

Aromatic Hydroxylation by Peroxydisulfate¹

Cheves Walling,* Donald M. Camaioni, and Sung Soo Kim

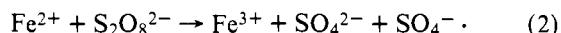
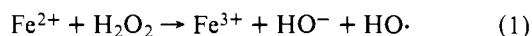
Contribution from the Department of Chemistry, University of Utah, Salt Lake City, Utah 84112. Received January 6, 1978

Abstract: In the presence of suitable metal ion oxidants, notably Cu^{2+} , $\text{S}_2\text{O}_8^{2-}$ brings about ring hydroxylation of a variety of aromatic molecules in modest to high yields. Observations are consistent with a scheme by which $\text{SO}_4^{\cdot-}$ radicals oxidize the aromatic to a radical cation, which can undergo reduction back to starting material, side-chain fragmentation, or reversible hydration to (a mixture of) hydroxycyclohexadienyl radicals. These in turn are oxidized to phenols by Cu^{2+} or other oxidants. The isomer distributions obtained on aromatic hydroxylation with either $\text{HO}\cdot$ or $\text{SO}_4^{\cdot-}$ radicals vary markedly with reaction conditions. With Cu^{2+} and other unselective oxidants three limiting conditions are approached: with $\text{HO}\cdot$ at low acidity, kinetic control by the point of $\text{HO}\cdot$ addition; with $\text{SO}_4^{\cdot-}$ at low acidity, kinetic control by the point of hydration of the intermediate radical cation; with either reagent in strong acid, thermodynamic control via equilibration of hydroxycyclohexadienyl radicals through the radical cation. Over tenfold changes in ortho-para ratios are observed with chloro- and some alkylbenzenes.

Although the reaction of aromatic molecules with peroxydisulfate has been extensively investigated, the products have usually been those of side-chain oxidation or cleavage.²⁻⁴ The only efficient example of ring hydroxylation has been the Elbs reaction (oxidation of phenols and amines in alkaline solution) where, at least in some cases, the process appears to be a simple electrophilic substitution.⁵

As part of our continuing investigation of Fenton's reagent and related reactions⁶ we have examined aromatic oxidations employing Fe^{2+} - $\text{S}_2\text{O}_8^{2-}$ systems, and, in a preliminary report,⁷ noted that substantial yields of phenolic products could be obtained in the presence of suitable oxidants, notably cupric ion. While our work was in progress, a number of other papers have appeared, bearing on the reaction and in general consistent with our initial interpretation.⁸⁻¹⁵ We here report further results of this study, and a comparison of the effect of reaction variables on products from Fe^{2+} - H_2O_2 and Fe^{2+} - $\text{S}_2\text{O}_8^{2-}$ systems which establish more firmly a number of details of our reaction scheme.

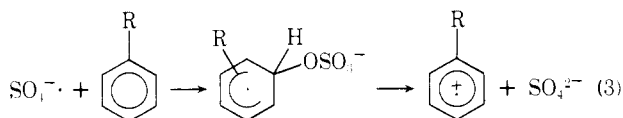
In our systems $\text{HO}\cdot$ and $\text{SO}_4^{\cdot-}$ radicals are produced by the well-established redox processes



and, we propose, react with aromatic substrates via the rather complex interrelated processes shown in Scheme I.

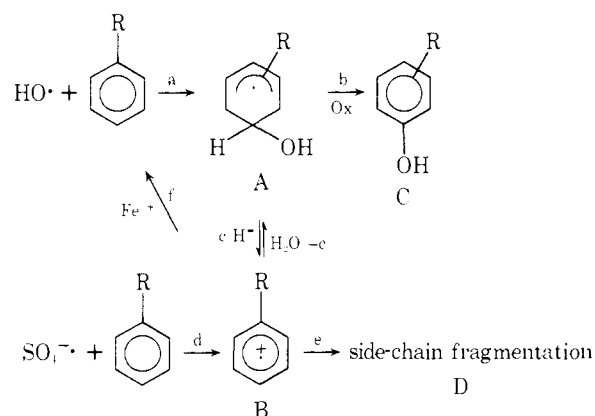
In the scheme, reaction a is well established by spectroscopic observation of hydroxycyclohexadienyl radicals in pulse-radiolysis experiments and rates have been measured for many aromatic molecules.¹⁶ The acid-catalyzed conversion of hydroxycyclohexadienyl radicals to radical cations, c, was first proposed by Norman¹⁷ and the latter have recently been directly observed spectroscopically from methoxy-⁸ and methyl-^{9,10} substituted benzenes. The reverse process is strongly supported by the work reported here and has been inferred from isotope exchange experiments with ¹⁸O-enriched water.¹⁸

The reaction of the $\text{SO}_4^{\cdot-}$ radical with the aromatic substrate, d, was initially suggested by Norman¹⁹ to be an addition-elimination process, although no intermediate cyclo-

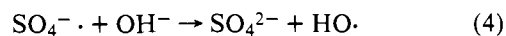


hexadienyl radical could be detected in flow ESR experiments, but most subsequent workers have considered it to be a one-step electron transfer.^{4,9,12} Rates of the overall process to the radical cation have been measured for a number of aromatic sub-

Scheme I



strates.¹² It should be noted that, if the two-step sequence (3) were correct, trapping of the intermediate by oxidation to an aryl sulfate ester would not lead to phenols under our conditions since aryl sulfuric acids hydrolyze only very slowly in cold, dilute acid.²⁰ Possible production of phenols via addition of hydroxyl radicals in peroxydisulfate systems can also be ruled out in acid media, for, while the reaction



is fast ($k = 6.5 \times 10^7$), the corresponding reaction with water is undetectably slow ($k < 3 \times 10^3$).²¹ Reactions b (cyclohexadienyl radical oxidation) and e (side-chain fragmentation) have been discussed in our previous papers^{6,22} and will be considered further below.

Results

From Scheme I, the optimum conditions for observing aromatic hydroxylation in peroxydisulfate systems should be at low acidities (to favor the reverse of c) and high levels of Cu^{2+} ion or other oxidant (to trap cyclohexadienyl radicals as they are produced). In addition, "inverse addition", i.e., slow addition of Fe^{2+} to the system containing peroxydisulfate and substrate, rather than addition of peroxydisulfate to Fe^{2+} -substrate, should serve to minimize reduction of intermediate radical cations back to starting material, reaction f.

Table I lists yields of phenolic products obtained under what should approach optimum conditions for a number of substrates. In most cases they are quite comparable with those obtained by the hydroxyl radical route (cf. subsequent tables).

Peroxydisulfate may be decomposed to $\text{SO}_4^{\cdot-}$ radicals, not only by the redox reaction (2), but also thermally and by cat-

Table I. Aromatic Hydroxylation by Peroxydisulfate^a

substrate	yield, %	
	phenols	other
benzene	64	biphenyl, <1
toluene	21	benzyl alcohol, 15
chlorobenzene ^b	50	
nitrobenzene	9	<i>p</i> -nitrophenyl OSO ₃ H, 3
benzyl alcohol ^c	6	benzaldehyde, 86
2-phenylethanol ^c	54	benzyl alcohol, 8
phenylacetic acid ^d	21	benzyl alcohol, 47
4-phenylbutanoic acid ^{d,e}	39	phenylbutyrolactone, 22 3-phenylpropanol, 11

^aAll runs by "inverse" addition of 0.05 M Fe²⁺ to systems [S₂O₈²⁻] ~ 2–10 × 10⁻³ M; [Cu²⁺], 0.24 M; [H⁺], 0.05 M unless noted, substrate, 0.05–0.1 M (two phase in some cases), *T* = 30 °C. Yields are based on S₂O₈²⁻. ^b[H⁺] = 0.1. ^c[H⁺] = 10⁻⁴. ^d[H⁺] = 10⁻². ^eCH₃CN = 30 vol %.

alytic quantities of Ag⁺. Table II shows that substantial yields of phenol can be obtained from benzene under these conditions providing that Cu²⁺ is present to trap intermediate hydroxycyclohexadienyl radicals, but that relatively little is obtained in its absence.

We have also examined the oxidation of most of the substrates in Table I in more detail as a function of reaction conditions, with particular attention to the isomer distribution in the phenolic products. Our results are listed in Tables III–VIII, together with some pertinent literature data.

We have previously noted that isomer distributions depend upon oxidant,¹⁷ pointing out that Fe³⁺, as an outer-sphere electron oxidant, should selectively oxidize *o*- and *p*-alkylcyclohexadienyl radicals to their cations, accounting for the relatively low yield of meta-substituted phenols observed in HO· hydroxylations with this oxidant. It was also suggested that any cations obtained from *m*-alkylhydroxycyclohexadienyl radicals might rearrange via protonated epoxides. However, results by Eberhardt¹⁴ with toluene using ferricyanide, a stronger outer-sphere oxidant, and highly effective in oxidizing hydroxycyclohexadienyl radicals,²³ indicate that such rearrangements are probably unimportant, since 22–24% yields of *m*-cresol can be obtained with this reagent.

We now show that substantially different isomer distributions may be observed in our systems with the *same* oxidant (usually Cu²⁺) depending on pH, and whether initial attack is by HO· or SO₄⁻.

If we assume, following Kochi's observations,²⁴ that Cu²⁺ is an unselective oxidant which effectively samples the hydroxycyclohexadienyl radical pool in Scheme 1, and that side-chain fragmentation competes poorly with radical cation hydration, three limiting circumstances may be approached. At low acidities in HO· systems, phenol isomer distributions will be under kinetic control and determined by the point of hydroxyl radical attack, reaction a. At low acidities with SO₄⁻, the distribution will again be under kinetic control, but now via the step involving hydration of the radical cation, c. At high acidities, using either HO· or SO₄⁻, hydroxycyclohexadienyl radicals can equilibrate via the radical cation, and either radical should yield the same thermodynamically determined distribution.

Our results with chlorobenzene (Table III) appear to show these differences. With HO· in weak acid the ortho:meta:para ratio is 58:10:32, while with SO₄⁻ it reaches 19:3:78, an eightfold change in ortho:para ratio. At high acidities, on the other hand, both systems favor the ortho isomer, to about the same amount (70:6:24 and 68:1:31, respectively). Ferricyanide in the SO₄⁻ reaction at low acidities gives an even higher selectivity to *p*-chlorophenol, although overall yields are low, perhaps because of the reduction of intermediates back to

Table II. Benzene Hydroxylations^a

conditions	yield, %	
	phenol	other
Fe ²⁺ , no Cu ²⁺	26	biphenyl, 48 ^b
Fe ²⁺ , Cu ²⁺	64	
thermal (75 °C)	10	biphenyl, 6 ^b
thermal + Cu ²⁺ (60 °C)	54	
10 ⁻³ M Ag ⁺ (40 °C)	3	polymers
Ag ⁺ , Cu ²⁺ (40 °C)	43	polymers

^aConditions as in Table I except as noted. ^bBased on 2C₆H₆ → C₁₂H₁₀. This correction was not made in our previous report.

Table III. Chlorobenzene Oxidations^a

system	oxidant [M]	[H ⁵]	chlorophenol
			yield, % ^b
SO ₄ ⁻ (I)	Cu ²⁺ [0.06]	<10 ⁻⁴	39 (27:3:70)
SO ₄ ⁻ (I)	Cu ²⁺ [0.24]	3 × 10 ⁻⁴	47 (21:3:76)
SO ₄ ⁻ (I)	Cu ²⁺ [0.53]	4 × 10 ⁻³	45 (19:3:78)
SO ₄ ⁻ (I)	Cu ²⁺ [0.24]	0.1	50 (52:3:45)
SO ₄ ⁻ (I)	Cu ²⁺ [0.24]	1	36 (68:1:31) ^c
SO ₄ ⁻ (I)	Fe ³⁺ [0.25]	0.2	44 (39:2:59)
SO ₄ ⁻ (I)	Fe ³⁺ [0.25]	1	48 (45:1:53)
SO ₄ ⁻ (I)	Fe(CN) ₆ ³⁻ [0.06]	4 × 10 ⁻⁵	8.2 (14:1:85) ^c
SO ₄ ⁻ (I)	Fe(CN) ₆ ³⁻ [0.06]	0.1	0.4 (11:0:89) ^c
HO· (N)	Fe ³⁺ [^d]	0.05	18 (58:10:32)
HO· (N)	Fe ³⁺ [^d]	0.5	9 (64:3:33)
HO· (N)	Cu ²⁺ [0.4]	0.05	36 (58:12:30)
HO· (N)	Cu ²⁺ [0.4]	0.5	38 (70:6:24)

^a(I) indicates inverse addition of 0.05 M Fe²⁺ to ~0.01 M S₂O₈²⁻, excess chlorobenzene (two-phase system); (N), addition of H₂O₂ to 0.02 M Fe³⁺. ^bYields based on peroxide; quantities in parentheses are ortho:meta:para ratios in chlorophenols. ^cApproximately 0.5–2% phenol formed. ^dNo added Fe³⁺ beyond that generated in reaction.

starting material as suggested by Eberhardt.¹⁵ Reactions using Fe³⁺ as the oxidant, on the other hand, show less variation in selectivity with conditions, perhaps because it is a less reactive and more selective oxidant. However, even here lower ortho:para ratios are found with SO₄⁻ than with HO·.

If fragmentation competes with hydration of the intermediate radical cation, interpretation of behavior in strong acid becomes more complicated since there will be less equilibration via paths c and -c. However, data on 2-phenylethanol (Table IV) and phenylacetic acid (Table V), where fragmentation becomes increasingly important, still resemble results with chlorobenzene.

With 2-phenylethanol, the HO· reaction at low acidity gives a 49:26:25 isomer distribution, a statistical ortho:para distribution and half the statistical meta isomer. With SO₄⁻ the ratio is 41:11:48; the thermal reaction in the presence of Cu²⁺ and use of ferricyanide giving similar results. In strong acid HO· and SO₄⁻ give comparable distributions with predominantly the ortho isomer as in the case of chlorobenzene. Phenylacetic acid systems exhibit similar trends.

Table VI lists less complete data for toluene. No significant yields of cresols could be obtained in strong acid, and apparently even at 0.05 M acid reaction c is important since, while our isomer distributions from S₂O₈²⁻ agree well with those reported by Eberhardt¹⁴ using Cu²⁺, they are significantly different from those he reports with ferricyanide, a more efficient trapping agent.

Table VII reports a few results with benzyl alcohol and substituted benzyl alcohols. With benzyl alcohol, fragmentation competes very seriously with hydration of the radical cation, since yields of phenols from SO₄⁻ are low compared

Table IV. 2-Phenylethanol Oxidations

system ^a	oxidant [M]	[H ⁺]	yield, % ^b		
			phenols (o:m:p)	BA	SG
SO ₄ ^{-•} (I)	Fe ³⁺ [0.26]	0.2	16 (48:4:48)	16	2
SO ₄ ^{-•} (I)	Cu ²⁺ [0.024]	<10 ⁻⁴	38 (50:11:39)	24	3
SO ₄ ^{-•} (I)	Cu ²⁺ [0.24]	3 × 10 ⁻⁴	54 (41:11:48)	8	<1
SO ₄ ^{-•} (I)	Cu ²⁺ [0.24]	0.05	31 (51:13:36)	25	2
SO ₄ ^{-•} (I)	Cu ²⁺ [0.24]	1.1	4 (71:9:20)	46	4
SO ₄ ^{-•} (T)	Cu ²⁺ [0.24]	3 × 10 ⁻⁴	38 (40:15:45)	17	1
SO ₄ ^{-•} (T)	Fe(CN) ₆ ³⁻ [0.01]	10 ⁻⁵	23 (41:15:44)	2	
SO ₄ ^{-•} (Ag)	Cu ²⁺ [0.24]	3 × 10 ⁻⁴	31 (42:15:43)	16	1
HO• (N)	Cu ²⁺ [0.24]	3 × 10 ⁻⁴	64 (49:26:25)	0.4	
HO• (N)	Cu ²⁺ [0.24]	0.01	63 (52:24:24)	3	
HO• (N)	Cu ²⁺ [0.24]	0.1	32 (61:18:22)	17	
HO• (N)	Cu ²⁺ [0.24]	1.0	6 (79:10:11)	26	
HO• (I)	Cu ²⁺ [0.24]	1.0	5 (76:11:13)	46	

^a(I) indicates inverse addition of 0.05 M Fe²⁺ to 0.01 M peroxide; (N), addition of 0.03 M peroxide to 0.01 M Fe²⁺; (T), thermal reaction at 60 °C, no Fe²⁺; (Ag), thermal reaction in presence of 10⁻³ M Ag⁺; 0.08 M phenylethanol in all reactions. ^bBased on peroxide; BA = benzyl alcohol; SG = styrene glycol.

Table V. Phenylacetic Acid Oxidations^a

system	oxidant [M]	[H ⁺]	yield, %	
			phenols (o:m:p)	BA
SO ₄ ^{-•} (I)	Fe ³⁺ [^b]	4 × 10 ⁻³	4 (54:12:34)	7 ^c
SO ₄ ^{-•} (I)	Cu ²⁺ [0.2]	10 ⁻²	21 (36:18:46)	47
SO ₄ ^{-•} (I)	Cu ²⁺ [0.24]	0.05	17 (41:19:39)	51
SO ₄ ^{-•} (I)	Cu ²⁺ [0.12]	1.1	2 (77:0:23)	45
SO ₄ ^{-•} (T)	Cu ²⁺ [0.2]	10 ⁻²	21 (36:25:39)	42
SO ₄ ^{-•} (Ag) ^d	Cu ²⁺ [0.2]	10 ⁻²	20 (36:24:40)	48
HO• (N) ^e	Cu ²⁺ [0.24]	0.05	55 (55:31:14)	23
HO• (N) ^e	Cu ²⁺ [0.08]	8 × 10 ⁻⁴	69 (45:31:24)	4
HO• (N) ^e	Cu ²⁺ [0.16]	0.25	15 (77:21:2)	58

^aSymbols as in previous tables. ^bNo Fe³⁺ added beyond that formed in reaction. ^cPlus 38% bibenzyl. ^dThermal reaction in presence of 6 × 10⁻⁴ M Ag⁺. ^eFrom ref 22.

Table VI. Toluene Oxidations^a

system	oxidant [M]	[H ⁺]	yield, %	
			phenols (o:m:p)	BA ^d
SO ₄ ^{-•} (I)	Cu ²⁺ [0.24]	0.05	21 (62:5:33)	15
SO ₄ ^{-•} ^b	Cu ²⁺ [0.005]	8 × 10 ⁻⁵	16 (63:3:34)	12 (3)
SO ₄ ^{-•} ^b	Cu ²⁺ [0.005]	4 × 10 ⁻³	9 (64:4:32)	15 (4)
HO• (N) ^c	Cu ²⁺ [0.24]	0.05	18 (59:12:29)	4 (2)
HO• (N) ^c	Fe ³⁺ [0.16]	0.2	6 (54:3:43)	11 (6)

^aSymbols as in previous tables. ^bFrom ref 15. ^cFrom ref 22. ^dBA = benzyl alcohol; numbers in parentheses, benzaldehyde.

with those from HO•, and the latter drop rapidly with increasing acid. Again, isomer distributions are quite different as conditions are varied, showing the same trends as previously. Hydroxyl radical additions were also investigated with some substituted benzyl alcohols. *p*-Chlorobenzyl alcohol is a solid with low water solubility, but the *m*-chloro isomer gives higher phenol yields than benzyl alcohol itself, a result consistent with an electron-withdrawing Cl reducing the rate of step c.

No significant yields of phenols were obtained from CH₃O- or NO₂-substituted benzyl alcohols. With *p*-methoxybenzyl alcohol this must be the consequence of the rapid conversion of the initial hydroxycyclohexadienyl radical to radical cation.⁸ The origin of the result with the nitrobenzyl alcohols is less obvious, since here there is little driving force for dehydration. Benzene and nitrobenzene are reported to have very similar rates of reaction with hydroxyl radicals.¹⁶ However, in our hands, a competitive oxidation of benzyl and *m*-nitrobenzyl alcohols (which give comparable yields of aldehydes alone) yielded 36% benzaldehyde and 4.5% *m*-nitrobenzaldehyde. It may be that with the nitro compounds reduced reactivity of the ring leads predominantly to direct side-chain oxidation.

Our results with nitrobenzene are shown in Table VIII.

Those employing HO• radicals show lower selectivity to *o*-nitrophenol than most of the data reported by Eberhardt.¹³ He has discussed the possible factors affecting isomer distributions in nitrobenzene hydroxylation, and we may here be seeing a selective reduction of *o*-nitrocyclohexadienyl radicals back to starting material by the appreciable concentrations of Fe²⁺ in our systems. The results with S₂O₈²⁻ are more interesting. First, nitrophenols are obtained, contrary to Eberhardt's report,¹⁵ although in low yield. Second, the monosulfate ester of *p*-nitrophenol is produced in small, but clearly detectable quantities, indicating that at least some of the attack by SO₄^{-•} involves addition, reaction 3, rather than electron transfer. Nitrobenzene, of course, is a particularly favorable substrate for such a process as we have been unable to detect any comparable phenyl sulfate ester in reactions with benzene. Combining phenol and sulfate yields indicates that 50–60% of the total product with S₂O₈²⁻ is the para isomer.

Discussion

Our findings we believe establish two major points. First, peroxydisulfate oxidations of aromatics via SO₄^{-•} radicals in the presence of suitable oxidants such as Cu²⁺ or Fe(CN)₆³⁻

Table VII. Oxidation of Benzyl Alcohols^a

system	oxidant [M]	[H ⁺]	yield, %	
			phenols (o:m:p)	RCHO
SO ₄ ^{-•} (I)	Cu ²⁺ [0.20]	3 × 10 ⁻⁴	6 (27:9:64)	86
HO• (N)	Cu ²⁺ [0.40]	0.05	33 (54:34:12)	44
HO• (N)	Cu ²⁺ [0.40]	0.5	5 (66:32:2)	83
HO• (N) (<i>p</i> -Cl)	Cu ²⁺ [0.40]	0.05	27 ^b	31
HO• (N) (<i>p</i> -Cl)	Cu ²⁺ [0.40]	0.5	5 ^b	37
HO• (N) (<i>m</i> -Cl)	Cu ²⁺ [0.40]	0.05	45 ^c	53
HO• (N) (<i>m</i> -Cl)	Cu ²⁺ [0.40]	0.5	20 ^c	70
HO• (N) (<i>p</i> -OCH ₃)	Cu ²⁺ [0.40]	0.05	tr	56
HO• (N) (<i>p</i> -NO ₂)	Cu ²⁺ [0.40]	0.05	0	37
HO• (N) (<i>m</i> -NO ₂)	Cu ²⁺ [0.40]	0.05	0	44

^aSymbols as in previous tables. ^bTwo isomers detected but not identified. ^cFour isomers detected but not identified.

Table VIII. Nitrobenzene Oxidations^a

system	oxidant [M]	[H ⁺]	yield, %	
			phenols (o:m:p)	sulfate ^b
SO ₄ ^{-•} (I)	Cu ²⁺ [0.19]	3 × 10 ⁻⁴	5.6 (48:15:38)	2.8
SO ₄ ^{-•} (I)	Cu ²⁺ [0.75]	5 × 10 ⁻³	7.1 (38:31:31)	2.1
SO ₄ ^{-•} (I)	Cu ²⁺ [0.19]	5 × 10 ⁻³	6.6 (52:15:33)	2.9
SO ₄ ^{-•} (I)	Cu ²⁺ [0.19]	0.05	8.8 (51:17:32)	3.0
HO• (N)	Fe ³⁺ [^c]	0.05	13 (15:35:50)	
HO• (N)	Fe ³⁺ [^c]	0.5	8.5 (5:55:40)	
HO• (N)	Cu ²⁺ [0.40]	0.05	14 (12:40:48)	
HO• (N)	Cu ²⁺ [0.40]	0.5	11 (14:45:41)	

^aSymbols as in previous tables. ^b*p*-Nitrophenylsulfuric acid. ^cNo Fe³⁺ added beyond that formed in reaction.

can lead to phenolic products with high to moderate selectivity from a variety of substrates. This in turn supports two important aspects of reaction Scheme I: that initial attack is predominantly on the aromatic ring, giving rise to an aromatic radical cation; that the cation in turn reacts rapidly with water to yield hydroxycyclohexadienyl radicals with a rate that competes favorably with side chain fragmentation processes.

Second, the scheme provides a basis for rationalizing the considerable range of phenolic isomer distributions observed under varying reaction conditions. HO• attack on aromatics in weakly acid systems containing adequate oxidant gives isomer distributions kinetically controlled by the point of HO• addition. For several alkylbenzenes with side-chain solubilizing groups, this is an ortho:meta:para ratio of roughly 50:25:25. Eberhardt reports similar results with toluene using ferricyanide as oxidant.¹⁴ With chlorobenzene the ratio is approximately 60:10:30, the meta position being less reactive. Under similar conditions Eberhardt obtains 43:21:36 from fluorobenzene.²⁴ It is only under these conditions that phenol isomer distributions may accurately reflect the initial point of attack on the aromatic ring. With SO₄^{-•} in weak acid, hydration of the radical cation becomes kinetically controlling, meta products decrease, and para products are favored (46–78%) with both chloro- and alkylbenzenes. Again, similar results have been noted by Eberhardt with toluene and fluorobenzene.¹⁵

At high acidities, using either HO• or SO₄^{-•} radicals, hydroxycyclohexadienyl radicals approach their equilibrium distribution, giving phenol distributions which are predominantly (68–79%) ortho with little (usually <10%) meta from both chloro- and alkylbenzenes. Decreased oxidant also shifts isomer distributions toward equilibrium. Further, when substrates are capable of side-chain fragmentation, both decreased oxidant and increased acidity favor apparent side-chain oxidation over phenol production. Finally, with both HO• and SO₄^{-•} reactions, use of Fe³⁺ in place of Cu²⁺ lowers yields of meta-substituted phenols.

In S₂O₈²⁻ oxidations under limiting conditions of high oxidant and low acidity, ratios of side-chain fragmentation products to phenols should correspond to the ratio of rate constants for radical cation fragmentation and hydration, k_e/k_{-c} . From the appropriate tables, these correspond to benzyl alcohol, 14.3; phenylacetic acid, 2.24; 2-phenylethanol, 0.15. Our data with toluene were not obtained at low enough acidity, but Eberhardt's results (solely cresols as products) indicate $k_e/k_{-c} < 0.01$. Since hydration rates of these structurally similar radical cations should be similar, these numbers are probably also the relative values of k_e 's. They vary by over a factor of 1000, but it should be noted must involve quite different processes: loss of a proton and CO₂ from phenylacetic acid, a proton and formaldehyde from 2-phenylethanol, and a proton alone from benzyl alcohol and toluene. We can also make a rough estimate of actual values of k_{-c} and k_e 's. Oxidation of phenylacetic acid by H₂O₂ at the lowest acidity gave 69% phenols and 4% benzyl alcohol. If we assume that the balance unaccounted for (27%) represents reduction of radical cation back to starting material by Fe²⁺ (present at an average concentration of 0.01 M), and take $k_f = 6 \times 10^8$ (the same as for anisole),⁹ then $0.01k_f/k_e = 27/4$, $k_e = 9 \times 10^5$, and $k_{-c} = 4 \times 10^5$.

Finally, our results with phenylacetic acid have bearing on an earlier study by Tanner and Osman.²⁵ They investigated the relative rates of the thermal reaction of substituted phenylacetates with S₂O₈²⁻, by determining the radioactivity of CO₂ produced using mixtures of ¹⁴C-labeled phenylacetate and unlabeled substituted phenylacetates, all in the presence of 0.27 M KOH. CO₂ formation was reported to be quantitative, and the data correlated best with σ^+ constants, $\rho^+ = -0.436$. They interpreted their results as arising from initial attack on the carboxyl group. From our own results predominant decarboxylation would also be anticipated in the absence of oxidant (cf. Table V) but arising from initial attack on the aromatic ring. Actually, just what the rate-determining step is under their conditions is uncertain. The selectivity they observed is less than would be anticipated from Neta's results on

SO₄⁻-aromatic reactions.¹² Further, in such a strongly alkaline solution conversion of SO₄⁻ to HO· should compete with attack on aromatic substrates,²¹ and the HO-O· equilibrium becomes significant.

Experimental Section

Reagents. Potassium peroxydisulfate was recrystallized twice from water, purity by titration >98%. Hydrogen peroxide was vacuum distilled before use. Other inorganic reagents (usually reagent grade perchlorates) were used as received. Purity of organic substrates was checked by gas-liquid chromatography (GLC) and they were distilled if necessary. Standard solutions were made up and used to prepare reaction mixtures.

Reactions were carried out by adding peroxide solutions dropwise to stirred mixtures of other reactants, (N) in tables, or by inverse addition (I) of Fe²⁺ solutions to substrate-peroxide solutions, all well stirred and thermostated under N₂ as described previously.²² Thermal reactions were carried out by mixing reagents, flushing with N₂, and heating in stoppered flasks in a thermostat.

Analyses of reaction mixtures were carried out as previously²² by GLC using previously calibrated internal standards and known reference materials. Phenols and alcohols were extracted, silylated, and analyzed. Best results were obtained by temperature programming on 5% SE-30 or 10% OV-1 on Chromosorb W or with nitrophenols, on 10% XE-60 on Chromosorb W. Benzaldehydes were separated on 5% Carbowax 20M or 10% OV-17 on Chromosorb W.

***p*-Nitrophenyl sulfate** was identified from nitrobenzene reactions by two techniques. First, phenols and other organics were extracted from the reaction mixture; the aqueous fraction was made 1 N in acid and refluxed for 1 h, and liberated nitrophenols were extracted and analyzed by GLC. Only *p*-nitrophenol was detected, and no phenols were obtained from hydrolysis of similar benzene oxidations. This technique was used to determine sulfate yields. Next, a nitrobenzene reaction, after extraction of phenols and other organic-soluble material, was made alkaline with KOH, precipitated Fe and Cu salts were removed by centrifuging, and the supernatant liquid was evaporated. Acetone extracts of the residue were spotted on Whatman no. 1 filter paper, dried, and developed using 2-butanone-water-diethylamine (92:1:7:2).²⁶ Both the sample and authentic potassium *p*-nitrophenyl

sulfate²⁷ gave spots, *R_f* 0.63, blue under UV illumination, which, when spotted with HCl and warmed, turned pale yellow, and darkened on exposure to NH₃.

References and Notes

- (1) Taken in part from the Ph.D. Thesis of D. M. Camaioni, University of Utah, 1978. Support of the work by the National Science Foundation is gratefully acknowledged.
- (2) G. Sosnovsky in "Organic Peroxides", Vol. 2, D. Swern, Ed., Wiley-Interscience, New York, N.Y., 1971, p 317. This reference reviews earlier work.
- (3) R. O. C. Norman and P. M. Storey, *J. Chem. Soc. B*, 1099 (1970).
- (4) M. E. Snook and G. A. Hamilton, *J. Am. Chem. Soc.*, **96**, 860 (1974).
- (5) E. J. Behrman, *J. Am. Chem. Soc.*, **85**, 3478 (1963).
- (6) C. Walling, *Acc. Chem. Res.*, **8**, 125 (1975).
- (7) C. Walling and D. M. Camaioni, *J. Am. Chem. Soc.*, **97**, 1603 (1975).
- (8) P. O'Neill, S. Steenken, and D. Schulte-Forhlinde, *J. Phys. Chem.*, **79**, 2773 (1975); **81**, 26,31 (1977).
- (9) K. Sehested, H. Corfittzen, H. C. Christensen, and E. J. Hart, *J. Phys. Chem.*, **79**, 310 (1975).
- (10) K. Sehested, J. Holcman, and E. J. Hart, *J. Phys. Chem.*, **81**, 1363 (1977).
- (11) J. Holcman and K. Sehested, *J. Phys. Chem.*, **80**, 1642 (1976).
- (12) P. Neta, V. Madhavan, H. Zemel, and R. W. Fessenden, *J. Am. Chem. Soc.*, **99**, 163 (1977).
- (13) M. K. Eberhardt, *J. Phys. Chem.*, **79**, 1913 (1975).
- (14) M. K. Eberhardt and M. I. Martinez, *J. Phys. Chem.*, **79**, 1917 (1975).
- (15) M. K. Eberhardt, *J. Org. Chem.*, **42**, 832 (1977).
- (16) L. M. Dorfman and G. E. Adams, National Bureau of Standards Report No. NSRDS-NBS-46, U.S. Government Printing Office, Washington, D.C., 1973.
- (17) R. O. C. Norman and R. J. Pritchett, *J. Chem. Soc. B*, 926 (1967).
- (18) N. A. Vysotskaya and L. G. Shevchuk, *Zh. Org. Khim.*, **9**, 2080 (1973).
- (19) R. O. C. Norman, P. M. Storey, and P. R. West, *J. Chem. Soc. B*, 1087 (1970).
- (20) G. N. Burkhardt, W. G. K. Ford, and E. Singleton, *J. Chem. Soc.*, 17 (1936).
- (21) E. Heyon, A. Treinin, and J. Wolf, *J. Am. Chem. Soc.*, **94**, 47 (1972).
- (22) C. Walling and R. A. Johnson, *J. Am. Chem. Soc.*, **97**, 363 (1975).
- (23) K. Bhatia and R. H. Schuler, *J. Phys. Chem.*, **78**, 2335 (1974).
- (24) J. K. Kochi in "Free Radicals", Vol. 1, J. K. Kochi, Ed., Wiley, New York, N.Y., 1973, Chapter 11; M. K. Eberhardt, *J. Phys. Chem.*, **81**, 1051 (1977).
- (25) D. D. Tanner and S. A. Osman, *J. Am. Chem. Soc.*, **90**, 6572 (1968).
- (26) L. Reio, *J. Chromatogr.*, **47**, 60 (1970).
- (27) J. Feigenbaum and C. A. Neuberger, *J. Am. Chem. Soc.*, **63**, 3529 (1941).

Regioselectivity as a Criterion for Mechanism in the Base-Promoted Opening of Methylbicyclo[6.1.0]nona-2,4,6-trienes

Stuart W. Staley,* Gerard E. Linkowski, and Marye Anne Fox

Contribution from the Department of Chemistry, University of Maryland, College Park, Maryland 20742. Received May 2, 1977

Abstract: Treatment of 1-, 2-, 3-, and 4-methyl-*cis*-bicyclo[6.1.0]nona-2,4,6-triene (**10–13**, respectively) and 2-methyl-*trans*-bicyclo[6.1.0]nona-2,4,6-triene (**14**) with potassium amide in liquid ammonia at 25 °C afforded various methyl-substituted aminomethylcyclooctatetraene dianions. Determination of the regioselectivities of these reactions, along with an absence of deuterium exchange in *cis*-bicyclo[6.1.0]nona-2,4,6-triene (**1**) on treatment with potassium *tert*-butoxide-dimethyl-*d*₆ sulfoxide, has led to the conclusion that the rate-limiting transition state for the overall reaction involves the deprotonation of **1** and its derivatives with little distortion from its tublike ground state conformation.

The methylenecyclooctatrienyl anion (**3**) is formed by the base-promoted ring opening of *cis*-bicyclo[6.1.0]nona-2,4,6-triene (**1**) or its *trans* isomer (**2**).^{1,2} The lithium salts of **3** and various derivatives of **3** are stable in liquid ammonia at -30 °C. In contrast, the potassium salts can be detected by NMR spectroscopy at -65 °C, but rapidly suffer amide attack at C₉ to afford aminomethylcyclooctatetraene dianions (**4**).^{2,3}

In this paper we employ the novel probe of regioselectivity in the ring opening of unsymmetrically substituted methyl derivatives of **1** and **2** in order to define the charge distribution in and therefore the geometry of the rate-limiting transmission state of the reaction.

Analysis of the Problem

cis-Bicyclo[6.1.0]nona-2,4,6-trienes were first proposed to