Tetrahedron. Vol 26, pp. 4603 to 4607. Pergamon Press 1970. Printed in Great Britain

SUBSTITUENT EFFECT ON *p*-SUBSTITUTED BENZOYLATION OF BENZENE*

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(*Received in Japan* 22 *April* 1970; *Received in the UK for publication* 30 *June* 1970)

Abstract—Substituent effect on *p*-substituted benzoylation of benzene catalysed by aluminium chloride has been studied in ethylene chloride, 1,1,2,2-tetrachloroethane or nitrobenzene at 50°. In ethylene chloride or tetrachloroethane, the reactivity of *p*-substituted benzoyl chloride increased in the following order: methyl < none < chloro < nitro substituent, with Hammett's ρ^+ of 1·3 or 1·4, respectively. The data in a nitrobenzene solution did not fit the Hammett relationship, and this is probably due to the complex formation between aluminium chloride and nitrobenzene.

IT HAS been reported that the Friedel–Craft acylation may depend not only on the reactivity of the aryl compound as an electron donor, but also on that of the acylating agent or its aluminium chloride coordination complex as an electron acceptor. Thus far, the kinetic studies on the acylation have dealt almost exclusively with the reactivity of the aryl compounds.[1] A few examples concerning the reactivity of the acylating agent have resulted in a rough comparison of the acylating agents, i.e., the decreasing order of chlorides is: benzoyl > butyryl > propionyl > acetyl.[2] In another study on substituted benzoylation of toluene in chlorobenzene, the effect of a *p*-substituent has been reported to give no linear relationship against the Hammett σ value.[3] The present study was undertaken to determine quantitatively the effect of a *p*-substituent of benzoyl chloride on the rate of benzoylation of benzene and to elucidate its mechanism.

$$p\text{-X-C}_6\text{H}_4\text{-COCl} + \text{C}_6\text{H}_6 \xrightarrow{\text{AlCl}_3} p\text{-X-C}_6\text{H}_4\text{-CO-C}_6\text{H}_5 + \text{HCl} \qquad (1)$$
$$(\text{X} = \text{-H}, \text{-NO}_2, \text{-Cl}, \text{-CH}_3)$$

Usually, the kinetics of acylation have been studied either by gravimetric analysis of isolated products or by titrimetry of the residual acid halides.[4–6] As the purity of aluminium chloride, solvent, reaction temperature and other conditions[7] affect the reactions, it is difficult to determine acylation rate under identical conditions.

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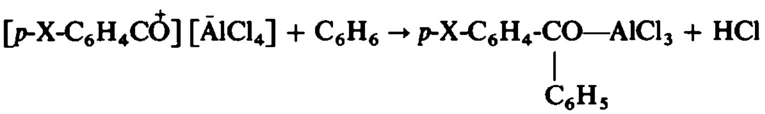
* Contribution No. 154.

Consequently a competitive reaction was used for *p*-substituted benzoylation toward benzene. Thus, *p*-substituted and unsubstituted benzoyl chlorides competed for benzene in the presence of aluminium chloride in ethylene chloride, tetrachloroethane, or nitrobenzene and the relative rate constants were determined from the ratio of the two benzophenones. Brown *et al.* have shown[8] that the benzoylation reaction exhibits simple second-order kinetics, i.e.,

$$v = k[\mathrm{ArCOCl \cdot AlCl_3}][\mathrm{PhH}] \qquad (2)$$

Here, k is essentially independent of the initial concentration of the reactants. In view of this rate law, the reaction mechanism may be Eq 3.

$$p\text{-X-}\mathrm{C_6H_4COCl} + \mathrm{AlCl_3} \rightleftharpoons [p\text{-X-}\mathrm{C_6H_4C}\overset{+}{\mathrm{O}}][\overset{-}{\mathrm{Al}}\mathrm{Cl_4}] \qquad (3a)$$



$$[p\text{-X-}\mathrm{C_6H_4C}\overset{+}{\mathrm{O}}][\overset{-}{\mathrm{Al}}\mathrm{Cl_4}] + \mathrm{C_6H_6} \rightarrow p\text{-X-}\mathrm{C_6H_4\text{-}}\underset{\mathrm{C_6H_5}}{\underset{|}{\mathrm{CO}}}\mathrm{\!-\!AlCl_3} + \mathrm{HCl} \qquad (3b)$$

When each a moles/l of substituted benzoyl chloride and benzoyl chloride were allowed to compete for a moles/l of benzene in the presence of $2a$ moles/l of aluminium chloride, the following equations are obtained, where x and y represent benzoyl chlorides with respective rate constants of k_1 and k_2 after time t.

$$\mathrm{d}x/\mathrm{d}t = k_1(a - x)(a - x - y) \qquad (4)$$

$$\mathrm{d}y/\mathrm{d}t = k_2(a - y)(a - x - y) \qquad (5)$$

Integration of Eq 5 divided by Eq 4 leads to the relative rate constant.

$$k_{\mathrm{rel}} = k_2/k_1 = \log[(a - y)/a]/\log[(a - x)/a] \qquad (6)$$

The analysis of the products by GLC gives the values of x and y and hence the individual rate constants.

Since it has been reported that the ratio of products in the Friedel–Crafts acylation may vary with the order of addition of reactants, benzene was a final addendum to a solution of acid halides and aluminium chloride.[9] The reaction was carried out in a homogeneous system except for *p*-nitrobenzoyl chloride in tetrachloroethane.

The values of rate constants relative to unsubstituted benzoyl chloride are summarised in Table 1. These data indicate that in a non-polar solvent such as ethylene chloride the reactivity of the acid chlorides increase with increasing order of electron-withdrawing effect of *p*-substituent in the ring. This may suggest that the electrophilicity of a carbonium ion in acid chloride–aluminium chloride complex increases the reaction rate. This tendency is similar to the substituent effect on S_N2 reaction of *p*-substituted benzyl chloride with sodium thiosulfate.[10]

With reactions in ethylene chloride or tetrachloroethane as solvents, the Hammett plot using σ^+ gives a good line with ρ^+ of 1·3 and 1·4, respectively (Figs 1 and 2). These facts confirm that benzoylation is an electrophilic substitution.

Even when the reaction time is extended to 3 hr, virtually no change of relative rate was observed, in spite of an increase of total yield.

TABLE 1. RELATIVE RATE CONSTANTS FOR p-SUBSTITUTED BENZOYLATION OF BENZENE

Solvent	Substituent of p-substituted benzoyl chloride	Product(%)[a]		Total yield (%)[a]	k_{rel}
		p-Substituted benzophenone	benzo-phenone		
$ClCH_2CH_2Cl$	CH_3, H	9·4	24·9	34·3	0·344
	Cl, H	34·1	24·6	58·7	1·479
	NO_2, H	73·9	14·8	88·7	8·405
	CH_3, H[b]	16·8	47·4	64·2	0·286
	Cl, H[b]	45·9	35·1	81·0	1·421
	NO_2, H[b]	85·4	14·6	100·0	12·218
$ClCH_2CH_2Cl$ 5 ml + $C_6H_5NO_2$ 5 ml	CH_3, H	32·6	40·3	72·9	0·764
$Cl_2CHCHCl_2$	CH_3, H	5·4	17·1	22·5	0·293
	Cl, H	23·1	15·9	39·0	1·520
	NO_2, H[c]	65·5	11·4	76·9	8·811
$C_6H_5NO_2$	CH_3, H	28·0	30·8	58·8	0·893
	Cl, H	30·1	33·1	63·2	0·890
	NO_2, H	24·7	33·4	58·1	0·699

[a] Yield base on benzene.
[b] Reaction time, 3 hr.
[c] Reaction mixture is heterogeneous during early 5 min.

In the above discussion, the substituent effect on the equilibrium of the formation of acid chloride–aluminium chloride complex (3a) was not taken into account. The opposite sign of ρ is expected for such a reaction, since it involves abstraction of chloride ion by an electrophilic reagent, $AlCl_3$. But in a non-polar solvent which does not form a complex with aluminium chloride, the substituent effect appears to be little because of the marked shift of the equilibrium to the complex side, i.e., the very low concentration of free benzoyl chloride.

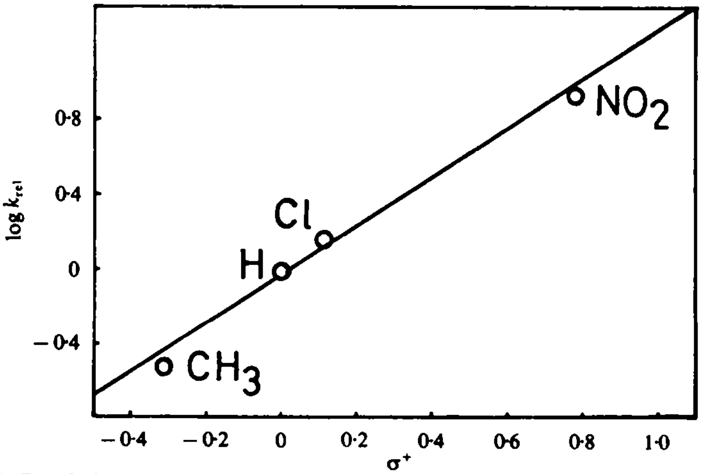


FIG 1. Correlation of the relative rate constants for the p-substituted benzoylation of benzene in ethylene chloride with σ^+ constants.

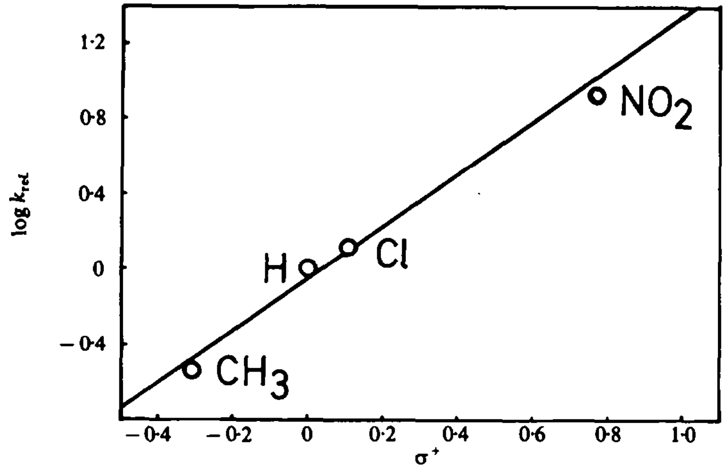


Fig 2. Correlation of the relative rate constants for the *p*-substituted benzoylation of benzene in tetrachloroethane with the σ^+ constants.

When the reaction is carried out using nitrobenzene as a solvent, the polar effect of substituent on the reactivity of the benzoyl chlorides does not fit the Hammett equation and the value of k_{rel} was maximum at unsubstituted benzoyl chloride. Two explanations[11] are conceivable for this phenomenon. (i) The complex formation between nitrobenzene and aluminium chloride weakens the activity of aluminium chloride, and the substituent effect on the equilibrium for the complex formation of acid chloride–aluminium chloride becomes more important.[12] Hence, the Hammett plot is not linear owing to this complication. (ii) Since the complex of acid chloride–aluminium chloride is highly polarised, it freezes out several polar nitrobenzene molecules from the surrounding medium and results in a bulky attacking species which suffers greater steric hindrance for the attack on benzene.[13] This is especially evident with benzoyl chloride carrying large substituent. Hence, the values of the relative rate constants are less than unity.

In conclusion, in a non-polar solvent such as ethylene chloride or tetrachloroethane, the effect of an electron-withdrawing group is correlated well with the Hammett equation, while in nitrobenzene the correlation fails due to its strong polarity. It has been reported[3] that the substituent effect in Friedel–Craft benzoylation of toluene does not fit the Hammett equation, but we found that a plot using σ^+ seems to be more linear.

EXPERIMENTAL

Materials. Constant boiling *p*-substituted benzoyl chlorides (prepared from corresponding benzoic acid and PCl_5) were used. Benzoic and *p*-nitrobenzoic acids were chemically pure. *p*-Chlorobenzoic and *p*-toluic acids were prepared from *p*-toluidine. Benzoyl chloride, b.p. 193–194° (lit. 198·5°); *p*-chlorobenzoyl chloride, b.p. 223° (lit. 220–223°); *p*-nitrobenzoyl chloride, b.p. 160–161° (27 mm) [lit. 150–152° (15 mm)]; *p*-toluyl chloride, b.p. 214–216° (lit. 214–216°). Benzene, nitrobenzene, ethylene chloride and tetrachloroethane were purified by the ordinary methods and distilled before use. Anhydrous $AlCl_3$ was prepared by the reaction of Al metal with dry HCl gas.

Competitive acylation reaction. In a 100 ml flask fitted with a condenser equipped with a $CaCl_2$ tube was placed 0·01 mole of each of two acylating agents in 10 ml solvent. To the soln was added 0·02 mole $AlCl_3$, and the mixture was stirred for 1·5 hr to complete the formation and dissolution of $AlCl_3$-complex. After addition of 0·01 mole benzene, the resulting mixture was stirred magnetically at 50° for more than 1 hr.

Analyses. The reaction mixture was poured into crushed ice containing 6 ml HCl, and the decomposed mixture was extracted with ether. The ether extract was washed with water, sat Na_2CO_3 aq and then water. After being dried over Na_2SO_4, the solvent was distilled off and the residue was analysed by means of GLC employing a Yanagimoto GCG-5DH model on a 2·25 m × 3 mm column packed with Apieson Grease L (30 wt%) on Celite 545 of 80–100 mesh with a He flow of 20 ml/min at 265° or 280°. Specific retention times were 6·9 min for benzophenone, 9·9 min for *p*-methylbenzophenone, 12·0 min for *p*-chlorobenzophenone and 12·6 min for *p*-nitrobenzophenone at column temp of 280°.

Acknowledgement—The authors wish to thank Prof. K. Matsui of Faculty of Technology, Kanazawa University, for many helpful discussions and suggestions during this work.

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