Electrophilic Properties of Benzoyloxy Radicals

MICHAEL E. KURZ[1a]

Department of Chemistry, Illinois State University, Normal, Illinois 61761

MARIA PELLEGRINI[1b]

Department of Chemistry, Columbia University, New York, New York 10027

Received July 31, 1969

Free-radical aromatic substitution by oxy radicals of the type $p\text{-}XC_6H_4CO_2\cdot$, where X = NO_2, H, or CH_3, was carried out with a series of aromatics. The oxy radicals were generated by the copper-catalyzed decomposition of the corresponding peroxide, $(p\text{-}XC_6H_4CO_2)_2$, at 60°. Yields of aryl benzoates, $p\text{-}XC_6H_4CO_2Ar$, ranged from *ca.* 20% with chlorobenzene to *ca.* 80% with anisole. Isomer distributions and relative rates of reaction were determined. From this data, partial rate factors for substitution by these radicals on anisole, toluene, and chlorobenzene were calculated. A plot of these factors *vs.* σ^+ substituent constants gave ρ values of −2.52, −1.61, and −1.28 for aromatic substitution by $p\text{-}O_2NC_6H_4CO_2\cdot$, $C_6H_5CO_2\cdot$, and $p\text{-}CH_3C_6H_4CO_2\cdot$, respectively. The effect of the *para* substituents on the degree of electrophilic character of the benzoyloxy radicals is in keeping with their normal electronic influences. A comparison of this system is made to the effect of substituents on the polarity of phenyl radicals.

Aromatic substitution reactions have often proven useful in qualitative and quantitative studies of the polar characteristics of free radicals.[2,3] By their reactivities in ring substitution, carbon radicals have been shown to be electrophilic, nucleophilic, or neutral, depending on the nature of the groups attached to the odd electron-bearing carbon. For example, methyl[2a,4] and cyclohexyl[5] radicals are nucleophilic, whereas trichloromethyl,[6] triphenylmethyl,[3a] and appropriately substituted phenyl radicals[2b,7] display electrophilic tendencies to varying extents.

This same technique, as well as other evidence,[8] has been used to demonstrate that oxy radicals are generally electrophilic;[9,10] yet little systematic work on the effect of varying the group attached to the oxy-radical site has been done.

Recently, a smooth method of intermolecular free-radical oxygenation of the type shown in eq 1 was

$$(RCO_2)_2 + ArH \xrightarrow{CuX_2} RCO_2Ar + RCO_2H \qquad (1)$$

$$R = i\text{-}C_3H_7O \text{ or } C_6H_5$$

discovered.[11] The salient step of the reaction involved addition to the ring by the oxy radical[12] followed by rapid conversion into product by a metal salt oxidant

$$RCO_2\cdot + ArH \underset{k_{-1}}{\overset{k_1}{\rightleftharpoons}} RCO_2ArH\cdot \underset{k_2}{\xrightarrow{CuCl_2}} RCO_2Ar + HCl + CuCl \qquad (2)$$

(eq 2). With cupric chloride, k_2 was shown to be much faster than k_{-1}, as evidenced by the complete lack of an isotope effect in the substitution process.[11c] Thus the aromatic ester product obtained gives a fairly reliable index of the reactivity pattern of the radical toward the aromatic compound, making this system appealing for further studies of oxy-radical behavior.

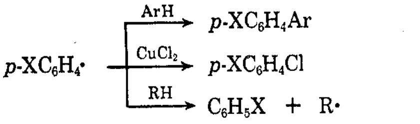
The purpose of this work was to quantitatively study the effects of substituents, X, on the electrophilic nature of benzoyloxy radicals, $p\text{-}XC_6H_4CO_2\cdot$, as gauged by their substitution reactions with a series of aromatic hydrocarbons.

Results

A series of substituted benzoyl peroxides, $(p\text{-}XC_6H_4CO_2)_2$, where X = NO_2, H, and CH_3, were synthesized and their cupric chloride catalyzed decomposition was carried out with toluene, chlorobenzene, and anisole in acetonitrile solution. *p,p'*-Dimethylbenzoyl peroxide was also allowed to react with acetophenone. The yields of the corresponding aryl benzoates as well as their isomer distributions are shown in Table I.

Other reaction products were analogous to those reported in an earlier study[11b] and are accounted for by decarboxylation of the benzoyloxy radical (eq 3) followed by the usual reactions of the resulting phenyl radical (eq 4–6).

$$p\text{-}XC_6H_4CO_2\cdot \longrightarrow p\text{-}XC_6H_4\cdot + CO_2 \qquad (3)$$



$$p\text{-}XC_6H_4\cdot \xrightarrow{ArH} p\text{-}XC_6H_4Ar \qquad (4)$$

$$p\text{-}XC_6H_4\cdot \xrightarrow{CuCl_2} p\text{-}XC_6H_4Cl \qquad (5)$$

$$p\text{-}XC_6H_4\cdot \xrightarrow{RH} C_6H_5X + R\cdot \qquad (6)$$

The decarboxylation reaction competed more strongly with oxygenation in the studies with the less reactive

---

[1] (a) To whom correspondence should be addressed at Illinois State University; (b) National Science Foundation Undergraduate Summer Research Participant, 1968.

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

[3] D. H. Hey in "Advances in Free Radical Chemistry," Vol. II, G. H. Williams, Ed., Logos Press, London, 1968, p 47.

[4] Recently, a reexamination has shown that methyl radical is slightly electrophilic (ρ = −0.1): W. A. Pryor, U. Tonellato, D. L. Fuller, and S. Jumonville, *J. Org. Chem.*, **34**, 2018 (1969).

[5] J. R. Shelton and C. W. Uzelmeier, *J. Amer. Chem. Soc.*, **88**, 5222 (1966).

[6] C. Walling, "Free Radicals in Solution," John Wiley & Sons, Inc., New York, N. Y., 1957, p 255.

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

[8] W. T. Dixon, R. O. C. Norman, and A. L. Buley, *J. Chem. Soc.*, 3625 (1964).

[9] R. O. C. Norman and J. R. Lindsay Smith in "Oxidases and Related Redox Systems," Vol. I, T. E. King, H. S. Mason, and M. Morrison, Ed., John Wiley & Sons, Inc., New York, N. Y., 1965, p 131.

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

[11] (a) M. E. Kurz and P. Kovacic, *J. Amer. Chem. Soc.*, **89**, 4960 (1967); (b) M. E. Kurz and P. Kovacic, *J. Org. Chem.*, **33**, 1950 (1968); (c) M. E. Kurz, P. Kovacic, A. K. Bose, and I. Kugajevsky, *J. Amer. Chem. Soc.*, **90**, 1818 (1968).

[12] Complete scrambling of the labeled oxygen in the aryl benzoate obtained from the system *p*-xylene-copper chloride-benzoyl peroxide-carbonyl-^{18}O [C. G. Reid and P. Kovacic, *J. Org. Chem.*, **34**, 3308 (1969)] as well as orientation similarities for the ester from runs with and without added copper salt[11c] indicated that the free oxy radical and not a radical-metal complex was the most likely attacking entity.

TABLE I

OXYGENATION IN THE SYSTEM BENZOYL PEROXIDE–COPPER CHLORIDE–AROMATIC COMPOUND

$(p\text{-}XC_6H_4CO_2)_2$, X	Aromatic compd	Aryl benzoates			
			Isomer distribution		
		Yield, %[b]	*ortho*	*meta*	*para*
NO_2	Toluene	47	58	18	24
NO_2	Anisole	89	66	<1	34
NO_2	Chlorobenzene	17	52	15	33
H	Toluene	41	56	19	25
H	Anisole	76	67	<1	33
H	Chlorobenzene	23	52	16	32
CH_3	Toluene	38	52	22	26
CH_3	Anisole	76	67	<1	33
CH_3	Chlorobenzene	25	47	21	32
CH_3	Acetophenone[c]	*d*	36	50	14

[a] Aromatic compound/benzoyl peroxide/$CuCl_2$ ratio = 30:1:0.3, trace of CuCl added, acetonitrile solvent, 60°. [b] Based on moles of product per mole of peroxide consumed. [c] Determined after hydrolysis to the phenols. [d] Not determined.

TABLE II

Relative Rates of Oxygenation with $p\text{-}XC_6H_4CO_2\cdot$

$(p\text{-}XC_6H_4CO_2)_2$, X	Aromatic compd	$k_{ArH}/k_{C_6H_6}$[a]		
		$[ArH]/[C_6H_6] = 1.0$	$[ArH]/[C_6H_6 = 0.2$	Avg
NO_2	Toluene	4.25	4.19	4.22
NO_2	Anisole	8.30	8.68	8.49
NO_2	Chlorobenzene	0.28	0.30	0.29
H	Toluene	2.54	2.40	2.47
H	Anisole	10.22	10.33	10.28
H	Chlorobenzene	0.49[b]	0.52	0.51
CH_3	Toluene	2.00	2.16	2.08
CH_3	Anisole	13.56	12.97	13.27
CH_3	Chlorobenzene	0.64[b]	0.58	0.61
CH_3	Acetophenone	0.27[b,c]	0.32[c]	0.30

[a] All values are the average of two runs corrected for concentration. The error involved ranged from ±0.03 to 0.08. [b] $[ArH]/[C_6H_6] = 0.1$. [c] Determined after hydrolysis to the phenols.

aromatics. Another process, hydrogen abstraction by the benzoyloxy radical, took place to a minor extent.[11b] In all cases these side reactions did not adversely affect the ring substitution process data.

To determine the relative rates of oxy-radical substitution, mixtures of aromatics were allowed to compete for a limited amount of peroxide. Table II symmarizes these results with the same series of hydrocarbons compared with benzene.

Partial rate factors were determined for the effect of substituents upon ring substitution by the three oxy radicals (Table III).

TABLE III

PARTIAL RATE FACTORS (*F*) FOR $p\text{-}XC_6H_4CO_2\cdot$ ATTACK

Aromatic substituent	*F* for $p\text{-}XC_6H_4CO_2\cdot$		
	$X = NO_2$	X = H	$X = CH_3$
m-CH_3	2.28	1.41	1.37
p-CH_3	6.08	3.70	3.24
p-OCH_3	17.35	20.03	25.4
m-Cl	0.13	0.25	0.38
p-Cl	0.57	0.98	1.17
m-$COCH_3$	...	...	0.44
p-$COCH_3$	...	...	0.25

The logarithms of the partial rate factors were plotted against σ^+ values (both established[13] and recently revised[14] values were used). A computerized least-squares treatment was used to determine the ρ values (Table IV).

TABLE IV

CALCULATED ρ VALUES FOR RING SUBSTITUTION

Radical	Brown's[a] σ^+		Swain's[b] σ^+	
	ρ	Avg deviation in log F[c]	ρ	Avg deviation in log F[c]
$p\text{-}CH_3C_6H_4CO_2\cdot$	−1.28[d,e]	0.047	−1.32[d,f]	0.038
$C_6H_5CO\cdot$	−1.61	0.044	−1.88	0.025
$p\text{-}O_2NC_6H_4CO_2\cdot$	−2.52[d]	0.058	−2.71[d]	0.104

[a] Reference 13. [b] Reference 14. [c] Deviation from calculated slope. [d] Corrected values, disregarding log $F_{p\text{-}OCH_3}$. [e] Used $F_{m\text{-}COCH_3}$. [f] Used $F_{m\text{-}COCH_3}$ and $F_{p\text{-}COCH_3}$.

A poor fit to the best straight line was noted for the log $F_{p\text{-}OCH_3}$ value for both the *p*-nitro- and *p*-methylbenzoyloxy radicals; so this value was not used in these slope computations. We are unable to determine the reason for this anomalous behavior at this time. Both sets of σ^+ constants gave calculated slopes from which the average point deviation was quite small. Slightly higher negative ρ values were obtained using Swain's values.[14]

We obtained a much better correlation using σ^+ rather than σ substituent values, indicating that resonance stabilization of oxy radical–aromatic adduct plays an important role.

On the basis of the $\rho\sigma$ treatment, it can be seen that the electrophilicity of the oxy radicals lies in the order $p\text{-}O_2NC_6H_4CO_2\cdot > C_6H_5CO_2\cdot > p\text{-}CH_3C_6H_4CO_2\cdot$. These results are consistent with the normal polar effects attributed to the nitro and methyl groups.[13a]

---

[13] (a) J. Hine, "Physical Organic Chemistry," 2nd ed, McGraw-Hill Book Co., Inc., New York, N. Y., 1962, pp 87, 90; (b) H. C. Brown and Y. Okamoto, *J. Amer. Chem. Soc.*, **80**, 4979 (1958).

[14] C. G. Swain and E. C. Lupton, Jr., *ibid.*, **90**, 4328 (1968).

As expected from structural considerations, all three radicals are appreciably more electron deficient than the hydroxyl radical ($\rho = -0.41$[10]).[15] Only the *p*-nitrobenzoyloxy radical is more polar than the isopropyl carbonate radical ($\rho = -2.30$[16]), however.

A comparison with the more thoroughly studied *t*-butoxy radical indicates that aroyloxy radicals are more effective in adding to unsaturated systems,[17] whereas *t*-butoxy radicals are more inclined toward hydrogen abstraction from donor molecules.[6] While there are basic differences in structure and in the cleavage reaction that each undergoes, it would appear the greater electrophilicity in the radical favors addition reactions compared with hydrogen abstraction. In light of the attraction of electrophiles to electron-rich π clouds, this is not unexpected. Thus differences in the polarity of radicals brought about by changes in structure can be very important in determining the mode of chain-transfer reactions of oxy radicals.

It is interesting to compare the effect of substituents in this system with their effect on the phenyl radical. The ρ values for aromatic substitution by the *p*-methylphenyl, phenyl, and *p*-nitrophenyl radicals, respectively, were 0.03, 0.05, and -0.81.[7] Comparable values were also found for abstraction from hydrogen donors by these same radicals.[17,18] Thus the corresponding oxy radicals are considerably more sensitive to substituent effects in the aromatic compound than are the phenyl radicals. This is in line with a recent report concerning polar effects in the addition to monomers by phenyl and benzoyloxy radicals.[19] The *p*-methyl substituent has more of an influence on the oxy radical than it does on the phenyl radical, while the *p*-nitro group has a fairly marked effect on both.

Experimental Section

Benzoyl peroxide (Lucidol) was recrystallized from chloroform-methanol before use. The substituted peroxides were prepared from sodium peroxide and the appropriate acid chloride[20] and analyzed for purity by standard procedures.[21] *p*-*p'*-Dinitrobenzoyl peroxide, mp 156° (lit.[20] mp 156°), was 99.6% pure, while *p,p'*dimethylbenzoyl peroxide, mp 139–140° (lit.[22] mp 136°), was 98.6% pure.

The aromatic hydrocarbons were checked for purity by vpc and used directly.

General Reaction.—The procedure used was essentially the same as described earlier,[11a] except that the amount of solvent had to be expanded to allow for the lower solubility of the substituted peroxides. A larger scale reaction was carried out with each peroxide in the presence of each aromatic compound to allow for product isolation and identification upon work-up. Reactions were carried out with or without stirring (no difference) in a constant-temperature bath at 60 ± 0.5°. Aliquots were periodically removed for titration to determine peroxide content, against a salt-solution blank. The reaction was considered complete when all the peroxide was consumed. Total reaction time ranged from 18 hr for *p,p'*-dimethylbenzoyl peroxide to 23 hr for *p,p'*-dinitrobenzoyl peroxide. For reactions involving the latter peroxide a small amount of an insoluble cupric salt precipitated from solution; the other reactions were homogeneous throughout. Reaction work-up was carried out as before.

Products were separated and analyzed by vpc using Varian Aerograph Models 90-P and Hy-Fi with 20% SE-30 on 60-80 firebrick columns. The products were compared with authentic aryl benzoates (which were synthesized from the appropriate phenol and acid chloride in the presence of pyridine or sodium hydroxide) by ir spectra and vpc retention time. In a few cases where authentics were not available, the vpc traces were so similar to analogous reactions that identity of the particular products was assumed.

Smaller scale reactions were carried out for 24 hr for the determination of yields, isomer distributions, and relative rates. A known amount of the appropriate authentic phenyl benzoate was added as an internal marker just before reaction work-up to determine yields. Quantitative determinations of isomer distributions, relative rates, and product yields were carried out after calibration for peak areas with three mixtures containing varying amounts of authentic ester products. Competition runs were done in duplicate as well as at two different ratios of benzene to substituted benzene substrate using a large excess of both.

The aryl esters from acetophenone could not be analyzed directly by vpc, but were hydrolyzed to the hydroxyacetophenones. Quantitative analysis of the phenols was done on a Beckman GC-2A using an SE-30 on firebrick column. Control runs done on mixture of the authentic esters indicated that the hydrolysis method was quantitative.

Registry No.—p-$O_2NC_6H_4CO_2\cdot$, 14337-48-5; $C_6H_5CO_2\cdot$, 1854-28-0; p-$CH_3C_6H_4CO_2\cdot$, 23074-26-2.

Acknowledgment.—We are grateful to the National Science Foundation Summer Research Program for partial support of this work, and to Professor Cheves Walling for his advice and the use of his facilities. We wish to thank Dr. Max Taylor for his assistance with the computerized least-squares treatment.

---

[15] The low selectivity of the hydroxyl radical may be due more to the very high rate and low activation energy of the reaction (which is almost diffusion controlled) than to a lower electron deficiency (our thanks to Professor Cheves Walling for this suggestion).

[16] P. Kovacic, C. G. Reid, and M. E. Kurz, *J. Org. Chem.*, **34**, 3302 (1969).

[17] R. F. Bridger and G. A. Russell, *J. Amer. Chem. Soc.*, **85**, 3754 (1963).

[18] W. A. Pryor, J. T. Echols, Jr., and K. Smith, *ibid.*, **88**, 1189 (1966).

[19] J. C. Bevington and R. Ito, *Trans. Faraday Soc.*, **64**, 1329 (1968).

[20] C. C. Price and E. Krebs, *Org. Syn.*, **23**, 65 (1943).

[21] L. S. Silbert and D. Swern, *J. Amer. Chem. Soc.*, **81**, 2364 (1959).

[22] A. T. Blomquist and A. J. Buselli, *ibid.*, **73**, 3883 (1951).