) to that radical. It is less electrophilic than the nitromethyl,[8] and a number of acyloxy radicals,[27,28] yet more so than most other carbon radicals.

Registry No. Benzene, 71-43-2; toluene, 108-88-3; anisole, 100-66-3; chlorobenzene, 108-90-7; fluorobenzene, 462-06-6; naphthalene, 91-20-3; *p*-dimethoxybenzene, 150-78-7; 1-(*m*-methylphenyl)-1-cyanoacetone, 38377-59-2; 1-(*o*-methylphenyl)-1-cyanoacetone, 75205-42-4; 1-(*p*-methylphenyl)-1-cyanoacetone, 27243-91-0; 1-(*m*-fluorophenyl)-1-cyanoacetone, 446-74-2; 1-(*m*-methoxyphenyl)-1-cyanoacetone, 25594-66-5; 1-(β-naphthyl)-1-cyanoacetone, 51074-12-5; 1-(α-naphthyl)-1-cyanoacetone, 31573-38-3; 1-(*p*-chlorophenyl)-1-cyanoacetone, 5219-07-8; (*m*-methylphenyl)acetone, 18826-61-4; (*o*-methylphenyl)acetone, 51052-00-7; (*p*-methylphenyl)acetone, 2096-86-8; (*m*-fluorophenyl)acetone, 1737-19-5; 1-naphthylacetone, 33744-50-2; 2-naphthylacetone, 21567-68-0; (*p*-chlorophenyl)acetone, 5586-88-9; (*m*-chlorophenyl)acetone, 14123-60-5; $Mn(OAc)_3$, 993-02-2; $Ce(OAc)_4$, 19475-87-7; D_2, 7782-39-0.

(24) Perkins, M. J. "Free Radicals"; Kochi, J. K., Ed.; Wiley: New York, 1973; Vol. II, p 231.
(25) Shelton, J. R.; Uzlemeier, C. W. *J. Am. Chem. Soc.* **1966**, *88*, 5222.
(26) Van Der Ploeg, R. E.; DeKorte, R. W.; Kooyman, E. C. *J. Catal.* **1968**, *10*, 52.
(27) Kurz, M. E.; Pellegrini, M. *J. Org. Chem.* **1970**, *35*, 990.
(28) Kovacic, P.; Reid, C. G.; Kurz, M. E. *J. Org. Chem.* **1969**, *34*, 3302.

Carbon–Hydrogen vs. Carbon–Carbon Bond Cleavage of 1,2-Diarylethane Radical Cations in Acetonitrile–Water[1]

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Radical cations of 1,2-diarylethanes and 1-phenyl-2-arylethanes (Ar = phenyl, *p*-tolyl, *p*-anisyl) were generated in acidic 70% acetonitrile–water by Cu^{2+}-catalyzed peroxydisulfate oxidation. The radical cations fragment mainly by loss of benzylic protons (C–H cleavage) rather than by alkyl C–C bond cleavage. The 1,2-diarylethanol products undergo further selective oxidation to aryl aldehydes and arylmethanols via rapid equilibration of diarylethane and diarylethanol radical cations. The radical cation of 2,3-dimethyl-2,3-diphenylbutane fragments efficiently by C–C cleavage, forming cumyl radical and cumyl cation. Oxidations of bibenzyl–bicumyl mixtures show selective oxidation of bicumyl dependent on total substrate concentration, providing evidence of equilibrating radical cations and showing that bicumyl fragments faster than bibenzyl loses protons. The effects of reaction conditions and substrate structure on reactivity are discussed.

In 1973, Trahanovsky and Brixius reported that the Ce(IV) oxidation of 1,2-diarylethanes occurred by electron transfer to form radical cations which then undergo cleavage of the ethylene bond.[2] Since this study, the

$$[ArCH_2CH_2Ar]^{+\cdot} \rightarrow ArCH_2^+ + ArCH_2\cdot \quad (1)$$

formation and reactions of aromatic radical cations in solution have received much study.[3-10] One reaction found to be common for alkylbenzene radical cations involves dissociation to benzylic radicals and hydrogen ions.[3,5,8,9,11]

$$[PhCH_3]^{+\cdot} \rightarrow PhCH_2\cdot + H^+ \quad (2)$$

(1) This work supported by the Gas Research Institute, Basic Coal Science Program, Contract No. 5081-260-0526.
(2) Trahanovsky, W. S.; Brixius, D. W. *J. Am. Chem. Soc.* **1973**, *95*, 6778–6780.
(3) (a) Walling, C.; Camaioni, D. M.; Kim, S. S. *J. Am. Chem. Soc.* **1978**, *100*, 4814–4818. Walling, C.; Camaioni, D. M. *Ibid.* **1975**, *97*, 1603. (b) Eberhardt, M. *J. Org. Chem.* **1977**, *42*, 832–835.
(4) Snook, M. E.; Hamilton, G. A. *J. Am. Chem. Soc.* **1974**, *96*, 860.
(5) Sehested, K.; Holcman, J.; Hart, E. J. *J. Phys. Chem.* **1977**, *81*, 1363. Holcman, J.; Sehested, K. *Ibid.* **1978**, *82*, 651.
(6) Yoshida, K. "Electrooxidation in Organic Chemistry: The Role of Cation Radicals as Synthetic Intermediates"; Wiley: New York, 1984.
(7) O'Neill, P.; Steenken, S.; Schulte-Frohlinde, D. *J. Phys. Chem.* **1975**, *79*, 2773; *Ibid.* **1977**, *81*, 26, 31.

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Table I. Oxidations of Bibenzyl by $S_2O_8^{2-}$ in 70% Acetonitrile-Water

			products, %[a]				
expt	$[Cu^{2+}]$	$[HClO_4]$	1,2-diphenylethanol	1,2-diphenylethylacetamide	benzaldehyde	benzyl alcohol	hydroxybibenzyls
1[b]	0.05	0.11	34	3	11	7	14 (48-0-52)[c]
2[d]	0.05	0.11	54	4	12	8	<1
3[e]	0.05	0.11	67	6	4	<1	<1
4[b]	0.10	0.011	22	3	4	3	41 (36-7-57)
5[b]	0.10	0.11	28	3	8	6	18 (41-7-52)
6[b]	0.10	1.00	31	7	17	9	<1

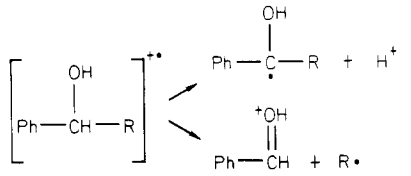
[a] Yields based on initial $[S_2O_8^{2-}]$. [b] By addition of $Fe(ClO_4)_2$ solution to a rapidly stirred solution containing 0.12 M bibenzyl, 0.014 M $S_2O_8^{2-}$, $HClO_4$, and $Cu(ClO_4)_2$ under N_2, $T = 25$ °C. [c] (o-m-p). [d] By addition of $S_2O_8^{2-}$ to reagents in solution brought to reflux (~83 °C) under N_2; no Fe^{2+} added. [e] Conditions as in expt 2, except 0.001 M $S_2O_8^{2-}$.

The driving force of this reaction is the relative stability of the benzyl radical and the large negative heat of solvation for the proton. Examples in which C–C cleavage from substituted benzene radical cations occurs include[3] eq 3 and 4. The driving force for these fragmentations

$$[PhCH_2CO_2H]^{+\cdot} \rightarrow PhCH_2\cdot + CO_2 + H^+ \quad (3)$$

$$[PhCH_2CH_2OH]^{+\cdot} \rightarrow PhCH_2\cdot + CH_2{=}O^+H \quad (4)$$

may be viewed as the formation of relatively stable ions and/or neutral molecules and benzyl radical. For the case of 1-phenylalkanols,[4] both proton loss and C–C cleavage pathways may occur depending on the stability of the alkyl radicals and ions formed. When R is secondary or tertiary



(5)

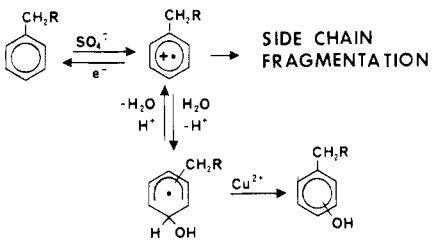
(and presumably benzylic), C–C cleavage is predominant, but when R is primary, proton loss is favored.[4] For the 1,2-diarylethanes studied by Trahanovsky and Brixius,[2] the relative contributions of proton loss and C–C cleavage pathways could not be determined because initial products suffered extensive secondary oxidation. Thus, this study was undertaken to examine the reactions of some diarylethanes under conditions which allow discrimination between C–C cleavage and proton loss pathways.

To generate the radical cations, we used peroxydisulfate oxidation because the system operates as a redox chain reaction, selectively forming radical cations and converting radical intermediates into identifiable products.[3,8] Initiation occurs by thermal decomposition or metal ion reduction of $S_2O_8^{2-}$ to generate sulfate radical anions, $SO_4^{-}\cdot$, which react with aromatics by electron transfer at rates which approach diffusion limits (i.e., 3×10^9 M^{-1} s^{-1} for benzene and 5×10^9 M^{-1} s^{-1} for anisole)[12] but abstract aliphatic hydrogen at much slower rates (10^5 M^{-1} s^{-1} for acetic acid,[13] 10^6 for *tert*-butyl alcohol,[13] and 10^7 for methanol[14]). Radical intermediates, formed by reaction

$$S_2O_8^{2-} \xrightarrow{\Delta} 2SO_4^{-}\cdot \quad (6)$$

$$M^{n+} + S_2O_8^{2-} \rightarrow M^{(n+1)+} + SO_4^{-}\cdot + SO_4^{2-} \quad (7)$$

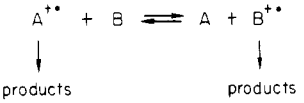
Scheme I



$$R\cdot + Cu(II) \rightarrow RCu(III) \xrightarrow{H_2O} ROH + Cu(I) + H^+ \quad (8)$$

of the radical cations, are oxidized to hydroxylic products by Cu^{2+} ions,[8,15] and Cu^+ ions, so formed, propagate the oxidation by regenerating $SO_4^{-}\cdot$, eq 7. As depicted in Scheme I, alkyl-substituted radical cations undergo competing reactions of side chain fragmentation and hydration. Though hydration is rapid, side chain fragmentation is favored in acidic media because dehydration of the hydroxyl adducts is acid catalyzed and fast.[5,7] However, phenolic products may be obtained if high concentrations of Cu^{2+} are used to trap the hydroxyl adducts as quickly as they form.[3]

Competitive oxidations of various aromatic substrates by $S_2O_8^{2-}$ may occur with selectivities that are not in accord with the rates of attack by $SO_4^{-}\cdot$.[8-10] For example, Walling



(9)

and co-workers[9] have pointed out that arylmethanes and arylmethanols show selectivities that would require rates of attack in excess of diffusion limits. Thus, partial equilibration of radical cations has been proposed, under which conditions selectivities are partly determined by the relative rates of side chain fragmentation.

With this background we present the results and conclusions of this study.

(8) Minisci, F.; Citterio, A.; Giordano, C. *Acc. Chem. Res.* **1983**, *16*, 27–32.
(9) Walling, C.; Zhao, C.; El-Taliawi, G. *J. Org. Chem.* **1983**, *48*, 4910–4914; **1983**, *48*, 4914–4917.
(10) Citterio, A.; Arnoldi, C. *J. Chem. Soc., Perkin Trans. 1* **1983**, 891–896.
(11) (a) Trahanovsky, W. S.; Young, L. B. *J. Org. Chem.* **1966**, *31*, 2033. (b) Kochi, J. K. In "Free Radicals"; Kochi, J. K., Ed.; Wiley: New York, 1973; Vol. I, pp 642–650.
(12) Neta, P.; Madhaven, V.; Zemel, H.; Fessenden, W. *J. Am. Chem. Soc.* **1977**, *99*, 163.
(13) Dogliotti, L.; Hayon, E. *J. Phys. Chem.* **1967**, *71*, 2511, 3802.
(14) Hayon, E.; Treinin, A.; Wilf, J. *J. Am. Chem. Soc.* **1972**, *94*, 47.
(15) Walling, C. *Acc. Chem. Res.* **1975**, *8*, 125–131. See ref 11b, pp 595–623.

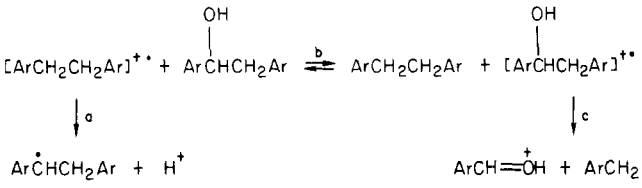
Table II. Oxidation of Toluene by $S_2O_8^{2-}$ in 70% Acetonitrile-Water[a]

		products, %[b]		
expt	$[HClO_4]$	benzyl alcohol	benzaldehyde	cresols (o-(m+p))
1	0.11	18	3	39 (54-46)
2	0.011	10	2	50 (49-51)
3	1.10	29	7	5 (56-44)

[a] 0.124 M toluene and 0.014 M $S_2O_8^{2-}$, other conditions as in expt 4, Table I, except as noted. [b] Based on $S_2O_8^{2-}$.

Results

Initial experiments were conducted with bibenzyl under conditions selected to favor fragmentation reactions of the radical cation (i.e., high acidity and 0.05 M Cu^{2+}; see Scheme I and introductory discussion). Reactions were carried out in 70% acetonitrile–water which enabled the use of 0.1 M concentrations of bibenzyl at room temperature. Two procedures were employed. One procedure, exemplified by experiment 1 of Table I, employed initiation by addition of Fe^{2+} at room temperature and the other, exemplified by experiment 2, employed thermal initiation at the reflux temperature (~83 °C) of the reaction mixture; no iron was present. For both these experiments, $S_2O_8^{2-}$ was present in an approximately 10-fold lower concentration than bibenzyl in order to suppress secondary oxidation. Thus, we found that 1,2-diphenylethanol and *N*-(1,2-diphenylethyl)acetamide constituted major fractions of the products with minor amounts of benzaldehyde and benzyl alcohol being formed. The proton loss pathway should form 1,2-diphenylethanol and the C–C cleavage pathway should form benzyl alcohol. However, oxidation of diphenylethanol via secondary pathways (eq 10) is expected to produce benzaldehyde and

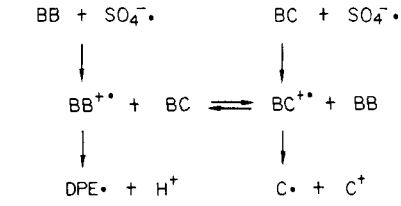


(10)

benzyl alcohol. Similar secondary oxidation pathways also will convert benzyl alcohol to benzaldehyde.[9] Since the benzaldehyde was formed in slight excess over benzyl alcohol, it seems plausible that both products mainly derive from the further oxidation of diphenylethanol. That only a small fraction of the benzyl alcohol is expected to have been oxidized to benzaldehyde is shown by the oxidation of toluene under comparable conditions, which yielded 18% benzyl alcohol and 3% benzaldehyde (see Table II, experiment 1). The assignment of benzaldehyde and benzyl alcohol as secondary oxidation products of diphenylethanol is further supported by experiments carried out at lower extents of oxidation. For example, when the concentration of $S_2O_8^{2-}$ was reduced by a factor of 10 and all other conditions were left unchanged (see Table I, experiment 3), yields of benzaldehyde and benzyl alcohol, based on $S_2O_8^{2-}$, were greatly reduced or nearly eliminated and the yield of diphenylethanol was correspondingly increased. This behavior is consistent with eq 10 as the pathway for the formation of products.

At this point in the work, experiments were carried out to test for the possibility that diphenylethanol is formed by an alternative mechanism not involving radical cation intermediates. A likely competing pathway could involve

Scheme II



attack of $SO_4^{-\cdot}$ on acetonitrile, present at ~13 M concentration, to form cyanomethyl radicals which in turn abstract benzylic hydrogen to form diphenylethyl radicals.

$$SO_4^{-\cdot} + CH_3CN \rightarrow \cdot CH_2CN + HSO_4^- \quad (11)$$

$$\cdot CH_2CN + PhCH_2CH_2Ph \rightarrow PhCH_2CHPh\cdot + CH_3CN \quad (12)$$

One difference between this mechanism and Scheme I is that attack by $\cdot CH_2CN$ should not produce phenolic products. Therefore, oxidations of bibenzyl and toluene were carried out under more optimum conditions for the formation of phenols (Fe^{2+} initiation, 0.1 M Cu^{2+}, 0.01 M $HClO_4$, experiment 4, Table I and experiment 2, Table II). Hydroxybibenzyls and cresols were found in yields of 41% and 50%, suggesting that a substantial fraction of the oxidation must form radical cations. To further substantiate the mechanism of Scheme I, the effect of increasing acidity was probed by carrying out oxidations in concentrations of $HClO_4$ as high as 1.0 M (other conditions unchanged). Experiments 4, 5, and 6 of Table I and 1 and 3 of Table II show that phenols decrease and side chain cleavage products increase with increasing acidity. This behavior is also in accord with Scheme I and parallels observations on the oxidations of phenylacetic acid[3] and phenylethanol[3] by $S_2O_8^{2-}$ in water.

Oxidations of bibenzyl carried out by the second procedure (thermal initiation, no iron) produced little phenols (compare experiments 1 and 2 of Table I). Therefore, in order to demonstrate the intermediacy of radical cations, 2,3-dimethyl-2,3-diphenylbutane (bicumyl) was oxidized. It is unlikely that side chain attack by $\cdot CH_2CN$ or $SO_4^{-\cdot}$ could cause cleavage of the central C–C bond. When the conditions in Table I, experiment 2 were used (except 0.05 M bicumyl and 0.005 M $S_2O_8^{2-}$), the products, 2-phenyl-2-propanol (cumyl alcohol), 122%, α-methylstyrene, 32%, and acetophenone, 5%, were produced (yields based on $S_2O_8^{2-}$). Presumably 2-phenyl-2-propanol and α-methylstyrene are derived from intermediate cumyl radical and cumyl cation, and acetophenone is a product of the oxidation of 2-phenyl-2-propanol.[4] The product yields correspond to an 85% conversion of $S_2O_8^{2-}$ to products (calculated by summing the yields, dividing by 2, and adding an additional 5% for the further oxidation). In a second experiment carried out without added $HClO_4$, nearly quantitative yields of products corresponding to a 93% conversion were obtained (2-phenyl-2-propanol, 161%, α-methylstyrene, 13%, acetophenone, 4%). These findings, together with the total results of bibenzyl and toluene, strongly support our premise that radical cations are generated by these oxidations.

$$[PhC(CH_3)_2C(CH_3)_2Ph]^{+\cdot} \rightarrow PhC(CH_3)_2^+ + PhC(CH_3)_2\cdot \quad (13)$$

Competitive oxidations of bicumyl (BC) and bibenzyl (BB) were carried out to observe the equilibration of the radical cations and determine which cleavage reaction is faster. From Scheme II, equilibration of the radical cations is bimolecular such that it should be sensitive to substrate

Table III. Competitive Oxidations of Bicumyl vs. Bibenzyl. Effect of Substrate Concentration, Acidity, and Percent CH_3CN on the Relative Reactivity[a]

		products[b]							
[BC + BB]	BC/BB	CA	MS	AP	DPE	S	BZ	BA	relative reactivity[c]
0.020	0.97	54	23	2.8	26	ND[d]	2.7	1.1	1.5
0.055	1.01	73	37	3.7	23	0.4	2.5	1.4	2.2
0.104	0.92	86	42	2.2	19	0.2	1.3	0.6	3.5
0.147	1.00	92	44	1.6	16	0.6	1.4	ND	4.0
0.180	0.39	77	42	1.1	24	1.2	1.8	ND	5.9
0.178[e]	0.38	100	7.3	1.5	25	1.4	1.8	ND	5.2
0.180[f]	0.39	23	95	0.8	20	0.8	2.6	ND	6.9

[a] 2×10^{-3} M $S_2O_8^{2-}$, other conditions as in Table I, expt 2, except as noted. [b] Yield based on $S_2O_8^{2-}$ consumed. CA (cumyl alcohol), MS (α-methylstyrene), AP (acetophenone), DPE (diphenylethanol and diphenylethylacetamide), S (stilbene), BZ (benzaldehyde), BA (benzyl alcohol). [c] $[^1/_2(CA + MS + AP)/(DPE + S + {}^1/_2(BZ + BA)]BB/BC$. [d] ND, not detected. [e] 0.01 M $HClO_4$. [f] 90% CH_3CN.

Table IV. Oxidations of 1,2-Di-*p*-tolylethane by $Cu^{2+}/S_2O_8^{2-}$ in 70% Acetonitrile-Water[a]

	% yield based on $[S_2O_8^{2-}]$	
products	expt 1	expt 2
1,2-di-*p*-tolylethanol	20	39
1-*p*-tolyl-2-(*p*-(hydroxymethyl)phenyl)ethane	6	5
N-(1,2-di-*p*-tolylethyl)-acetamide	2	1
p-tolualdehyde	20	6
p-methylbenzyl alcohol	16	8

[a] 0.10 M DTE, 0.012 M $S_2O_8^{2-}$ (expt 1) or 0.0012 M $S_2O_8^{2-}$ (expt 2), other conditions as in Table I, expt 2.

Table V. Oxidation of 1-Phenyl-2-*p*-tolylethane by $Cu^{2+}/S_2O_8^{2-}$[a]

	% yield based on $[S_2O_8^{2-}]$	
products	expt 1	expt 2
phenyltolylethanols	35[b]	43
p-phenethylbenzyl alcohol	18	14
N-(phenyltolylethyl)-acetamide	2	2
tolualdehyde	10	3
benzyl alcohol	7	ND[c]
benzaldehyde	1	3
p-methylbenzyl alcohol	1	ND

[a] 0.15 M PTE, 0.015 M $S_2O_8^{2-}$ (expt 1) or 0.0015 M $S_2O_8^{2-}$ (expt 2) other conditions as in Table I, expt 2. [b] Approximately 1% 1-phenyl-2-tolylethanol, the remainder is 2-phenyl-1-tolylethanol. [c] ND, none detected.

concentrations. We expect that at low concentrations of substrates, side chain cleavage reactions may be fast compared to equilibration so that product distributions are governed by initial attack of $SO_4^{-\cdot}$, whereas at high substrate concentrations equilibration is competitive with or even faster than cleavage so that product distributions are partly or wholly dependent on the relative rates of side chain cleavage. In Table III are the results of oxidations of several bicumyl–bibenzyl mixtures. The oxidation conditions were analogous to those previously employed to oxidize bibenzyl (Table I, experiment 2) and bicumyl, except for the last two experiments, in which less acid or higher percent CH_3CN were used. From the product yields, the amounts of BC and BB consumed were calculated by using the formula, BC consumed = $^1/_2$(CA + MS + AP) and BB consumed = DPE + S + $^1/_2$(BZ + BA), where CA is cumyl alcohol, MS is α-methylstyrene, AP is acetophenone, DPE is diphenylethanol plus diphenylethylacetamide, S is stilbene, BZ is benzaldehyde, and BA is benzyl alcohol. The reactivity of bicumyl relative to bibenzyl varies proportionally from 1.4 to 6.0 over the concentration range 0.02 M to 0.18 M total substrate, providing additional evidence for the mechanism of equilibrating radical cations and showing that $BC^{+\cdot}$ fragments faster than $BB^{+\cdot}$ loses a proton. Small amounts of secondary oxidation products, benzaldehyde, benzyl alcohol, and acetophenone were observed showing that the radical cation cleavage reactions which form these products must be even faster than the cleavage of $BC^{+\cdot}$ since the diphenylethanol and cumyl alcohol are formed in much lower concentrations. The last two experiments of Table III show that a lower acidity causes the oxidation to be less selective, whereas a higher percent of CH_3CN causes the oxidation to be more selective. Although the effects are smaller than the concentration effects, their occurrence is consistent with the equilibration mechanism. The effects of increasing acidity or percent CH_3CN should retard the proton loss reaction of $BB^{+\cdot}$ because the proton-accepting ability of the medium is decreased.

The effects observed in these experiments are presented to show the equilibration of radical cations, though the results can be explained by irreversible electron transfer in the direction to form $BC^{+\cdot}$. However, we expect very similar oxidation potentials for BB and BC; therefore, the reverse electron transfer is expected as well.

Our study was then expanded to include other 1,2-diarylethanes. Results for the compounds 1,2-di-*p*-tolylethane (DTE), 1-phenyl-2-*p*-tolylethane (PTE), and 1-*p*-anisyl-2-phenylethane (APE) appear in Tables IV, V and

Table VI. Oxidations of 1-*p*-Anisyl-2-phenylethane by $Cu^{2+}/S_2O_8^{2-}$ in 70% Acetonitrile-Water[a]

			products, %			
expt	$[HClO_4]$	$[S_2O_8^{2-}]$	1-(*p*-anisyl)-2-phenylethanol	*p*-anisaldehyde	benzyl alcohol	benzaldehyde
1	0.11	0.012	17	14	9	7
2	0.11	0.0010	39	4	ND	4
3	NA	0.012	39	22	17	2
4	NA	0.0012	77	9	6	2

[a] 0.10 M APE, other conditions as in Table I, expt 2 except as noted. NA, none added. ND, none detected.

VI, respectively. Oxidations were carried out under conditions similar to the thermally initiated oxidations of bibenzyl. Products are analogous to those observed for bibenzyl, mainly 1,2-diarylethanols, aryl aldehydes, and arylmethanols. For DTE and PTE, additional products corresponding to proton loss from the *p*-methyl group were also formed. Minor amounts (1–5% total) of diaryl-

$$[ArCH_2CH_2C_6H_4CH_3]^{+\cdot} \xrightarrow{-H^+} ArCH_2CH_2PhCH_2\cdot \xrightarrow[H_2O]{Cu^{2+}} ArCH_2CH_2PhCH_2OH \quad (14)$$

ethylacetamides and substituted stilbenes and α-phenylacetophenones were also detected. Overall, for a given set of reaction conditions, the yields of aryl aldehydes and arylmethanols increased and the yields of diarylethanols decreased as the strength and number of electron-donating ring substituents increased. Compare experiments 2 (Table I), 1 (Table IV), 1 (Table V), and 1 (Table VI). However, yields of aryl aldehydes tended to exceed arylmethanols and lower extents of oxidation favored formation of diarylethanols, suggesting that proton loss and further oxidation of diarylethanols are dominant pathways of product formation. In support of this view are the results from the unsymmetrically substituted PTE and APE.

For PTE, it was found that in addition to the formation of 2-phenyl-1-tolylethanol, a small amount of 1-phenyl-2-tolylethanol was formed. Though the isomeric alcohols could not be resolved by capillary GC, their identities and relative amounts were unambiguously established by GC–MS techniques. The GC peak for the tolylphenylethanols contained fragment ions (*m/e*) 121 and 106. Mass spectra of authentic samples of 2-phenyl-1-tolylethanol and 1-phenyl-2-tolylethanol show that these ions are unique to and are base ions for the respective alcohols (see Experimental Section). From the relative intensities of these ions [100 (121), 3.5 (106)] it is estimated that ~2–5% of the phenyltolylethanol product is the 1-phenyl isomer. Also, the products *p*-tolualdehyde, benzyl alcohol, benzaldehyde, and *p*-methylbenzyl alcohol were found in 10%, 7%, 2%, and 1% yields. This distribution is consistent with their formation by further oxidation of a mixture of phenyltolylethanols in which 2-phenyl-1-tolylethanol predominates. A control experiment was carried out in which 2-phenyl-1-*p*-tolylethanol was subjected for 1 h to similar reaction conditions (except no $S_2O_8^{2-}$ was present). Analyses by GC and GC–MS showed that the alcohol was partially solvolyzed (5%) yielding nearly equal amounts of *p*-methylstilbene and *N*-(2-phenyl-1-*p*-tolylethyl)acetamide, but not 1-phenyl-2-*p*-tolylethanol. In view of all these findings the contribution to products by the competing pathway of C–C cleavage is probably small. If we assume no C–C cleavage then approximately 71% of the fragmentation occurs by proton loss from the methylene α to the tolyl group, 2% by proton loss from the methylene α to the phenyl group, and 27% by proton loss from the methyl group.

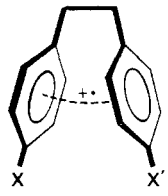
For APE, the overall yield of products was dependent on the acidity, and optimum yields were obtained in the absence of added $HClO_4$ (compare experiments 1 and 3 and 2 and 4 of Table VI). Nonetheless, all conditions gave 1-anisyl-2-phenylethanol as the major product (structure confirmed by GC–MS), accompanied by lesser amounts of *p*-anisaldehyde, benzyl alcohol, and benzaldehyde. Small amounts of *p*-methoxystilbene and α-phenyl-4-methoxyacetophenone and trace amounts of *p*-methoxybenzyl alcohol were also detected. The near absence of *p*-methoxybenzyl alcohol and the fact that the yields of anisaldehyde are approximately equal to the sum of the benzyl alcohol and benzaldehyde yields suggest that anisaldehyde, benzyl alcohol, and benzaldehyde form mainly by further oxidation of the proton loss product, 1-anisyl-2-phenylethanol. This argument assumes that some benzyl alcohol is further oxidized to benzaldehyde. If C–C cleavage of $APE^{+\cdot}$ had occurred, then substantial yields of *p*-methoxybenzyl alcohol would have been observed. Supportive of this conclusion were oxidations of *p*-methoxytoluene under conditions identical with experiments 1 and 3, which gave *p*-methoxybenzyl alcohol and *p*-anisaldehyde in yields of 53% and 4% and 31% and 20% for the respective experiments, suggesting that a major fraction of the methoxybenzyl alcohol, if formed by C–C cleavage, would have survived further oxidation.

1,2-Di-*p*-anisylethane was similarly oxidized though complete analyses were not carried out. Like experiments conducted on APE, total yields were dependent on [$HClO_4$]. In the presence of 0.11 M $HClO_4$, yields of anisaldehyde and *p*-methoxybenzyl alcohol were 32% and 29%, respectively, and in the absence of added $HClO_4$ yields were 47% and 38%, respectively. Positive identification of 1,2-di-*p*-anisylethanol as a product could not be made due to lack of an authentic standard, though any GC peaks having retention times consistent with the compound could not have amounted to more than 1%. In view of the results on the oxidation of APE and the oxidation of methoxytoluene, it would seem plausible that this product distribution also results from the pathway involving initial proton loss and further oxidation, though participation of the C–C cleavage pathway cannot be ruled out.

Discussion

Accepting the above mechanisms for primary and secondary oxidation, the sum of our results indicate that the 1,2-diarylethane radical cations, formed in acetonitrile–water, fragment mainly by proton loss. Neither strong acid (up to 1 M $HClO_4$ for bibenzyl and 0.1 M for other diarylethanes), nor electron donating *p*-methyl or *p*-methoxy groups detectably enhanced the C–C cleavage pathway; instead they tended to favor further oxidation of diarylethanols. On the other hand, C–C cleavage is favored by α-substitution. For bicumyl, the methyl groups make C–C cleavage efficient not only by precluding proton loss but by lowering the barrier to C–C cleavage. Similarly, substitution of a hydroxyl group for an α-hydrogen greatly accelerates the C–C cleavage reaction. This fact is amply demonstrated by the propensity exhibited by diarylethanols to undergo further oxidation in the presence of diarylethanes. Evidently, the α-substituents favor C–C cleavage by stabilizing the transition state without stabilizing the radical cation, whereas the *p*-substituents stabilize both the radical cation and the transition state such that the barrier to C–C cleavage is not necessarily reduced. From eq 10, it is evident that the degree of secondary oxidation will be sensitive to all factors which affect rates of proton loss (a), electron transfer (b), and C–C cleavage (c). From this work it is observed that acidity, substrate concentrations, and electron-donating *p*-substituents favor secondary oxidation. High acidities slow the rate of proton loss and high concentrations of substrates increase electron transfer reaction rates. Both effects can favor secondary oxidation. Electron-donating *p*-substituents may slow down proton loss by stabilizing the radical cation and they also may lower the barrier to C–C cleavage of diarylethanols by stabilizing the cleavage intermediates (see eq 10). The magnitude of these effects are difficult to predict. However, either or both effects will favor secondary oxidation.

It is interesting to speculate about the structure of these radical cations. We observe that diarylethanes undergo greater secondary oxidation than arylphenylethanes. Though a small enhancement of path c (eq 10) might be expected due to the substituent on the β-ring, greater secondary oxidation might also be due to a slower rate of proton loss caused by the diarylethane radical cations being more stable than the corresponding arylphenylethane radical cations. Such would be the case if the radical cations had sandwich structure 1 which enabled charge



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resonance between both rings. Our observation of proton loss from both methylenes in phenyltolylethane and the observation of Delcourt and Rossi[16] of visible absorption bands (600–800 nm) in the spectrum of bibenzyl radical cation in acetonitrile would be consistent with such a structure.

Experimental Section

Reagents were obtained from commercial sources (Aldrich, Pfaltz & Bauer, Alfa, and Burdick & Jackson) or were synthesized (in which case, identities were verified by NMR, IR, and MS) and were purified as required, except for ammonium peroxydisulfate, in which case concentrations were calculated based on the titrated purity, determined by reduction with standard Fe^{2+} solutions and titration of excess with standard Ce(IV) solution. Stock solutions of $S_2O_8^{2-}$ were used or discarded within four days after preparation.

1,2-Diphenylethanol: Addition of benzaldehyde to benzylmagnesium chloride; mp 67 °C.

***N*-(1,2-Diphenylethyl)acetamide**: Solvolysis of 1,2-diphenylethanol in refluxing acetonitrile, catalyzed by H_2SO_4; mp 152 °C.

4-Hydroxybibenzyl: Catalytic hydrogenation of 4-hydroxystilbene using 10% Pd on charcoal; mp 103 °C.

1,2-Di-*p*-tolylethane: Reaction of *p*-methylbenzyl alcohol with McMurray's reagent ($TiCl_3$–$LiAlH_4$)[17] and reaction of *p*-methylbenzyl bromide with magnesium in ether; recrystallized from ethanol; mp 82 °C.

1,2-Di-*p*-tolylethanol: Addition of *p*-tolualdehyde to (*p*-methylbenzyl)magnesium chloride; recrystallized from hexane; mp 77 °C.

***N*-(1,2-Di-*p*-tolylethyl)acetamide**: Solvolysis of 1,2-di-*p*-tolylethanol in refluxing acetonitrile, catalyzed with H_2SO_4; mp 172 °C.

1-*p*-Tolyl-2-(*p*-(hydroxymethyl)phenyl)ethane: 4-Chloro-4′-methylstilbene by Wittig reaction[18] of the adduct of $(C_6H_5)_3P$ and α-bromoxylene with *p*-chlorobenzaldehyde. Cis and trans isomers were isolated by liquid chromatography on alumina. The cis isomer was a hexane soluble oil and the trans isomer was a crystalline solid (mp 205 °C) which eluted with tetrahydrofuran–hexane solvent. These compounds were then hydrogenated to 1-(*p*-tolyl)-2-(*p*-chlorophenyl)ethane by diimide reduction[19] or by protonolysis of the BH_3 adduct in refluxing acetic acid.[20] Catalytic hydrogenation with Pd/C partially hydrogenolized the phenyl–Cl bond. This compound was reacted with lithium metal in ether followed by CO_2 to give 4-(2-(*p*-tolyl)ethyl)benzoic acid; mp 210 °C. The carboxylic acid group was reduced with $LiAlH_4$ to yield product; mp 99 °C.

1-*p*-Anisyl-2-phenylethane: Catalytic hydrogenation of 4-hydroxystilbene (Aldrich) over 5% Pd/C followed by methylation with NaOH and dimethyl sulfate in THF–H_2O. Purified by vacuum sublimation; mp 63 °C.

1-*p*-Anisyl-2-phenylethanol: Addition of *p*-anisaldehyde to benzylmagnesium chloride; mp 57 °C.

2-Phenyl-1-*p*-tolylethanol: Addition of *p*-tolualdehyde to benzylmagnesium chloride; mp 68 °C; MS (EI), *m/e* (relative intensity) 65 (17), 77 (25), 91 (46), 92 (22), 93 (40), 119 (6), 121 (100), 122 (8).

1-Phenyl-2-*p*-tolylethanol: Addition of benzaldehyde to *p*-methylbenzylmagnesium chloride and isolated by forward phase high performance liquid chromatography on silica; mp 48 °C; MS (EI), *m/e* (relative intensity) 77 (33), 79 (41), 91 (26), 103 (5), 104 (3), 105 (19), 106 (100), 107 (39).

1-Phenyl-2-*p*-tolylethane: Dehydration of 2-phenyl-1-tolylethanol in refluxing benzene over Amberlyst-15 strong acid resin (Aldrich) and catalytic hydrogenation over 5% Pd/C; mp 24 °C.

α-Phenyl-4-methoxyacetophenone: Pyridine–chlorochromate oxidation[21] of 1-anisyl-2-phenylethanol.

Oxidations. Reactions were carried out by mixing aliquots of stock solutions of the reagents to give 10-mL volumes of solutions described in the tables. Initiation was accomplished by slow addition (0.1 mL/min) of a 0.1 M $Fe(ClO_4)_2$ solution (0.01 M $HClO_4$ and 70% CH_3CN in H_2O) introduced with a syringe pump to the rapidly stirred deoxygenated reactants (procedure 1) or by rapid addition of the $S_2O_8^{2-}$ solution to the reactants brought to reflux (~83 °C) under N_2 (procedure 2). After addition of ~1 mL of Fe^{2+} or after 20–30 min of reflux, an aliquot of internal standard solution was added and the mixture was transferred to a separatory funnel, diluted with 75 mL of H_2O, acidified with H_2SO_4, and extracted with four 10-mL volumes of CH_2Cl_2, which were combined and dried over anhydrous Na_2SO_4.

Analyses. Gas chromatographic (GC) analyses of the reaction extracts were carried out on an HP-5880A gas chromatograph (Level 4 microprocessor), factory equipped for capillary column operation. SE-52 or DB-5 columns (30 m, fused silica open tubular from J&W Scientific) were used with temperature programming from 100–300 °C. Gas chromatographic–mass spectrometric analyses were carried out on an HP-5985 instrument, which used "answer" software and was modified so that the 60 m × 0.32 mm I.D. silica column (DB-5, 1 μm film thickness) led directly into the ion source. Most products were identified by coinjection with authentic compounds and identities of many products were corroborated by GC–MS. *o*-Hydroxybibenzyl and *m*-hydroxybibenzyl were assigned on the basis that retention times and peak areas relative to *p*-hydroxybibenzyl were in accord with the order of elution and distribution of cresols from toluene. Methyl substituted α-phenylacetophenones were assigned on the basis of retention characteristics and GC–MS spectral data. α-(*p*-Tolyl)-*p*-methylacetophenone: MS (EI), *m/e* (relative intensity) 65 (9), 77 (42), 78 (9), 79 (15), 91 (20), 103 (12), 105 (100), 121 (15), 226 (M^+, 5). α-Phenyl-*p*-methylacetophenone: MS (EI), *m/e* (relative intensity) 65 (15), 91 (100), 92 (8), 210 (M^+, 12). Response factors were determined from original standards under conditions identical with analyses and found to be linear and reproducible over the concentration range 0.1–10 × 10^{-4} M. When authentic samples were not available response factors were estimated. As many as three internal standards were used to quantify early, intermediate, and late retention time peaks. Yields of products were calculated based on $S_2O_8^{2-}$. Most table entries are averages of duplicate or triplicate runs.

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Registry No. BB, 103-29-7; $BB^{+\cdot}$, 75331-18-9; BB (*o*-OH deriv), 7294-84-0; BB (*m*-OH deriv), 33675-75-1; BB (*p*-OH deriv), 6335-83-7; BC, 1889-67-4; $BC^{+\cdot}$, 89165-02-6; CA, 536-60-7; MS,

(16) Delcourt, M. O.; Rossi, M. J. *J. Phys. Chem.* **1982**, *86*, 3234–39.
(17) McMurray, J. E.; Silvestri, M. G.; Fleming, M. P.; Hoe, T.; Grayston, N. W. *J. Org. Chem.* **1978**, *43*, 3249.
(18) Wittig, G.; Schoellkopf, U. *Org. Synth.* **1960**, *40*, 66.
(19) Ohno, M.; Okamoto, M. "Organic Syntheses"; Wiley: New York, 1973; Collect Vol. V, pp 281–285.
(20) Brown, H. C.; Murray, K. *J. Am. Chem. Soc.* **1959**, *81*, 4108.
(21) Corey, E. J.; Suggs, J. W. *Tetrahedron Lett.* **1975**, 2647–2650.

98-83-9; AP, 98-86-2; S, 588-59-0; BZ, 100-52-7; BA, 100-51-6; $PhC^+(CH_3)_2$, 16804-70-9; $PhC\cdot(CH_3)_2$, 4794-07-4; $(NH_4)_2S_2O_8$, 7727-54-0; $S_2O_8^{2-}$, 15092-81-6; $PhCH(OH)CH_2Ph$, 614-29-9; $PhCH_2Cl$, 100-44-7; $PhCH(NHAc)CH_2Ph$, 21511-90-0; CH_3CN, 75-05-8; $4\text{-}HOC_6H_4CH{=}CHPh$, 3839-46-1; $4\text{-}CH_3C_6H_4CH_2Br$, 104-81-4; $4\text{-}CH_3C_6H_4CH(OH)CH_2C_6H_4\text{-}4\text{-}CH_3$, 54881-85-5; $4\text{-}CH_3C_6H_4CH_2Cl$, 104-82-5; $4\text{-}CH_3C_6H_4CH(NHAc)CH_2C_6H_4\text{-}4\text{-}CH_3$, 89165-04-8; $4\text{-}CH_3C_6H_4CH_2CH_2C_6H_4\text{-}4\text{-}CH_2OH$, 89165-05-9; *cis*-$4\text{-}ClC_6H_4CH{=}CHC_6H_4\text{-}4\text{-}CH_3$, 89165-06-0; *trans*-$4\text{-}ClC_6H_4CH{=}CHC_6H_4\text{-}4\text{-}CH_3$, 3041-83-6; $(C_6H_5)_3P$, 603-35-0; $4\text{-}CH_3C_6H_4CH_2P^+(C_6H_5)_3Br^-$, 2378-86-1; $4\text{-}ClC_6H_4CHO$, 104-88-1; $4\text{-}CH_3C_6H_4CH_2CH_2C_6H_4\text{-}4\text{-}Cl$, 89165-07-1; $4\text{-}CH_3C_6H_4CH_2CH_2C_6H_4\text{-}4\text{-}CO_2H$, 89165-08-2; $4\text{-}CH_3OC_6H_4CH(OH)CH_2Ph$, 5422-47-9; $4\text{-}CH_3OC_6H_4CHO$, 123-11-5; $4\text{-}CH_3C_6H_4CH(OH)CH_2Ph$, 20498-63-9; $PhCH(OH)CH_2C_6H_4\text{-}4\text{-}CH_3$, 20498-68-4; $PhCH{=}CHC_6H_4\text{-}4\text{-}CH_3$, 4714-21-0; $4\text{-}CH_3OC_6H_4COCH_2Ph$, 1023-17-2; $Fe(ClO_4)_2$, 13933-23-8; $Cu(ClO_4)_2$, 13770-18-8; Cu^{2+}, 15158-11-9; $C_6H_5CH_3$, 108-88-3; $C_6H_5CH_3^{+\cdot}$, 34504-47-7; $2\text{-}CH_3C_6H_4OH$, 95-48-7; $3\text{-}CH_3C_6H_4OH$, 108-39-4; $4\text{-}CH_3C_6H_4OH$, 106-44-5; $4\text{-}CH_3C_6H_4CH_2CH_2C_6H_4\text{-}4\text{-}CH_3$, 538-39-6; $4\text{-}CH_3C_6H_4CH_2CH_2C_6H_4\text{-}4\text{-}CH_3^{+\cdot}$, 89196-12-3; $4\text{-}CH_3C_6H_4CHO$, 104-87-0; $4\text{-}CH_3C_6H_4CH_2OH$, 589-18-4; $4\text{-}CH_3C_6H_4CH_2CH_2Ph$, 14310-20-4; $4\text{-}CH_3C_6H_4CH_2CH_2Ph^{+\cdot}$, 89165-03-7; $PhCH_2CH_2C_6H_4\text{-}4\text{-}CH_2OH$, 34224-29-8; $4\text{-}CH_3OC_6H_4CH_2CH_2Ph$, 14310-21-5; $4\text{-}CH_3OC_6H_4CH_2CH_2Ph^{+\cdot}$, 89165-01-5.

Migrations in Oxidations of Mesidine

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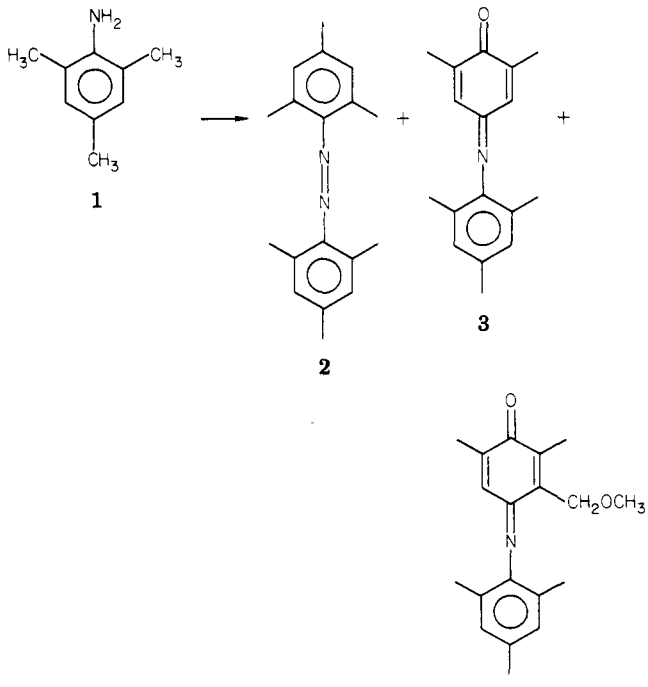
The oxidation of mesidine in methanolic media by ferricyanide, dichromate, and persulfate afforded an anil **4** containing a shifted methoxymethyl group in addition to the principal anil **3** formed by oxidative dealkylation. Possible intermediates **6**, **7**, and **8** were prepared and oxidized to the product anils. Oxidations of related anilines **9**, **10**, and **13** did not parallel those of mesidine but afforded analogues of **3**. There is significant spectral evidence for anils with alkyl shifts but little for anils analogous to **4**.

In a prior communication we reported the unusual formation and migration of a methoxymethyl group during the oxidation of 2,4,6-trimethylaniline (mesidine) in methanolic media.[1] Herein we describe details, extensions, and certain limitations of this reaction.

The oxidations of mesidine (**1**) in methanol–water mixtures afford usually three products, whose formations are influenced by the acidity of the media. The azo compound **2** is the principal product in basic systems; anil **3** [2,6-dimethyl-*p*-benzoquinone 4-(2,4,6-trimethylanil)] is the principal product in acidic systems with or without methanol; anil **4** [2,6-dimethyl-3-(methoxymethyl)-*p*-benzoquinone 4-(2,4,6-trimethylanil)] is a significant product in acidic systems containing methanol. The mechanism of removal or shifts of the methyl groups has been postulated to involve *para*-imino methides which add water to form hydroxymethyl groups or methanol to form methoxymethyl groups.[2] The hydroxymethyl groups can be eliminated in a subsequent coupling step as formaldehyde. The hydroxymethyl groups cannot be eliminated after coupling and migrate to the adjacent carbon to restore aromaticity. An analogous mode of dealkylation through a quinone methide has been shown for 2,4,6-trimethylphenol (mesitol).[3] Although migrations in methanolic media were not observed for mesitol, such reactions have been reported extensively for enzymatic oxidations of tyrosine and related compounds and are called commonly the NIH shift.[4]



Results and Discussion

Oxidizing Agents. The formation of the anil **4** in the oxidation of mesidine was observed initially with a solution of potassium ferricyanide and ammonium acetate in a water and methanol (volume ratio, 6:1) mixture. The range of acidity of such systems was 6.4 to 6.7. The reaction times were slow—five to ten days to achieve full conversion of mesidine to compounds **2**, **3**, and **4** in yields of 2%, 54%, and 17%, respectively. The ferricyanide to mesidine ratio was 7.6 to 1. The importance of the acidity level was

(1) Goldstein, S. L.; McNelis, E. *J. Org. Chem.* **1973**, *38*, 183.

(2) Saunders, B. C.; Wodak, J. *Tetrahedron* **1967**, *23*, 473.
(3) McNelis, E. *J. Am. Chem. Soc.* **1966**, *88*, 1074.
(4) Jerina, D. M.; Daly, J. W.; Landis, W.; Witkop, B.; Udenfriend, S. *J. Am. Chem. Soc.* **1967**, *89*, 3347.

0022-3263/84/1949-1613$01.50/0