Aromatic Oxygenation with Diisopropyl Peroxydicarbonate–Cupric Chloride. Isotope Effects and Relative Rates[1]

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Abstract: A scheme involving reversible addition by the isopropoxycarboxy radical to the aromatic nucleus followed by oxidative conversion to ester by the metal salt is presented for oxygenation with diisopropyl peroxydicarbonate–cupric chloride. This approach is compatible with results from nonmetallic oxidants. The absence of a primary isotope effect with benzene–hexadeuteriobenzene was demonstrated for the ester product, which is construed as evidence for the effectiveness of cupric salt oxidation of the radical adduct. Prior literature analogy is pointed out. The roles of ligand transfer and electron transfer in oxidation of the substituted cyclohexadienyl radical are discussed with cupric chloride and cupric perchlorate as representative cases. The relative rates and isomer distributions are indicative of the electrophilic nature of the attacking radical.

The direct introduction of oxygen into the aromatic nucleus has been carried out with diisopropyl peroxydicarbonate in the presence of small amounts of cupric chloride.[3] Tolyl isopropyl carbonates were formed in good yield from toluene under mild conditions. The stoichiometry of the reaction is presented in eq 1. A radical chain mechanism (eq 2–5) was proposed[3] involving copper chloride in a redox capacity and isopropoxycarboxy radicals. In a preliminary communication,[4] two possibilities were set forth for the aromatic substitution process (eq 3): oxidation of the oxy radical with cupric chloride followed by electrophilic substitution (eq 6), or attack by isopropoxycarboxy radical onto the aromatic nucleus with subsequent oxidative conversion of the resulting radical complex under the agency of cupric chloride (eq 7). Recent data[3] indicate that the former path is unlikely. Furthermore, prior workers have found oxy radicals to be passive toward oxidation by cupric salts.[5]

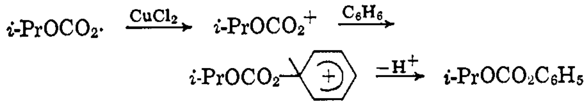
$$(i\text{-PrOCO}_2)_2 + \text{ArH} \xrightarrow{\text{CuCl}_2} \text{ArOCO}_2\text{Pr-}i + \text{CO}_2 + i\text{-PrOH} \quad (1)$$

$$(i\text{-PrOCO}_2)_2 \longrightarrow 2i\text{-PrOCO}_2\cdot \quad (2)$$

$$i\text{-PrOCO}_2\cdot + \text{ArH} + \text{CuCl}_2 \longrightarrow \text{ArOCO}_2\text{Pr-}i + \text{CuCl} + \text{HCl} \quad (3)$$

$$(i\text{-PrOCO}_2)_2 + \text{CuCl} \longrightarrow i\text{-PrOCO}_2\cdot + \underset{\text{I}}{\text{CuClOCO}_2\text{Pr-}i} \quad (4)$$

$$\text{I} + \text{HCl} \longrightarrow \text{CuCl}_2 + i\text{-PrOH} + \text{CO}_2 \quad (5)$$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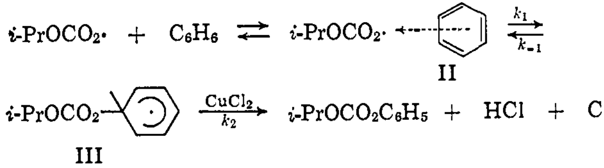
II

III

(7)

It is the purpose of this paper to present additional evidence bearing on the mechanism of the aromatic substitution step. In this connection studies were made of isotope effects and relative rates. In addition, the significance of the isomer distributions and nature of the inorganic oxidant are treated.

Results and Discussion

The scheme we propose for aromatic substitution with diisopropyl peroxydicarbonate–cupric chloride (eq 7) involves reversible formation of a σ complex (III). It is not unreasonable to suggest an initial, unstable π complex (II) derived from the relatively long-lived[6] isopropoxycarboxy radical. Evidence for complexes between alkoxy radicals and aromatic substrates has been found, but these interactions are recognized[7,8] as being weaker than those entailing the chlorine atom as the radical entity.[9] Since the equilibrium is not shifted appreciably in the absence of added oxidant, the isopropoxycarboxy radical is free to undergo decarboxylation (eq 8) with resultant formation of the typical products.[3]

$$i\text{-PrOCO}_2\cdot \longrightarrow i\text{-PrO}\cdot + \text{CO}_2 \quad (8)$$

Inorganic Oxidants. A small amount (<1%) of oxygenation was found to take place with toluene in our system even without additives.[3] With anisole, an electron-rich aromatic, the ester product from thermal homolysis of the peroxydicarbonate was formed in increased yield (Table I). The lack of by-products attributable to the radical adduct (III) suggests that partitioning of this species occurs only *via* reversion to reactants or conversion to phenolic esters. Addition of various oxidants,[10] *e.g.*, oxygen, bromine, or iodine, resulted in increased substitution (Table I). This is consistent with oxygen's ability to rearomatize intermediate σ complexes.[11] Conducting the reaction in the

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[3] M. E. Kurz and P. Kovacic, *J. Am. Chem. Soc.*, **89**, 4960 (1967).

[4] P. Kovacic and M. E. Kurz, *ibid.*, **88**, 2068 (1966).

[5] H. E. De La Mare, J. K. Kochi, and F. F. Rust, *ibid.*, **85**, 1437 (1963).

[6] M. E. Kurz and P. Kovacic, *J. Org. Chem.*, in press.

[7] G. A. Russell, *ibid.*, 24, 300 (1959); E. L. Patmore and R. J. Gritter, *ibid.*, 27, 4196 (1962).

[8] C. Walling and P. J. Wagner, *J. Am. Chem. Soc.*, **86**, 3368 (1964).

[9] G. A. Russell, *ibid.*, 80, 4987, 4997 (1958).

[10] M. E. Kurz and P. Kovacic, *J. Org. Chem.*, **33**, 266 (1968).

[11] M. Eberhardt and E. L. Eliel, *ibid.*, 27, 2289 (1962); R. T.

Table I. Reaction of Diisopropyl Peroxydicarbonate with Aromatic Compounds in the Presence of Oxidants[a]

Aromatic	Oxidant	Aryl isopropyl carbonates: Yield, %[b]	*o*	*m*	*p*
Toluene[c]	None[d]	0.7	51	13	36
Toluene[e]	Oxygen[f]	6.6	49	20	31
Toluene[e]	Iodine[g]	5.2	55	20	25
Toluene[e]	Bromine[g]	7	61	12	27
Toluene[c]	$CuCl_2$[h]	85	57	15	28
Toluene[e]	$Cu(ClO_4)_2$[h,i]	26	73	8	19
Anisole	None[d]	7	44	7	49
Anisole	$CuCl_2$[h]	99	63	<1	36

[a] Aromatic:peroxide = 16.5–17.3:1, 2 hr, 60°, acetonitrile solvent; see general procedure. [b] See Experimental Section for yield basis. [c] See ref 3. [d] In the absence of air. [e] See ref 10. [f] A continuous stream of oxygen was introduced. [g] Oxidant:peroxide = 1.5:1. [h] Oxidant:peroxide = 0.3:1. [i] Hexahydrate.

Table II. Product Isotope Effect

Expt	Cupric salt	Reactant benzene,[a] I_{78}/I_{84}	Phenyl isopropyl carbonate[a] I_{94}/I_{99}	I_{121}/I_{126}
1	$CuCl_2$	1.00[b]	1.05	1.02
2	$CuCl_2$	1.00[b]	1.04	1.01
3	$CuCl_2$	1.04	1.03	1.07
4	$CuCl_2$	1.04	1.03	1.06
5	$Cu(ClO_4)_2$	1.00	1.03	1.00

[a] Average of several measurements; see Experimental Section. [b] I_{78}/I_{84} for benzene recovered after the reaction was found to be 1.05 in experiment 1 and 1.03 in experiment 2.

presence of cupric chloride gave excellent yields of aryl ester from both toluene and anisole, in keeping with the fact that copper salts have been shown to be efficient oxidants for cyclohexadienyl radicals.[12–14] These findings are readily rationalized on the basis of the mechanism shown in eq 7, with the yield being dependent on the facility with which III is oxidized. In electrophilic substitution, recent reports indicate that either a π or σ complex may be crucially involved depending upon the conditions.[15] Similarly, one can imagine oxidation taking place at some point between the extremes of II and III.

The over-all aromatic substitution scheme encompassing the effects of metal halides and other oxidants has analogy in earlier literature. The formation of a radical complex followed by oxidation involving a metal salt has been proposed in cases involving a variety of radicals of the oxy,[12,13,16,17] amino,[18] and carbon[19,20] types. Oxidants other than metal salts also play an effective role. As illustrations, increased yields of biaryls were realized with oxygen[11] and nitro compounds[21] in aromatic phenylation with benzoyl peroxide.

Isotope Effects. Studies with diisopropyl peroxydicarbonate, benzene, and cupric chloride indicated a clean oxygenation transformation (phenyl isopropyl carbonate in 76% yield) accompanied by the expected by-products, isopropyl alcohol and acetone.[1b] As a result, the system was amenable to studies of possible deuterium isotope effects. Equimolar amounts of benzene and hexadeuteriobenzene were allowed to compete for a limited amount of peroxide–cupric chloride under the usual reaction conditions.[3] The derived aryl isopropyl carbonates were isolated and analyzed by mass spectrometry (Table II). Virtually identical quantities of phenyl- and pentadeuteriophenyl isopropyl carbonates were obtained in all cases. Similar results were observed when cupric perchlorate was substituted for the metal halide.

The absence of a primary isotope effect[22] indicates that conversion of the cyclohexadienyl radical intermediate III to product occurs much faster than reversion to reactants (eq 7, $k_2 \gg k_{-1}$) when cupric salt catalysis is employed. This finding is in keeping with the efficiency and high rates of carbon radical oxidation by cupric salts.[12–14,23–25]

It is worthwhile noting similarities and differences in comparison with previous homolytic substitution systems which have been subjected to deuterium isotope studies. In general, isotope effects arose only in cases where rearomatization of the σ complex was not a facile process, *i.e.*, when radical attack was nonreversible, other paths competed with loss of a hydrogen atom from the complex, and when the attack was reversible, dissociation took place with comparable ease.[26] Phenylation with benzoyl peroxide[27,28] and hydroxylation with Fenton's reagent[16,29] are examples of the former case while intramolecular cyclization of 2-phenylbenzoyloxy radical to benzocoumarin[30] is illustrative of the latter. In phenylation the isotope effects arising from competition for arylcyclohexadienyl radicals between biaryl formation and alternative pathways could be eliminated by use of radical sources such as phenylazotriphenylmethane,[31] nitrosoacetanilide,[31] or diazonum salt and base,[28] as a result of the efficiency of triphenylmethyl-[28,32] and nitroxide-type[33] radicals in the rearomatization process.

Morrison, J. Cazes, N. Samkoff, and C. A. Howe, *J. Am. Chem. Soc.*, 84, 4152 (1962).

(12) W. W. Kaeding, H. O. Kerlinger, and G. R. Collins, *J. Org. Chem.*, 30, 3754 (1965).

(13) J. K. Kochi and R. D. Gilliom, *J. Am. Chem. Soc.*, **86**, 5251 (1964).

(14) S. C. Dickerman and I. Zimmerman, *ibid.*, 86, 5048 (1964).

(15) G. A. Olah in "Friedel–Crafts and Related Reactions," Vol. I, G. A. Olah, Ed., Interscience Publishers, Inc., New York, N. Y., 1963, Chapter XI.

(16) J. R. L. Smith and R. O. C. Norman, *J. Chem. Soc.*, 2897 (1963).

(17) W. W. Kaeding and G. R. Collins, *J. Org. Chem.*, 30, 3750 (1965); W. G. Toland, *J. Am. Chem. Soc.*, 83, 2507 (1961).

(18) F. Minisci and R. Galli, *Tetrahedron Letters*, 433 (1965); F. Minisci and R. Galli, *ibid.*, 1679 (1965).

(19) D. H. Hey, K. S. Y. Liang, and M. J. Perkins, *ibid.*, 1477 (1967).

(20) J. K. Kochi, *J. Am. Chem. Soc.*, 87, 3609 (1965).

(21) D. H. Hey, M. J. Perkins, and G. H. Williams, *Chem. Ind.* (London), 83 (1963); C. D. Hall, *ibid.*, 384 (1965); G. B. Gill and G. H. Williams, *J. Chem. Soc.*, *Sect. B*, 880 (1966); G. R. Chalfont, D. H. Hey, K. S. Y. Liang, and M. J. Perkins, *Chem. Commun.*, 367 (1967).

(22) The absence of a primary isotope effect would also be consistent with electrophilic substitution by an oxonium ion (eq 6) since proton loss from an intermediate arenonium ion is generally a facile process.

(23) J. K. Kochi and R. V. Subramanian, *J. Am. Chem. Soc.*, 87, 4855 (1965).

(24) J. Kumamoto, H. E. De La Mare, and F. F. Rust, *ibid.*, 82, 1935 (1960); J. K. Kochi, *ibid.*, 78, 4815 (1956).

(25) J. K. Kochi, *Science*, 155, 415 (1967).

(26) For a discussion of deuterium isotope effects in homolytic aromatic substitution, see L. Melander, "Isotope Effects on Reaction Rates," The Ronald Press Co., New York, N. Y., 1960, p 123.

(27) E. L. Eliel, S. Meyerson, Z. Welvart, and S. H. Wilen, *J. Am. Chem. Soc.*, 82, 2936 (1960).

(28) E. L. Eliel, J. G. Saha, and S. Meyerson, *ibid.*, 30, 2451 (1965).

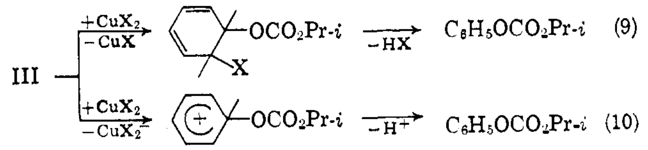
(29) L. M. Dorfman, I. A. Taub, and R. E. Bühler, *J. Chem. Phys.*, **36**, 3051 (1962).

(30) D. B. Denney and P. P. Klemchuk, *J. Am. Chem. Soc.*, 80, 3289 (1958); F. D. Greene, G. R. Van Norman, J. C. Cantrill, and R. D. Gilliom, *J. Org. Chem.*, 25, 1790 (1960).

(31) E. L. Eliel, M. Eberhardt, O. Simamura, and S. Meyerson, *Tetrahedron Letters*, 749 (1962).

(32) D. H. Hey, M. J. Perkins, and G. H. Williams, *J. Chem. Soc.*, 110 (1965); J. F. Garst and R. S. Cole, *Tetrahedron Letters*, 679 (1963); G. A. Russell and R. F. Bridger, *ibid.*, 737 (1963).

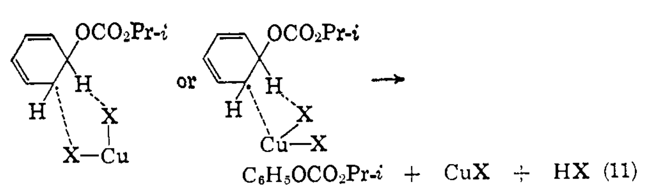
Nature of the Oxidative Rearomatization. The degree of success in the oxygenation reaction is quite dependent on the nature of the metal salt oxidant. Of a variety of copper salts investigated, the halides were found to be superior, while those of perchloric and tetrafluoroboric acids gave low yields of ester, and the ones from weak acids were ineffective.[10] Although it is difficult to establish the precise details of the oxidative conversion, one might apply as limits the two extremes of ligand transfer (eq 9) and electron transfer (eq 10)



(X = anion). Cupric halides generally react with carbon radicals by ligand transfer oxidation,[24,25,34,35] while the highly ionic salts function by an electron-transfer mechanism.[5,25,34,35] Kochi has suggested that whereas various factors (*e.g.*, structure of the free radical, nature of the metal species and counterions) may favor oxidation of carbon radicals by one or the other route, in many cases the reaction can be regarded as involving components of both processes.[25,34,35] Certain facts, *e.g.*, higher yields from aromatic substitution with ligand transfer agents,[10] are more in keeping with eq 9 when metal halides are involved. A related scheme may also pertain to halogen. However, the limited success with highly ionic salts,[10] *e.g.*, cupric perchlorate (Table I), which favor electron transfer indicates that oxygenation may also occur inefficiently *via* eq 10.

It is noteworthy that the oxygenation reaction exhibits a marked selectivity toward the oxidant, whereas a wide variety of copper salts can be used in oxidation of simple alkyl or alkenyl radicals.[25,34,35] Perhaps the presence of the electron-withdrawing ester function discourages the electron-transfer pathway, a process which necessitates the generation of positive charge in the transition state.[5,25,36] Carbon radicals containing electron-withdrawing groups near the site of the unpaired electron generally are not oxidized by the usual electron-transfer salts, but instead undergo ready reaction *via* ligand transfer.[25,36]

One should also consider cyclic transition states as shown in eq 11 which entail concurrent β-hydrogen removal (illustrated with one of the canonical resonance



forms). This hypothesis can also be applied to related systems reported in the prior literature. Perhaps interaction of the metal portion with the π system plays a role as has been proposed for the oxidation of allylic radicals by copper salts.[25,37] The favorable stereochemistry associated with the postulated structures may be an additional factor contributing to the good yields with cupric chloride. A concerted process has been proposed in the electron-transfer oxidation of alkyl radicals by copper salts.[5,38]

The reason for the discrepancies, large and small, from a common isomeric pattern in the various processes remains to be elucidated.[19] Since there is some variation in isomer distribution with a given substrate in the different systems, it is unlikely that the radical is completely free in all cases. Complexing with metal halide may occur in some instances through the odd-electron character or by an acid–base type interaction.[10] Alternatively, a concerted interaction involving the aromatic substrate, peroxide, and metal halide (*e.g.*, cuprous chloride) may be operative in the induced-decomposition step leading directly to nuclear attack.

Relative Rates and Orientation. In an effort to characterize the attacking entity more fully, relative rate studies were carried out with a number of aromatic compounds in copper chloride catalyzed oxygenation (Table III). The substrates displayed rates of from 3.7 to 46 times that of benzene. Good agreement was noted among the toluene–benzene systems investigated at various ratios of the two competitors, indicating the validity of the treatment. The similarity of the $k_{m\text{-xylene}}/k_{\text{benzene}}$ ratio, calculated from the product of $(k_{m\text{-xylene}}/k_{\text{toluene}})(k_{\text{toluene}}/k_{\text{benzene}})$, to that actually observed provided a further check. A somewhat larger degree of variance was evidenced with mesitylene.

Table III. Relative Rate Data for Oxygenation with Diisopropyl Peroxydicarbonate–Cupric Chloride[a]

ArH′	ArH	Molar ratio, ArH′/ArH	$k_{\text{ArH}'}/k_{\text{ArH}}$ Obsd[b]	$k_{\text{ArH}'}/k_{\text{ArH}}$ Calcd	Av rel rate
Toluene	Benzene	0.83	3.19	3.81	3.77 ± 0.08
Toluene	Benzene	0.44	1.66	3.75	
Toluene	Benzene	0.17	0.64	3.76	
m-Xylene	Benzene	0.72	11.32	15.67[c]	15.67 ± 0.04
m-Xylene	Toluene	0.87	3.72	4.46[c]	
p-Xylene	Benzene	0.44	4.06	9.30	9.3 ± 0.1
Mesitylene	Benzene	0.38	1.77	39.9	45.8 ± 7.6
Mesitylene	Benzene	0.17	9.04	52.9	
Mesitylene	Benzene	0.084	3.83	45.5	
Anisole	Benzene	0.11	2.67	24.9	24.9 ± 0.3

[a] Total aromatic:peroxide:$CuCl_2$ = 70–89:1:0.4, acetonitrile solvent, 60°, 1 hr; see Experimental Section. [b] Each value is the average of two runs in close agreement. [c] A $k_{m\text{-xylene}}/k_{\text{benzene}}$ value of 16.80 was obtained as the product of $(k_{m\text{-xylene}}/k_{\text{toluene}})(k_{\text{toluene}}/k_{\text{benzene}})$.

Both the isomer distributions and relative rates bear out the notion of electrophilicity associated with the attacking entity. In particular the results from competitive oxygenation are decidedly indicative of polar character.[15] However, the data *per se* should not be construed as evidence for an ionic pathway (*vide supra*). The over-all findings can best be interpreted on the basis of intermediate formation of an isopropoxycarboxy radical which is quite electrophilic. Considerable data

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[33] C. Rüchardt and B. Freudenberg, *Tetrahedron Letters*, 3623 (1964); C. Rüchardt and E. Merz, *ibid.*, 2431 (1964); G. R. Chalfont and M. J. Perkins, *J. Am. Chem. Soc.*, **89**, 3054 (1967).

[34] J. K. Kochi, *Tetrahedron*, **18**, 483 (1962).

[35] J. K. Kochi and H. E. Mains, *J. Org. Chem.*, **30**, 1862 (1965).

[36] J. K. Kochi and D. M. Mog, *J. Am. Chem. Soc.*, **87**, 522 (1965); J. K. Kochi and F. F. Rust, *ibid.*, **84**, 3946 (1962).

[37] J. K. Kochi, *ibid.*, **84**, 3271 (1962); A. L. J. Beckwith and G. W. Evans, *Proc. Chem. Soc.*, 63 (1962).

[38] J. K. Kochi, *J. Am. Chem. Soc.*, **85**, 1958 (1963).

has accumulated which points to the electrophilic nature of oxy radicals,[16,39,40] making difficult clear-cut distinctions based on isomer distributions and relative rates alone.

The relative rates of 25 and 3.8 in our principal system with anisole and toluene, respectively, are quite interesting in comparison to other aromatic oxygenation systems. These values are significantly lower than those from electrophilic oxygenation with diisopropyl peroxydicarbonate–aluminum bromide[41] ($k_{\text{toluene}}/k_{\text{benzene}}$ = 16.8) and with trifluoroperacetic acid[42] ($k_{\text{anisole}}/k_{\text{benzene}}$ = 530), but at the same time somewhat higher than in the case of homolytic substitution with Fenton's reagent ($k_{\text{anisole}}/k_{\text{benzene}}$ = 6.4).[42] Based on these data and structural considerations, it is apparent that the isopropoxycarboxy radical is more electrophilic than the corresponding hydroxyl entity.[43]

Certain other free-radical aromatic substitutions involve attacking species which exhibit polar characteristics. Thus, although the extensively studied phenyl radical[44] possesses very little polar nature (ρ value of +0.05[45]), related aryl radicals display somewhat enhanced nucleophilic, or even marked electrophilic, character depending on the substituent.[44a,45] Saturated carbon radicals, *e.g.*, methyl[44b] and to a greater degree cyclohexyl,[46] are generally nucleophilic, but with the proper substituents they can be electrophilic, *e.g.*, trichloromethyl[47] and triphenylmethyl.[44b] Many of the noncarbon radicals in which the unpaired electron is associated with an electronegative element, such as oxygen, nitrogen, or sulfur, exhibit electrophilic properties.[48]

Experimental Section

Materials. The aromatic reactants, acetonitrile, and *t*-butyl alcohol, of high purity according to glpc, were used directly. Hexadeuteriobenzene (Stohler Isotopes, 99.5% pure) was found to contain less than 3% of pentadeuterated contaminant by mass spectrometry. For one set of duplicate runs in the benzene–hexadeuteriobenzene competition (experiments 1 and 2 in Table II), freshly opened samples of benzene (Eastman Spectral Grade) and acetonitrile (Matheson Coleman and Bell, Spectral Grade, 0.03% water) were employed, and cupric chloride (Fisher) was dried in an oven for 12 hr before use. Generally, cupric chloride and cupric perchlorate hexahydrate (K & K Laboratories) were used without purification.

We are grateful to the Pittsburgh Plate Glass Co. for generous samples of diisopropyl peroxydicarbonate.

Aromatic Oxygenation with Diisopropyl Peroxydicarbonate. The general procedure is described elsewhere.[3] A solution of diisopropyl peroxydicarbonate (0.5 *N*) in the appropriate aromatic substrate was added in the usual manner to the acetonitrile solution with or without catalyst.

Unless otherwise noted, yields of the carbonate esters are based on the stoichiometry of 1 mol/mol of peroxide (eq 1) and comprise the average of two or more runs which were in satisfactory agreement.

Competitive Oxygenation. 1. Substituted Aromatics *vs.* Benzene. Cupric chloride (2 mmol) was dissolved in acetonitrile (150 ml); the aromatic reactants were added, and the resulting solution was brought to 60° and blanketed with nitrogen as in the general procedure for oxygenation.[3] Diisopropyl peroxydicarbonate (5 mmol total) in acetonitrile (0.5 *N*, 10 ml) was then added. The molar ratio of total aromatic:peroxide:catalyst was 70–89:1:0.4. Following addition of the peroxide solution, reaction was allowed to proceed for 1 hr. After the usual quenching and work-up, the carbonate esters were analyzed by glpc (glpc column 1[3]). The molar ratio of products was obtained by comparing the respective area ratios to plots of area *vs.* mole ratios for known mixtures of the products. Duplicate runs were performed for each competition.

A less preferred alternative method entailed addition of a solution of the peroxide in a portion of the aromatic substrates to a mixture of the remainder of the aromatic components and cupric chloride in acetonitrile.

2. Benzene–Hexadeuteriobenzene. The same general approach as in 1 was taken. This time, however, the aromatics were carefully weighed and added to the metal halide solution, followed by introduction of the peroxide (0.5 *N*) in acetonitrile (8 ml). The molar ratio of reactants was aromatics:peroxide:$CuCl_2$ = 16.7:1:0.37. At the end of 1 hr, an aliquot was saved and the remainder carefully worked up in the usual manner.[3] Half of the resulting organic mixture was subjected to reduced-pressure distillation at room temperature for removal of most of the benzene–hexadeuteriobenzene. The residue was used for mass spectral analysis of the product esters without further purification since benzene did not interfere.

Authentic Materials. Three of the carbonate esters were prepared by a literature procedure:[49] *m*-tolyl isopropyl carbonate, bp 94–97° (1.7 mm) (*Anal.* Calcd for $C_{11}H_{14}O_3$: C, 68.02; H, 7.27. Found: C, 68.37; H, 7.51); 2,5-xylenyl isopropyl carbonate, bp 94–95° (1.8 mm) (*Anal.* Calcd for $C_{12}H_{16}O_3$: C, 69.20; H, 7.75. Found: C, 69.37; H, 7.71); and 2,6-xylenyl isopropyl carbonate, bp 90–91° (1.4 mm) (*Anal.* Calcd for $C_{12}H_{16}O_3$: C, 69.20; H, 7.75. Found: C, 69.13; H, 7.57). The remaining carbonate esters are reported elsewhere.[3,41]

Analytical Procedures. The glpc instruments and columns are described elsewhere,[3] as are the methods of determining product yields, isomer distributions, and peroxide content.

Mass Spectrometry. All mass spectra were obtained with a Consolidated Electrodynamics Corporation mass spectrometer, Model No. 21-103C, using an all-glass inlet system heated at 150°. The temperature of the source was 250°. The ionizing energy was maintained at 70 eV and the ionizing current at 10 μamp. The samples were expanded into a 3-l. bulb connected to the mass spectrometer through a gold leak. The pressure in the analyzer tube was maintained close to 10^{-6} mm.

The mass spectrum of phenyl isopropyl carbonate has been discussed by Brown and Djerassi[50] who have established that the peak at *m*/*e* 121 corresponds to $(C_6H_5OCO)^+$ and $(C_6H_5O{=}CHCH_3)^+$. The composition of the peak at *m*/*e* 94 was found to be $(C_6H_5OH)^+$, indicating the transfer of a hydrogen from the isopropyl group.

Since the intensity of the molecular ion of the ester was very weak, this species could not be used for mass spectral analysis of the reaction products. Therefore, the fragment ions at *m*/*e* 121 and *m*/*e* 94 were compared to the corresponding ions at *m*/*e* 126 and *m*/*e* 99 from the deuterated ester. In calculating the intensities of the strong peaks at *m*/*e* 99 for $(C_6D_5OH)^+$ and *m*/*e* 94 for $(C_6H_5OH)^+$ corrections were made for the accompanying weak peaks at *m*/*e* 98 and *m*/*e* 93, respectively. The comparatively weaker peaks at *m*/*e* 121 and 126 were more satisfactory because the intensity of peaks at *m*/*e* 120 and 125 were negligible. However, it should be noted that the results from both methods were in good agreement.

The analyses of benzene–hexadeuteriobenzene mixtures were conveniently carried out by comparing the relative intensity of the molecular ions, $(C_6H_6)^+$ at *m*/*e* 78 and $(C_6D_6)^+$ at *m*/*e* 84.

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(39) W. T. Dixon, R. O. C. Norman, and A. L. Buley, *J. Chem. Soc.*, 3625 (1964); R. O. C. Norman and G. K. Radda, *Proc. Chem. Soc.*, 138 (1962).

(40) M. Anbar, D. Meyerstein, and P. Neta, *J. Phys. Chem.*, **70**, 2660 (1966).

(41) P. Kovacic and M. E. Kurz, *J. Am. Chem. Soc.*, 87, 4811 (1965).

(42) A. J. Davidson and R. O. C. Norman, *J. Chem. Soc.*, 5404 (1964).

(43) Preliminary results (P. Kovacic, C. G. Reid, and M. E. Kurz, unpublished work) from a Hammett correlation (limited number of points) with σ^+ values indicate a ρ value of approximately −2, compared to −0.41 (σ values) for hydroxyl radical.[40]

(44) G. H. Williams, "Homolytic Aromatic Substitution," Pergamon Press, New York, N. Y., 1960: (a) Chapter 4; (b) Chapter 6.

(45) R. Ito, T. Migita, N. Morikawa, and O. Simamura, *Tetrahedron*, 21, 955 (1965).

(46) J. R. Shelton and C. W. Uzelmeier, *J. Am. Chem. Soc.*, **88**, 5222 (1966).

(47) G. A. Russell and R. C. Williamson, Jr., *ibid.*, 86, 2357 (1964).

(48) R. O. C. Norman and R. Taylor, "Electrophilic Substitution in Benzenoid Compounds," Elsevier Publishing Co., New York, N. Y., 1965, p 116.

(49) D. S. Tarbell and E. J. Longosz, *J. Org. Chem.*, 24, 774 (1959).

(50) P. Brown and C. Djerassi, *J. Am. Chem. Soc.*, **88**, 2469 (1966).

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Stereospecificity in Ozonide and Cross-Ozonide Formation

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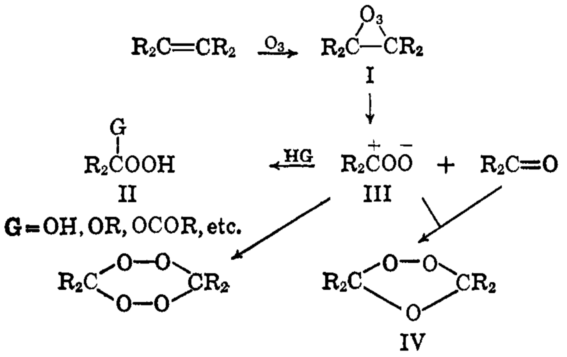
Abstract: Additional data are presented in regard to stereospecificity in ozonide and cross-ozonide formation, as evidenced by *cis–trans* ratios. The effect of solvent, temperature, and concentration changes on these ratios and other aspects of ozonolysis are discussed. It is shown that the results herein presented, as well as those from other laboratories, are explicable on the basis of a refined Criegee mechanism, involving the stereoselective decomposition of *cis* and *trans* initial ozonides to isomeric *syn* and *anti* zwitterions and the stereoselective recombination of these with aldehydes to give final ozonides.

The proposal (1949–1953) of the Criegee mechanism[2–4] for the classical ozonolysis reaction not only placed the reaction on a sound theoretical basis, but greatly stimulated research in the field, of both a theoretical and a practical nature. The mechanism is outlined in Scheme I. The evidence for the Criegee mechanism and its key zwitterionic intermediate III is most convincing. It includes: (1) interception of the zwitterion III by participating solvents to give substituted hydroperoxides II, or with reactive foreign aldehydes to give ozonides other than that of the olefin itself;[4] (2) the formation of the same ozonide from two structurally different olefins which, however, yield the same zwitterion and carbonyl moieties;[4] (3) the formation of cyclic oxyhydroperoxides from olefins having a properly placed hydroxy functional group;[5] and (4) the formation of cross ozonides[6] from unsymmetrical olefins.[7–11]

Scheme I



plus polymeric peroxides and ozonides

Early, however, facts began to accumulate which were difficult to explain on the basis of the simple Criegee mechanism outlined in Scheme I, necessitating the realization that either there is another mechanism for ozonide IV formation (possibly an intramolecular rearrangement of the initial ozonide) competing with the Criegee mechanism,[12] or else the Criegee mechanism needs refinement. These observations include: (1) the early failure of Criegee[13] to find cross ozonides upon ozonolysis of either 3-heptene or a mixture of 3-hexene and 4-octene, possibly because he was not using concentrated enough solutions or high enough temperatures;[8] (2) the findings of Briner and coworkers[14] that *cis* and *trans* isomers of 1-arylpropenes do not give the same proportions of ozonide on the one hand and aldehydes and polymeric peroxides on the other hand; (3) the finding that *cis* and *trans* olefins not only give different ozonide–polymeric peroxide ratios, but often different *cis–trans* ozonide ratios;[10,15–21] (4) the recent important and exciting discovery that even

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(1) To whom inquiries concerning this paper should be directed.

(2) R. Criegee and G. Wenner, *Ann.*, **564**, 9 (1949).

(3) R. Criegee, *ibid.*, **583**, 1 (1953).

(4) P. S. Bailey, *Chem. Rev.*, **58**, 925 (1958).

(5) (a) A. Rieche and M. Schulz, *Chem. Ber.*, **98**, 3623 (1965); (b) A. Rieche, M. Schulz, and D. Becker, *ibid.*, **98**, 3627 (1965).

(6) The term "normal ozonide" is used to describe the parent ozonide obtained from ozonolysis of an olefin. For an unsymmetrical olefin it is the unsymmetrical ozonide, whereas the two symmetrical ozonides obtained are termed "cross ozonides." See ref 7.

(7) L. D. Loan, R. W. Murray, and P. R. Story, *J. Am. Chem. Soc.*, **87**, 737 (1965).

(8) G. Riezebos, J. C. Grimmelikhuysen, and D. A. Van Dorp, *Rec. Trav. Chim.*, **82**, 1234 (1963).

(9) O. S. Privett and E. C. Nickell, *J. Am. Oil Chemist's Soc.*, **41**, 72 (1964).

(10) O. Lorenz and C. R. Parks, *J. Org. Chem.*, **30**, 1976 (1965).

(11) Earlier references to cross ozonides also appear, but their significance was not emphasized: (a) M. Indo, *Nippon Kagaku Zasshi*, **80**, 537 (1959); *Chem. Abstr.*, **55**, 4404 (1961); (b) T. Vrbaski and R. J. Cvetanovic, *Can. J. Chem.*, **38**, 1063 (1960); (c) O. Lorenz and C. R. Parks, *Rubber Chem. Technol.*, **36**, 201 (1963).

(12) P. S. Bailey, S. B. Mainthia, and C. J. Abshire, *J. Am. Chem. Soc.*, **82**, 6136 (1960).

(13) R. Criegee, *Record Chem. Progr.* (Kresge-Hooker Sci. Lib.), **18**, 111 (1957).

(14) (a) E. Briner, E. Dallwigk, and M. Ricca, *Helv. Chim. Acta*, **41**, 1390 (1958); (b) E. Briner and M. Ricca, *ibid.*, **41**, 2178 (1958); (c) E. Briner and S. Fliszar, *ibid.*, **42**, 1310, 2063 (1959).

(15) R. Criegee, S. S. Bath, and B. von Bornhaupt, *Chem. Ber.*, **93**, 2891 (1960).

(16) G. Schröder, *ibid.*, **95**, 733 (1962).

(17) P. Kolsaker, *Acta Chem. Scand.*, **19**, 223 (1965).

(18) F. L. Greenwood and B. J. Haske, *Tetrahedron Letters*, 631 (1965).

(19) R. W. Murray, R. D. Youssefyeh, and P. R. Story, *J. Am. Chem. Soc.*, **88**, 3143 (1966).

(20) F. L. Greenwood, *ibid.*, **88**, 3146 (1966).

(21) R. W. Murray, R. D. Youssefyeh, and P. R. Story, *ibid.*, **89**, 2429 (1967).