

Friedel–Crafts Oxygenation of Anisole and Alkylbenzenes with Diisopropyl Peroxydicarbonate¹

Peter Kovacic and Michael E. Kurz²

Contribution from the Department of Chemistry, Case Institute of Technology, Cleveland, Ohio. Received July 13, 1965

Diisopropyl peroxydicarbonate reacted with anisole and various alkylbenzenes in the presence of aluminum chloride to yield oxygenated materials—aryl isopropyl carbonates and presumably $\text{ArOCO}_2\text{AlCl}_2$. Factors influencing the type of oxygenated product formed are discussed. Evidence is presented for primacy of heterolytic oxygen–oxygen cleavage, rather than initial alkylation. Caustic and acid were used to convert the oxygen-containing products to phenols (over-all yields of 15 to 76%). The phenolic isomer distributions obtained with the various substrates indicated an electrophile of moderate bulkiness. Lower molecular weight organic products and neutral, nonoxygenated materials were determined, and their mode of formation is treated. Carbon dioxide evolution was also studied. More complete data were obtained for competitive oxygenation.

Introduction

Whereas aromatic oxygenation³ involving radical intermediates has received considerable attention, the literature dealing with the analogous electrophilic process is relatively sparse. Reagents which have been used to effect electrophilic oxygenation include hydrogen peroxide in the presence of sulfuric acid^{4a} or boron trifluoride etherate,^{4b} peroxy acids alone⁵ or with a Lewis acid promoter,⁶ and diaroxy peroxides in conjunction with a Friedel–Crafts catalyst.^{7,8} With very simple aromatics the reactions are generally characterized by poor yields of monoxygenated products. However, in the case of more highly substituted substrates, e.g., mesitylene, very good yields have been reported.^{6a} Compelling evidence for the involvement of polar intermediates was derived from orientation,⁹ catalytic effects,^{4,6,7} and the occurrence of Wagner–Meerwein rearrangements.^{6b,c} Davidson and Norman⁹ demonstrated that the isomer distributions and relative rates for the reaction of trifluoroacetic acid and boron trifluoride with various aromatics were different from those obtained using hydroxyl radicals as the reagent. An unusual oxygenation process

has been observed on treatment of aromatic hydrocarbons with nitric acid in acetic anhydride.¹⁰ In addition to the expected nitration pathway, introduction of an acetoxy group was found to occur. Acetoxylation has also been effected by treating anisole with lead tetraacetate.¹¹ Various lines of evidence pointed to an electrophilic mechanism. Thermal decomposition of nitrobenzenesulfonyl peroxides in aromatic reactants gave rise to phenolic esters of the type, $\text{O}_2\text{NC}_6\text{H}_4\text{SO}_2\text{OAr}$.¹² An ionic reaction scheme was favored on the basis of the partial rate factors. The prior literature is treated in more detail elsewhere.¹³

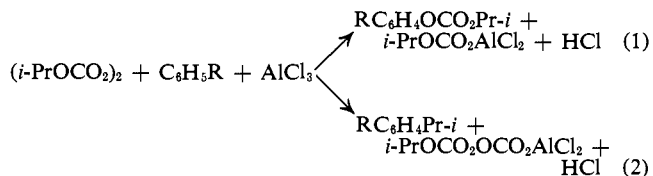
Razuvaev and co-workers succeeded in introducing a cyclohexyloxy-carboxy group directly into the aromatic nucleus of toluene and benzene using dicyclohexyl peroxydicarbonate in the presence of a small amount of ferric chloride.¹⁴ Very recently, a report appeared concerning oxygenation of toluene to cresols in 50% yield with diisopropyl peroxydicarbonate and aluminum chloride catalyst.¹⁵ An electrophilic mechanism was indicated by the cresol isomer distribution, the $k_{\text{toluene}}/k_{\text{benzene}}$ value, necessity of a Friedel–Crafts catalyst, and absence of products expected from radical intermediates. These constituted the first cases of highly selective conversion of simple aromatic hydrocarbons to the monoxygenated product.

The objectives of this work were to extend the scope of the diisopropyl peroxydicarbonate reaction to other aromatic substrates (principally anisole and alkylbenzenes) and to further elucidate the mechanistic aspects.

Results and Discussion

In general the oxygenations were carried out at $0 \pm 5^\circ$ with aromatic–diisopropyl peroxydicarbonate–aluminum chloride in 15:1:2 molar ratio. *o*-Dichlorobenzene was used as solvent for the solid aromatic substrates. The nature of the oxygenated product was determined both before and after caustic hydrolysis.

In the earlier work¹⁵ it was not established whether oxygenation (eq. 1) or alkylation (eq. 2) occurs initially.



(1) Paper II. Aromatic Oxygenation.

(2) National Science Foundation Fellow, summer 1964; from the forthcoming Ph.D. Thesis of M. E. K.

(3) This term is used to designate direct introduction of RO (R = hydrogen, alkyl, acyl, etc.) into the aromatic nucleus.

(4) (a) D. H. Derbyshire and W. A. Waters, *Nature*, **165**, 401 (1950); (b) J. D. McClure and P. H. Williams, *J. Org. Chem.*, **27**, 24 (1962).

(5) (a) R. D. Chambers, P. Goggin, and W. K. R. Musgrave, *J. Chem. Soc.*, 1804 (1959); (b) J. D. McClure and P. H. Williams, *J. Org. Chem.*, **27**, 627 (1962).

(6) (a) C. A. Buehler and H. Hart, *J. Am. Chem. Soc.*, **85**, 2177 (1963); (b) A. J. Waring and H. Hart, *ibid.*, **86**, 1454 (1964); (c) H. Hart and C. A. Buehler, *J. Org. Chem.*, **29**, 2397 (1964); (d) H. Hart, C. A. Buehler, A. J. Waring, and S. Meyerson, *ibid.*, **30**, 331 (1965).

(7) D. Z. Denney, T. M. Valega, and D. B. Denney, *J. Am. Chem. Soc.*, **86**, 46 (1964).

(8) J. T. Edward, H. S. Chang, and S. A. Samad, *Can. J. Chem.*, **40**, 804 (1962).

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

(10) A. Fischer, J. Packer, J. Vaughan, and G. J. Wright, *ibid.*, 3687 (1964).

(11) D. R. Harvey and R. O. C. Norman, *ibid.*, 4860 (1964).

(12) R. L. Dannley and G. E. Corbett, *J. Org. Chem.*, to be published.

(13) S. T. Morneweck, Ph.D. Thesis, Case Institute of Technology, 1965.

(14) G. A. Razuvaev, N. A. Kartashova, and L. S. Boguslavskaya, *J. Gen. Chem. USSR*, **34**, 2108 (1964). We plan to treat this oxygenation method at greater length in a subsequent publication.

(15) P. Kovacic and S. T. Morneweck, *J. Am. Chem. Soc.*, **87**, 1566 (1965).

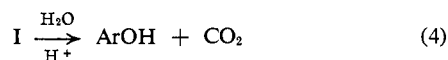
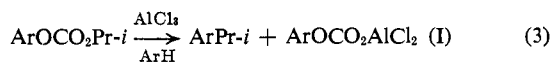
We now have in hand evidence for the primacy of the oxygenation process. With one exception, aryl isopropyl carbonate was found to be present at the conclusion of reaction (Table I). At the end the mixture was exposed to cold, aqueous acid, under which conditions the carbonate ester was shown to be stable. Initial cleavage of the peroxide according to eq. 2 would lead to the formation of isopropylated aromatic in amounts at least equal to the aryl isopropyl carbonate.¹⁶ Although in the oxygenation of anisole an 86% yield of anisyl isopropyl carbonate was formed, there was only 12% of isopropylanisole, indicating that initial cleavage at the peroxide linkage is the preferred route (eq. 1).¹⁷

Table I. Nature of the Oxygenated Product^a

Aromatic reactant	Oxygenated product, %	
	ArOH	ArOCOOPr- <i>i</i>
Anisole	0	100
Mesitylene	11	89
Pseudocumene	18	82
<i>p</i> -Xylene ^b	43	57
<i>m</i> -Xylene	58	42
<i>o</i> -Xylene	66	34
Toluene	100	0
Toluene ^c	35	65
Durene ^d	35	65
Pentamethylbenzene ^d	73	27

^a Based on expected oxygenated products only; oxygenated materials from disproportionation products are excluded (see General Procedure). ^b 13 ± 5°. ^c -30 ± 5°. ^d In *o*-dichlorobenzene solvent (see General Procedure).

Another type of oxygenated material, phenolic in nature, was also present, apparently formed mainly by the indicated sequence.



The composition of the oxygenated product varied widely depending upon the aromatic reactant, from 100% of carbonate esters in the case of anisole to 100% of cresols with toluene (Table I).

Various methods were used for characterization of the oxygenated products: gas chromatography, infrared and n.m.r. spectroscopy, physical constants, and comparison with authentic materials. A number of the requisite esters (Table II) were synthesized by interaction of isopropyl chloroformate with the appropriate phenol.¹⁸

It is tempting to speculate as to the underlying factors relating aromatic structure to the nature of the oxygenated product. In the case of anisole an important aspect may be deactivation of aluminum chloride by coordination with the ether. There is ample analogy in previous reports of complexing by anisole with Lewis acids, e.g., boron trifluoride,¹⁹ aluminum chloride,²⁰

(16) See ref. 15, eq. 1 and 2.

(17) Although the evidence is not quite as conclusive, we believe a similar pathway pertains in the hydrocarbon series. On the assumption that the aryl isopropyl carbonate is more resistant to dealkylation than is the peroxide, an alternative possibility should also be considered in these cases (ref. 15, eq. 2).

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

Table II. Aryl Isopropyl Carbonate Esters

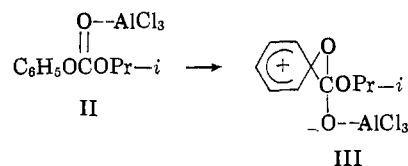
Ar in ArOCO ₂ Pr- <i>i</i>	B.p., °C. (mm.)	Elemental anal. ^a			
		C, %		H, %	
		Calcd.	Found	Calcd.	Found
<i>p</i> -Anisyl	110-112 (0.7)	62.84	63.00	6.71	6.80
<i>o</i> -Anisyl	116-117 (1.9)	62.84	63.02	6.71	6.71
<i>p</i> -Tolyl	94 (1.5)	68.02	68.01	7.27	7.24
<i>o</i> -Tolyl ^b	81-84 (1.1)	68.02	68.03	7.27	7.49
2,4-Xylenyl	93-94 (1.6)	69.20	69.26	7.75	7.96
Mesityl	86-89 (0.6)	70.24	70.19	8.17	8.13

^a Performed by Dr. Weiler and Dr. Strauss, Oxford, England, and Galbraith Laboratories, Knoxville, Tenn. ^b The analytical sample was obtained by gas chromatography of the distilled product.

and phenol.²¹ It is reasonable to designate catalyst strength as a significant factor in ester dealkylation (eq. 3). Friedel-Crafts alkylation by esters is a well-established reaction.²² The anisyl isopropyl carbonates were unchanged even after prolonged reaction times, emphasizing their reluctance to undergo degradation in this system.

In addition, steric interactions may play vital roles. Support for this hypothesis is provided by the relationship between aromatic structure and composition of the oxygenated product in the hydrocarbon series. The per cent of ester component decreased in the order: mesitylene > pseudocumene > *p*-xylene > *m*-xylene > *o*-xylene > toluene. The presence of *ortho* substituents in the ester would be expected to interfere with formation of the complex (II) which is believed to be the precursor for subsequent dealkylation.

Perhaps consideration should also be given to phenonium ion participation. Involvement of this type of structure (III) would be expected to hinder dealkylation.



Alkyl substituents, particularly in the *ortho* and *para* positions, should enhance the contribution of structure III. Since the xylene data are not in keeping with the postulate, this phenomenon is deemed a minor contributor at best. Similar schemes have been invoked in the carboxy inversion reaction⁷ and solvolysis of β -arylethyl halides.²³

Studies in the toluene system point up the importance of the temperature variable. Although no ester was detected at 0°, 65% of the oxygen-containing product was of this form at -30°. Evidently at the higher temperature the initially formed ester undergoes rapid loss of the isopropyl group. Confirmation was provided by the observation that tolyl isopropyl carbonates

(19) H. Meerwein and H. Maier-Hüser, *J. prakt. Chem.*, **134**, 51 (1932).

(20) G. Baddeley, *J. Chem. Soc.*, 330 (1944).

(21) B. B. Wayland and R. S. Drago, *J. Am. Chem. Soc.*, **86**, 5240 (1964).

(22) F. A. Drahowzal in "Friedel-Crafts and Related Reactions," Vol. II, Part 1, G. A. Olah, Ed., Interscience Publishers, Inc., New York, N. Y., 1964, Chapter XX; C. A. Thomas, "Anhydrous Aluminum Chloride in Organic Chemistry," Reinhold Publishing Corp., New York, N. Y., 1941, p. 673 ff.

(23) R. Baird and S. Winstein, *J. Am. Chem. Soc.*, **85**, 567 (1963).

Table III. Solvent Effect on ArOCO₂Pr-*i*/ArOH Product Ratio

System	— ArOH, % —		ArOCO ₂ Pr- <i>i</i> ,	
	Neat ^a	In <i>o</i> -C ₆ H ₄ Cl ₂ ^b	Neat ^c	In <i>o</i> -C ₆ H ₄ Cl ₂ ^b
Diisopropyl peroxydi-carbonate-aluminum chloride-mesitylene	12	41	88	59
Mesityl isopropyl carbonate-aluminum chloride-mesitylene	15	50	85	50

^a See general procedure. ^b *o*-Dichlorobenzene-mesitylene-aluminum chloride-peroxide or carbonate = 15/5/2/1 molar ratio. ^c Simulated reaction conditions (see the Experimental Section).

Table IV. Phenolic End Products

Aromatic	Phenolic end products	
	Yield, % ^a	Isomer distribution, %
Toluene	52 ^b	<i>o</i> -(34), <i>m</i> -(11), and <i>p</i> -(55) cresol ^c
Ethylbenzene	15 ^d	<i>o</i> -, <i>m</i> -, and <i>p</i> -ethylphenol
<i>o</i> -Xylene	34	3,4-(74) and 2,3-(26) xylenol
<i>m</i> -Xylene	48	2,4(91) and 2,6-(9) xylenol
<i>p</i> -Xylene ^e	24 ^f	2,5-xylenol
Tetralin	22 ^g	5,6,7,8-tetrahydro-1-(29) and 2-(71)naphthol
Mesitylene	66	Mesitol
Pseudocumene	22 ^h	2,4,5- and 2,3,5-(87), and 2,3,6-(13)trimethylphenol
Durene ⁱ	50 ^j	Durophenol
Pentamethylbenzene ^k	75 ^l	Pentamethylphenol
Anisole	76 ^m	<i>o</i> -(20) and <i>p</i> -(80) methoxyphenol

^a Yield of nonrearranged, nondisproportionated phenolic products after caustic hydrolysis (see General Procedure). ^b Cymenols, 4%. ^c Reference 15. ^d Phenol, 19%; diethylphenol, 4%, and residue, 8%. ^e 13 ± 5°. ^f 2,4,5-Trimethylphenol, 1%. ^g Unidentified phenolic product, 1%. ^h 2,5-Xylenol, 1%. ⁱ *o*-C₆H₄-Cl₂-durene-AlCl₃-peroxide = 25/5/2/1. ^j Pentamethylphenol, 13%. ^k *o*-C₆H₄Cl₂-pentamethylbenzene-AlCl₃-peroxide = 15/5/2/1. ^l Durophenol, 1%. ^m Phenol, 2%.

Table V. Orientation from Peroxides and Aromatics

Aromatic	Reagent	Conditions	Isomer distribution, % ^a	Ref.
Toluene	CF ₃ CO ₃ H	0–10°, CH ₂ Cl ₂	<i>o</i> -(78), <i>m</i> -(2), and <i>p</i> -(20) cresol	9
<i>o</i> -Xylene	HNO ₃ -Ac ₂ O	0°, neat	4-Acetoxy- <i>o</i> -xylene	10
<i>m</i> -Xylene	90% H ₂ O ₂ -BF ₃	10–15°, CH ₂ Cl ₂	2,4-(66) and 2,6-(34) xylenol	4b
<i>m</i> -Xylene	CF ₃ CO ₃ H	0°, CH ₂ Cl ₂	2,4-(70) and 2,6-(30) xylenol	5a
Anisole	CF ₃ CO ₃ H	0–10°, CH ₂ Cl ₂	<i>o</i> -(74) and <i>p</i> -(26) methoxyphenol	9
Anisole	(<i>p</i> -O ₂ NC ₆ H ₄ CO ₂) ₂ -AlCl ₃	22°, neat	<i>o</i> -(25) and <i>p</i> -(75) methoxyphenol	8
Anisole	Pb(OAc) ₄	80°, neat	<i>o</i> -(35) and <i>p</i> -(65) acetoxyanisole	11

^a Based on monooxygenated product.

suffered quantitative dealkylation under simulated reaction conditions at 0°.

Results from durene and pentamethylbenzene cannot validly be compared directly with the other data since *o*-dichlorobenzene solvent was used with these solid hydrocarbons. The diluent was found to exercise an important influence upon the ArOCO₂Pr-*i*/ArOH product ratio. Several experiments involving the mesitylene reaction proved conclusively that *o*-dichlorobenzene promotes loss of the alkyl group from the ester (Table III). Addition of the solvent decreased the ratio from 88:12 for the neat system to 59:41. Similarly, with mesityl isopropyl carbonate under

simulated reaction conditions, the presence of the haloaromatic lowered the ratio from 85:15 to 50:50. Rationalization of the observed effect may be found in the relatively high dielectric constant for *o*-dichlorobenzene (7.5) as compared with the values (2.3–2.6) for the aromatic hydrocarbons,²⁴ and possibly in solvation entailing the *n*-electrons of nuclear chlorine.

The reaction mixtures were next subjected to caustic hydrolysis in order to transform the ester stage completely to the phenolic form. Using this technique (Table IV) we observed quite attractive yields (66–76%) of monohydric phenols from anisole, mesitylene, and pentamethylbenzene. Moderately good results (48–52% yield) were obtained with durene, *m*-xylene, and toluene. Pseudocumene, *o*- and *p*-xylene, tetralin, and ethylbenzene gave the lowest yield values (15–34%). Only in the case of ethylbenzene and durene were there significant amounts of phenols formed by disproportionation. With few exceptions, *e.g.*, mesitylene, this method provides higher yields of monohydroxylated product than do the alternative techniques. Previous oxygenation procedures have generally been characterized by the formation of higher oxidation products from the simpler alkylbenzenes. This situation was particularly serious for those cases in which an unsubstituted position was present *ortho* or *para* to the oxygen introduced. Similar drawbacks have been noted with aromatic ethers, in addition to the undesirable feature of accompanying demethylation.¹⁴

Isomer distributions were determined for the phenolic products in order to obtain information concerning mechanistic features, particularly steric aspects. In addition, comparisons were made with other electrophilic oxygenations (Table V). Several specific aspects of the prior work should be noted. Orientation data from the reaction of trifluoroperacetic acid with toluene and anisole were obtained by extrapolation.⁹ Also, treatment of *m*-xylene with trifluoroperacetic acid^{5a} or hydrogen peroxide-boron trifluoride etherate^{4b}

yielded appreciable quantities of more highly oxidized materials, thus diminishing the usefulness of the reported distributions. From a scrutiny of the orientation data for the various oxygenating species in the different systems, one can arrange these electrophiles in the indicated order of decreasing size: Ac₂O-HNO₃ > (*i*-PrOCO₂)₂-AlCl₃ ≈ (*p*-O₂NC₆H₄CO₂)₂-AlCl₃ > Pb(OAc)₄ > CF₃CO₃H ≈ H₂O₂-BF₃. Other factors, such as activity, would also be expected to influence orientation.

(24) "International Critical Tables," Vol. VI, E. W. Washburn, Ed., McGraw-Hill Book Co., Inc., New York, N. Y., 1929.

Further insight in relation to the steric question was obtained by comparison of isomer distributions from our oxygenation reactions with the corresponding data for alkylation (Table VI). The electrophile from diisopropyl peroxydicarbonate-aluminum chloride exhibits a bulkiness smaller than that in *t*-butylation, but greater than the one involved in isopropylation.

Table VI. Orientation in Isopropylation and *t*-Butylation

Aromatic	Reagent ^a	Isomer distribution, %	Ref.
Toluene	<i>i</i> -PrCl	<i>o</i> : <i>m</i> : <i>p</i> = 47:15:38	<i>b</i>
Toluene	<i>t</i> -BuCl	<i>o</i> : <i>m</i> : <i>p</i> = 0:9:91	<i>b</i>
<i>o</i> -Xylene	<i>i</i> -PrBr	1,2,3:1,2,4 = 46:54	<i>c</i>
<i>o</i> -Xylene	<i>t</i> -BuBr ^d	1,2,3:1,2,4 = 0:100	<i>e</i>
<i>m</i> -Xylene	Propylene	1,2,3:1,3,4:1,3,5 = 16:74:10	<i>c</i>
<i>m</i> -Xylene	Isobutylene	1,3,5 = 100	<i>e</i>

^a With AlCl₃-CH₃NO₂. ^b P. Kovacic and J. J. Hiller, Jr., *J. Org. Chem.*, **30**, 1581 (1965). ^c G. A. Olah, S. H. Flood, S. J. Kuhn, M. E. Moffatt, and N. A. Overchuck, *J. Am. Chem. Soc.*, **86**, 1046 (1964). ^d With SnCl₄-CH₃NO₂. ^e G. A. Olah, S. H. Flood, and M. E. Moffatt, *ibid.*, **86**, 1060 (1964).

Since the system containing aluminum chloride as catalyst is heterogeneous at all times, attempts were made to procure quantitative data under homogeneous conditions. Using aluminum bromide as a promoter, we were able to effect homogeneity initially. However, some solid separated during the course of reaction. The cresol isomer distribution (*o*:*m*:*p* = 30:12:58) obtained under these conditions is similar to that (*o*:*m*:*p* = 34:11:55) observed with aluminum chloride.

In addition, competitive oxygenations involving various aromatic hydrocarbons were investigated (Table VII). In order to ascertain the accuracy of this method, experiments were carried out to establish whether or not the desired competition was being realized. Altering the relative concentrations of the aromatic competitors showed that the relative rate constant remained the same within experimental error on the assumption of a first-order dependence in aromatic (Table VII). Consequently, the observed relative rates appear to be real, representing direct competition of the substrates. The relative rate of oxygenation of *m*-xylene vs. benzene, calculated from $k_{m\text{-xylene}}/k_{\text{toluene}}$ and $k_{\text{toluene}}/k_{\text{benzene}}$, is 83. The average value of 16.8 for $k_{\text{toluene}}/k_{\text{benzene}}$ indicates a fairly active electrophile, which is consistent with the orientation data. With aluminum chloride the relative rate was lower, 9.6.¹⁵ Hence various lines of evidence deem it unlikely that extraneous phenomena such as surface effects play a significant role in oxygenation.

In certain cases a careful search was made for lower molecular weight organic products. After work-up, the anisole oxygenation mixture contained substantial amounts (about 50%) of isopropyl alcohol, together with trace amounts of isopropyl chloride. Both of these products were also present when pentamethylbenzene comprised the substrate. In addition, the effect of aluminum chloride on diisopropyl peroxydicarbonate was determined in more inert media such as cyclohexane (no oxygenation) and *o*-dichlorobenzene (only 5% oxygenation). Isopropyl alcohol was a

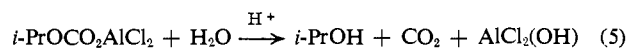
Table VII. Relative Rates of Oxygenation^a

ArH/ArH'	Molar ratio	Obsd. relative rate	$k_{\text{ArH}}/k_{\text{ArH}'}$
Toluene-benzene	1/1	16.5	16.5
Toluene-benzene	1/1	17.2	17.2
Toluene-benzene	1/3	5.10	15.3
Toluene-benzene	1/3	5.23	15.7
Toluene-benzene	1/6.4	2.87	18.4
Toluene-benzene	1/6.4	2.78	17.8
			Av. 16.8
<i>m</i> -Xylene-toluene	1/1	5.1	5.1
<i>m</i> -Xylene-toluene	1/1	4.8	4.8
			Av. 4.9
<i>m</i> -Xylene-toluene ^b	1/1	9.0	9.0
<i>m</i> -Xylene-toluene ^b	1/1	6.8	6.8
<i>m</i> -Xylene-toluene ^b	1/3	2.96	8.9
<i>m</i> -Xylene-toluene ^b	1/3	3.25	9.7
			Av. 8.6

^a See the Experimental Section. ^b In *o*-dichlorobenzene solvent.

major product (21–23%), accompanied by isopropyl chloride (5–11%) and small amounts of acetone (1–3%).

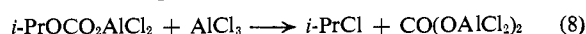
Several routes come to mind in connection with isopropyl alcohol formation.



Phenyl isopropyl carbonate is known to suffer loss of carbon dioxide to some extent in the presence of aluminum chloride.¹⁵ By analogy the indicated process may occur.

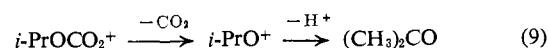


Generation of isopropyl chloride can be envisioned by a process entailing decomposition of a carbonate ester structure (eq. 8) or from reaction of isopropyl



alcohol with aluminum chloride.²⁵ Ease of alkylation by isopropyl chloride may be the reason why the highest yields of alkyl halide were obtained with the more inert substrates.

The trace quantities of acetone suggest limited participation of the illustrated transformations (eq. 9)



(the fully charged oxonium ion is used for simplicity). No acetone was detected from reactions with the more active aromatics.

In addition, quantitative studies were made of the gases, particularly carbon dioxide, which evolved during reaction and subsequent work-up. Several analytical methods were used. It is apparent from Table VIII that a relationship exists between aromatic structure and carbon dioxide evolution. The amount of gas liberated during reaction decreased with increasing activity of the aromatic substrate. Presumably there is competition between oxygenation and carbon dioxide formation. The material balance relative to CO₂ groups was ascertained (Tables VIII and IX). In general,

(25) J. F. Norris and B. M. Sturgis, *J. Am. Chem. Soc.*, **61**, 1413 (1939); however, note that more drastic conditions were used in the prior work.

this moiety was quite well accounted for on the basis of carbon dioxide formed during reaction and work-up, stable aryl isopropyl carbonate product, and unchanged peroxide.

Table VIII. Material Balance. CO₂ Groups^a

Reactant	CO ₂ groups, % ^b			Total
	Evolved During reaction	During hydrol- ysis	Present in ArOCO ₂ - Pr- <i>i</i>	
<i>o</i> -Dichlorobenzene	39	41	0	89 ^c
Toluene ^d	22	59	0	81
Ethylbenzene	18	52	0	70
Pentamethylbenzene	7	67	10	84
Cyclohexane	26	27	0	87 ^e

^a See gas evolution studies, method A. ^b Based on the stoichiometry: 2 moles of CO₂ per mole of peroxide. ^c Includes 9% present as unchanged peroxide. ^d See ref. 15. ^e Includes 34% present as unchanged peroxide.

Table IX. Material Balance. CO₂ Groups^a

Aromatic	CO ₂ groups, % ^b			Total
	Evolved During reaction	During hydrol- ysis	Present in ArOCO ₂ - Pr- <i>i</i>	
Mesitylene	13	56	30	99
Anisole	13	56	38	107

^a See gas evolution studies, method B. ^b Based on the stoichiometry: 2 moles of CO₂ per mole of peroxide.

It was previously established that aryl isopropyl carbonate-aluminum chloride can also act as a source of carbon dioxide to some degree.¹⁵ A more thorough investigation revealed that the extent of decarboxylation was fairly constant in the series, phenyl,¹⁵ tolyl, and *m*-xylenyl (Table X).

Table X. Material Balance. CO₂ Groups from Carbonate Esters^a

Ar in ArOCO ₂ Pr- <i>i</i>	CO ₂ groups, %			Total
	Evolved During reaction	During hydrol- ysis	Unchanged ArOCO ₂ - Pr- <i>i</i>	
Tolyl (<i>o</i> : <i>m</i> : <i>p</i> = 34:11:55)	19	91	0	110
<i>m</i> -Xylenyl	22	78	34	134

^a See gas evolution studies, method B.

Using the anisole reaction, we determined the effect of variation in reaction time on yield of products (Table XI). The data show that carbon dioxide is generated at a fairly steady rate during the 2–6 hr. interval even though the ester level remained unchanged. It is clear that in this system the ester does not serve as a generator of carbon dioxide. Iodometric analysis of the reaction mixture immediately after completion of peroxide addition (2 hr.) indicated no unreacted peroxide. Hence decomposition of diisopropyl peroxydicarbonate itself is not a likely pathway for the steady gas evolution observed. A possible precursor may well be *i*-PrOCO₂AlCl₂ (eq. 6).

Table XI. Effect of Time on Product Yield in Oxygenation of Anisole

Time, hr.	Product, % ^a					
	CO ₂	HCl	Anisyl- isopropyl carbonates		Isopropyl- anisoles	
			<i>o</i>	<i>p</i>	<i>o</i>	<i>p</i>
2	16	17	17	68	3.0	1.6
3	26	24	..	..	..	..
4	33	37	17	71	6.0	2.7
5	42	..	..	..	..	..
6	51	..	17	69	8.1	3.8
6 ^b	137	..	18	70	15	7
26 ^{c,d}	...	..	0	0	66	66

^a Based on moles of product per mole of peroxide (see gas evolution procedures). ^b After addition to ice-HCl. ^c 4 hr. at 0°, 22 hr. at 25°, then adding to ice-HCl. ^d *o*-(13%) and *p*-(54%) methoxyphenol were isolated.

An investigation was carried out on the nature of the nonoxygenated products formed from the aromatic reactants. Table XII summarizes the findings. Except for anisole and the higher alkylbenzenes, mono-isopropylated materials constituted the principal products arising from alkylation. Diisopropylation occurred to a limited extent in certain cases. The isopropyl groups in the starting peroxide are embodied in the aromatic substrates to varying extents: 71–93% for toluene,¹⁵ the xylenes and pseudocumene, 35%

Table XII. Neutral, Nonoxygenated, Aromatic Products

Aromatic reactant	Neutral, nonoxygenated, aromatic product		Isopropyl groups accounted for, % ^b
	Substituted benzene	mmoles ^a	
Toluene ^{c,d}	1-Methyl-3- <i>i</i> -propyl	146	93
	1-Methyl-3,5-di- <i>i</i> -propyl	20	
<i>o</i> -Xylene ^d	1,2-Dimethyl-4- <i>i</i> -propyl	156	84
	1,2-Dimethyl-3- <i>i</i> -propyl	2	
	1,3-Dimethyl-5- <i>i</i> -propyl	2	
	1,2,4-Trimethyl	5	
	Methyl	2	
	Unidentified products (2)	4	
<i>m</i> -Xylene	1,3-Dimethyl-5- <i>i</i> -propyl	91	71
	1,3-Dimethyl-4- <i>i</i> -propyl	38	
	Unidentified products (2)	6	
<i>p</i> -Xylene	1,4-Dimethyl-2- <i>i</i> -propyl	124	85
	1,3-Dimethyl-5- <i>i</i> -propyl	22	
	1,2,4-Trimethyl	37	
	1,2,4-Trimethyl-5- <i>i</i> -propyl	4	
	Methyl	14	
	Unidentified product	10	
Pseudocumene	1,2,4-Trimethyl-5- <i>i</i> -propyl	153	77
	1,2,4,5-Tetramethyl	10	
	1,3- and 1,4-dimethyl	7	
	1,2-Dimethyl	5	
Durene	1,2,3,4,5-Pentamethyl	59	35
	1,2,4-Trimethyl-5- <i>i</i> -propyl	55	
	Tetramethyl- <i>i</i> -propyl ^e	15	
	1,2,4-Trimethyl	5	
Pentamethyl- benzene	Hexamethyl	71	15
	1,2,4,5- and 1,2,3,5-tetra- methyl	28	
Anisole	Tetramethyl- <i>i</i> -propyl ^e	29	9
	1-Methoxy-2- <i>i</i> -propyl	11	
	1-Methoxy-4- <i>i</i> -propyl	6	

^a Per 100 mmoles of diisopropyl peroxydicarbonate (see General Procedure). ^b Based on the stoichiometry: two isopropyl groups per mole of peroxide. ^c See ref. 15. ^d Product yields based on isolation technique. ^e Tentative; identification based solely on infrared spectrum and g.l.p.c. retention time.

Table XIII. Fate of the Peroxide Isopropyl Groups^a

Aromatic reactant	Neutral, nonoxygenated, aromatic product, %	Oxygenated product, ArOCO ₂ -Pr- <i>i</i> , %	Isopropyl groups accounted for, %
Toluene ^b	93	0	93
<i>o</i> -Xylene	84	7	91
<i>m</i> -Xylene	71	10	81
<i>p</i> -Xylene	85	8	93
Pseudocumene	77	9	86
Durene	35	19	54 ^c
Pentamethylbenzene	15	11	26 ^d
Anisole	9	38	47 ^e

^a Based on the stoichiometry: two isopropyl groups per mole of peroxide (see General Procedure). ^b See ref. 15. ^c Isopropyl alcohol and isopropyl chloride yields not determined. ^d Qualitative detection of isopropyl alcohol (major) and isopropyl chloride (minor). ^e Approximately 50% of isopropyl alcohol was isolated.

for durene, 15% for pentamethylbenzene, and 9% for anisole. Steric factors, particularly important for durene and pentamethylbenzene, would influence the ease of alkylation.

Of course, the yield is also related to stability of the corresponding carbonate ester, ArOCO₂Pr-*i*. Inspection of Table XI shows that whereas the oxygenated product from anisole is present in high yield after 2 hr. and remains unchanged after 6 hr., isopropylation occurred to a much lesser degree and at a slow, steady rate. Presumably, this alkylation involves one or more agents derived from the anionic portion of the peroxide cleavage reaction, e.g., *i*-PrOCO₂AlCl₂, *i*-PrOAlCl₂, or *i*-PrCl. Experiments carried out under simulated reaction conditions demonstrated that isopropyl alcohol is not an alkylating agent. At a higher temperature and longer time (22 hr. at 25°, after 4 hr. at 0°), the yield of isopropylanisoles increased markedly, whereas the content of anisyl isopropyl carbonate decreased to 0%.

Isomerization and disproportionation reactions are involved in many instances during formation of the hydrocarbon products. Small amounts of unidentified, higher boiling material were usually present.

Isopropyl alcohol and isopropyl chloride account for some of the alkyl groups of the peroxide in the reactions with anisole and pentamethylbenzene. In addition, isopropyl groups are incorporated in ArOCO₂Pr-*i* to varying degrees. Therefore, several pathways delineate their fate. The gross accounting is presented in Table XIII. Recovery of these groups is greater than 80% in the case of toluene, the xylenes, and pseudocumene.

Experimental Section

Materials. The aromatic reagents and standards for analysis, which were usually subjected to gas chromatographic examination, possessed a purity of at least 98%. In general, they were commercial materials which were used directly. Phenol and the cresols were purified by distillation. Cyclohexane and *o*-dichlorobenzene (contained 10% of *para* isomer) were distilled from calcium hydride. We are grateful to the Pittsburgh Plate Glass Co. for generous samples of diisopropyl peroxydicarbonate.

Aromatic Oxygenation with Diisopropyl Peroxydicarbonate. General Procedure. The major portion of the aromatic reactant (1.5 moles total) was cooled to 0° in a three-neck flask equipped with stirrer, thermometer, gas inlet tube, gas collector, and addition funnel. After the apparatus was purged with nitrogen, a slow flow was maintained. Following introduction of aluminum chloride (0.2 mole), a solution of diisopropyl peroxydicarbonate (0.1 mole) in the remainder of the aromatic reagent was added slowly during 1.5 hr. at 0 ± 5° (exothermic reaction). In some cases the liberated hydrogen chloride was titrated with caustic (phenolphthalein indicator). After an additional 1.5 hr. at 0 ± 5°, the reaction mixture was mixed with concentrated hydrochloric acid (100 ml.) and crushed ice (500 g.). The solid was broken up, the layers were separated, and a small aliquot was taken from the organic layer for gas chromatographic analysis (g.l.p.c. column 1). After the aqueous fraction was extracted with ether, the organic solutions were combined, washed twice with 75-ml. portions of 0.1 *N* ferrous sulfate solution, and then freed of ether by evaporation. Hydrolysis was effected with 5% alcoholic potassium hydroxide (150 ml.) at reflux under nitrogen for 2 hr. After most of the ethanol was removed *in vacuo*, water was added, the mixture was thoroughly shaken, and the layers were separated. The organic fraction was extracted once more with 10% sodium hydroxide, the basic layers were combined and acidified with hydrochloric acid-ice. The free phenol was then extracted thoroughly with ether, the extract was dried, and the ethereal solution of the crude phenol was concentrated and subjected to gas chromatographic analysis (g.l.p.c. column 1) in order to obtain the composition of the phenolic product and the isomer distribution where applicable. In most cases the crude phenol was distilled under reduced pressure through a Bantamware distillation head containing a Vigreux column. There was usually less than 0.3 g. (7%) of distillation residue. The higher melting phenols (mesitol, durophenol, and pentamethylphenol) were obtained by crystallization.

Unless otherwise noted, yields of oxygenated products (phenols and carbonate esters) were based on the stoichiometry of 1 mole of oxygenated product per mole of peroxide (eq. 1). Yields were obtained by gas chromatographic analysis (g.l.p.c. column 1) on an aliquot of the reaction mixture both before and after hydrolysis of any carbonate ester present. Due to work-up losses, isolated yields of the phenolic products were usually 1–5% lower than those obtained by g.l.p.c. analysis. Because of incomplete solubility of pentamethylphenol, durophenol, and mesitol in aqueous caustic, Claisen's reagent (made by dissolving potassium hydroxide (28 g.) in water (20 ml.), and then diluting with methanol to 80 ml.) was used to extract these phenols. Nevertheless, the isolated yields of mesitol and pentamethylphenol were about 25% lower than those obtained by g.l.p.c. analysis.

o-Dichlorobenzene was used as a diluent in some reactions, *o*-dichlorobenzene–aromatic–aluminum chloride–peroxide = 15:5:2:1 (molar ratio). This haloaromatic was also used as a solvent when solid aromatics were oxygenated, usually with a 20:5:2:1 molar ratio of solvent–aromatic–aluminum chloride–peroxide.

Product Identification. A. Phenolic Products. The phenolic distillates (in some cases the crude phenolic extract was used) were analyzed by gas chromatography (g.l.p.c. column 1). Isomers were separated and collected. Identification was made by comparison with authentic materials (g.l.p.c. retention time and infrared spectrum).

B. Carbonate Esters. The carbonate esters formed in the oxygenations were obtained pure by gas chromatographic separation and collection before caustic hydrolysis of the reaction mixtures. In some of the mesitylene and anisole oxygenations the esters were isolated by distillation. In most cases comparison was made with authentic materials (Table II) (infrared spectrum and g.l.p.c. retention time). Alternatively, identification was based on the characteristic infrared spectrum²⁶ (strong C=O absorption, 5.6–5.75 μ ; strong C—O absorption, 7.8–8.0 μ) and on disappearance of the g.l.p.c. peak of the ester during hydrolysis accompanied by enhancement of the corresponding phenol peak.

C. Nonoxygenated Aromatic Products. Distillation of the neutral organic material was carried out in all cases except for the durene and pentamethylbenzene reactions. After unchanged starting material was removed, the residue was fractionated *in vacuo*. Some components were obtained in pure form, whereas others were subsequently collected by gas chromatography. Comparison with authentic materials was made (infrared spectrum, index of refraction, g.l.p.c. retention time, and in some cases the n.m.r. spectrum). In this manner the isopropyltrimethylbenzenes (we are grateful to Professor R. M. Roberts for the infrared spectra), isopropylxylenes, isopropylanisoles, and disproportionated products were identified (Table XII). Analysis of the neutral fraction from the oxygenation of mesitylene indicated that the major nonoxygenated product was 5-isopropyl-1,2,4-trimethylbenzene and that a minor component was 2-isopropyl-1,3,5-trimethylbenzene. However, four other components were not identified. The neutral products from the tetralin reactions were not characterized.

D. Low-Boiling Products. The reaction mixture was stirred with distilled ice-hydrochloric acid, and the layers were separated carefully. An aliquot of the organic fraction was analyzed iodometrically, and the peroxide was found to be essentially 100% decomposed in most cases. Both the organic and aqueous fractions were distilled carefully under atmospheric pressure, and the components boiling under 100° were collected. The distillates then were analyzed (g.l.p.c. column 2). The products, which were separated and collected by g.l.p.c., were compared with authentic samples (infrared spectrum). This technique was used to analyze low-boiling material formed in the reactions of diisopropyl peroxydicarbonate with anisole, pentamethylbenzene, *o*-dichlorobenzene, and cyclohexane. The major product in all cases was isopropyl alcohol. Isopropyl chloride was found in trace amounts with anisole, and in larger amounts with the other three reactants. In addition, traces of acetone and another product which was not identified were found with *o*-dichlorobenzene and cyclohexane.

(26) J. L. Hales, J. I. Jones, and W. Kynaston, *J. Chem. Soc.*, 618 (1957).

Carbon Dioxide Analysis. Method A. 1. From Diisopropyl Peroxydicarbonate-Aluminum Chloride-Aromatic. The general procedure was followed. The gases were swept out with nitrogen into a potassium hydroxide solution which was then titrated (pH meter). Carbon dioxide content was calculated from the volume of acid required to neutralize bicarbonate. The amount of hydrochloric acid generated was obtained from the difference between the initial and final total alkalinity of the potassium hydroxide solution. In this manner it was possible to determine the amount of both gases simultaneously.

At the end of the desired reaction time, ice-hydrochloric acid was slowly added to the reaction mixture. The evolved gas was trapped in fresh caustic solution and analyzed.

2. From Sodium Bicarbonate. Sodium bicarbonate (4.2 g., 0.05 mole) in 100 ml. of water was treated during 1 hr. at 0° with excess dilute hydrochloric acid, and the solution was stirred for 2 hr. The carbon dioxide in duplicate runs amounted to 0.044 mole (88%) and 0.041 mole (82%).

Method B. 1. From Aryl Isopropyl Carbonate-Aluminum Chloride-Aromatic. The carbonate ester (0.02 mole) in 25 ml. of the aromatic was added to aluminum chloride (0.04 mole) in the remainder of the aromatic (0.6 mole) at 0° during 1.5 hr. The reaction mixture was stirred for an additional 1.5 hr. No nitrogen was introduced. The gas outlet tube led into an inverted graduated cylinder (2 l.) filled with a 75% saturated solution of sodium sulfate. Carbon dioxide content was calculated by measuring the amount of solution displaced from the graduated cylinder, assuming the perfect gas law and correcting to standard temperature and pressure.

A mixture of ice-hydrochloric acid was then added slowly to the reaction mixture during 1 hr., and the gas was collected. Carbon dioxide evolution from these two stages is presented for various aromatics in Table X.

2. From Sodium Bicarbonate. Sodium bicarbonate (8.4 g., 0.1 mole) in 100 ml. of water was treated during 1.5 hr. at 0° with excess dilute hydrochloric acid, and the solution was stirred for another 1.5 hr. The carbon dioxide, determined in duplicate runs, amounted to 0.098 mole (98%) and 0.096 mole (96%).

Authentic Isopropylxylenes. Five isopropylxylene isomers were prepared by the procedure of Nightingale and Carton.²⁷ Fractional distillation and gas chromatographic separation and collection were used to obtain pure samples (Table XIV). Isopropylation of *m*-xylene led to formation of 4-isopropyl-1,3-dimethylbenzene as the major product together with 5-isopropyl-1,3-dimethylbenzene and a higher boiling material as minor products. *o*-Xylene gave equal amounts of 4-isopropyl- and 3-isopropyl-1,2-dimethylbenzene along with a substantial amount of higher molecular weight product. In the case of *p*-xylene, 2-isopropyl-1,4-dimethylbenzene was the minor product, plus major quantities of less volatile substances.

Aryl Isopropyl Carbonate-Aluminum Chloride-Aromatic. The carbonate ester (0.02 mole) in 25 ml. of the

(27) D. Nightingale and B. Carton, Jr., *J. Am. Chem. Soc.*, 62, 280 (1940).

Table XIV. Isopropylxylenes

x, x' in x, x' - (CH ₃) ₂ - C ₆ H ₃ CH- (CH ₃) ₂	Characteristic infrared bands, cm. ⁻¹	n_D^{20}		G.l.p.c. retention time, min. ^a
		Obsd., 24°	Lit., 20° ^b	
2,3	782(s), 717(s)	1.5093	1.5102	13.6
3,4	815(s), 716(m), 878(m)	1.4988	1.4991 ^c	11.6
3,5	843(s), 702(s) ^d	1.4943	1.4950	8.8
2,4	813(s), 870(w)	1.5003	1.5013	10.6
2,5	806(s), 880(w), 730(w)	1.5008	1.5010	10.0

^a G.l.p.c. column 1, 180°, 85 ml. of helium/min. ^b A. U. Topchiev, R. N. Volkov, and S. U. Zavgorodnii, *Dokl. Akad. Nauk SSSR*, **134**, 844 (1960). ^c A. Klages and F. Sommer, *Ber.*, **39**, 2306 (1906). ^d 846 (s), 703 (s), F. D. Rossini, K. Li, and R. B. Ries, American Petroleum Institute Research Project 44, 1956, Ser. No. 1765.

aromatic was added to aluminum chloride (5.4 g., 0.04 mole) in the remainder of the aromatic (0.6 mole) at 0° during 1.5 hr. Hydrochloric acid was bubbled into the solution periodically during the total reaction time of 3 hr. The reaction mixture was stirred with hydrochloric acid (25 ml.) and crushed ice (100 g.), and the organic layer was separated and subjected to analysis (g.l.p.c. column 1).

Competitive Oxygenations. General Procedure. The two aromatic reactants were mixed together in the desired molar ratios (2 moles total). Diisopropyl peroxydicarbonate (0.02 mole) was dissolved in a 50-ml. portion of this mixture. Aluminum bromide (0.045 mole) was dissolved in the remainder in a drybox, and the resulting solution was placed in a 1-l., three-neck flask equipped with stirrer, addition funnel, thermometer, gas inlet, and gas collector. A slow stream of nitrogen was maintained through the system. The peroxide solution was then added during 15 min. at 0 ± 3°. The mixture turned black and a solid formed. After an additional 15 min. the reaction mixture was worked up in the usual manner. The crude phenolic products were analyzed (g.l.p.c. column 3).

When *o*-dichlorobenzene solvent was employed, a solution of diisopropyl peroxydicarbonate in 1 mole of the halobenzene was added to the aromatic reactants, aluminum bromide, and *o*-dichlorobenzene (1 mole).

Analytical Procedures. A. Gas Chromatography. An Aerograph A-90-P gas chromatograph was used:

copper columns, block temperature 250°, injector temperature 300°, bridge current 180 ma.; sample size 5–40 μl. with the appropriate attenuations. Column 1 was 10 ft. × 0.25 in., 15% Apiezon L on acid-washed Chromosorb P (35–80 mesh), 150–250°, 60–90 ml. of helium/min. Column 2 was 10 ft. × 0.25 in., 15% Carbowax 20M on Chromosorb P (30–60 mesh); 110°, 60 ml. of helium/min. Column 3 was 11 ft. × 0.25 in., 15% Apiezon L on acid-washed Chromosorb P (30–60 mesh), 220°, 70 ml. of helium/min.

B. For Peroxides. An iodometric method²⁸ was used. The commercial diisopropyl peroxydicarbonate exhibited a purity of 95% based on this procedure.

C. For Phenolic Products. The isomer distributions of the cresols were determined by infrared spectroscopy (cyclohexane solvent) with a Beckman IR 8 spectrophotometer according to the previous method.¹⁵

The isomer distributions of the products from anisole, *o*- and *m*-xylene, tetralin, and pseudocumene were obtained by g.l.p.c. analyses (g.l.p.c. column 1). Known mixtures of the various isomeric phenolic products were prepared in the corresponding aromatic reactant. A plot was made of the peak area ratio vs. the concentration ratio, and the data from the various product mixtures were compared to this plot. Analyses of the phenol-cresol, cresol-*m*-xylenol, and phenol-*m*-xylenol mixtures obtained from competitive oxygenation experiments were done in a similar manner (g.l.p.c. column 3).

D. For Product Yields. Solutions of either trichlorobenzene or pentamethylbenzene in the aromatics were used as internal standards to determine yields of the various reaction products (phenols, carbonate esters, and neutral substances). Solutions of the authentic reaction products of known concentration were prepared and mixed in various proportions with the internal standard solution. Plots were made of the peak area ratio vs. concentration ratios of product to marker. Then an aliquot of the reaction mixture was diluted 1:1 with the internal standard solution, and the product:standard ratios compared to the plots. The data are recorded in Tables I, III, IV, XI, and XII.

Acknowledgment. We are grateful to the National Science Foundation for support of this work.

(28) F. Strain, W. E. Bissinger, W. R. Dial, H. Rudoff, B. J. DeWitt, H. C. Stevens, and J. H. Langston, *J. Am. Chem. Soc.*, **72**, 1254 (1950).