

## SHORT COMMUNICATION

### VARIATION OF $\rho_X(\rho_{\text{nuc}})$ WITH THE EXTENT OF BOND MAKING IN $S_N2$ TRANSITION STATES

IKCHOON LEE AND HAN JOONG KOH

*Department of Chemistry, Inha University, Incheon 402-751, Korea*

AND

BYUNG CHOON LEE

*Department of Chemistry, Choongbuk National University, Chongju 360-763, Korea*

The magnitude  $\rho_X(\rho_{\text{nuc}})$  is shown to decrease with increase in the extent of bond making estimated by the kinetic isotope effect for the reactions of Y-benzoyl chlorides with anilines,  $\text{XC}_6\text{H}_4\text{NH}_2$ , in acetonitrile at  $25.0^\circ\text{C}$

The magnitude of  $\rho_X(\rho_{\text{nuc}})$  in  $S_N2$  reactions is often loosely related to the extent of bond formation in the transition state (TS) within a series of reactions.<sup>1</sup> For example, the magnitude of  $\rho_X$  increases in parallel with that of  $\rho_{XY}$ :

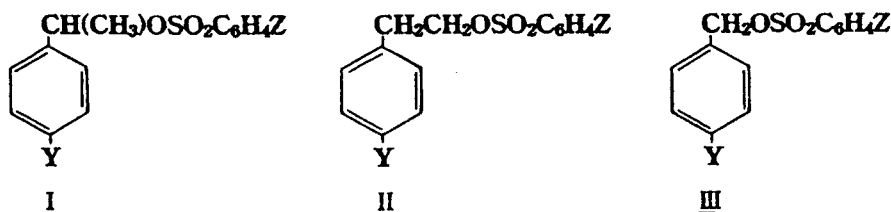
$$\log(k_{XY}/k_{\text{HH}}) = \rho_X\sigma_X + \rho_Y\sigma_Y + \rho_{XY}\sigma_X\sigma_Y \quad (1)$$

where  $\rho_{XY}$  is the cross-interaction constant<sup>2</sup> between substituents (X) in the nucleophile and those (Y) in the substrate, as the substituent Y is varied to a more electron-withdrawing one for reactions of *para*-Y-substituted 1- (**I**)<sup>3</sup> and 2-phenylethyl (**II**)<sup>4</sup> and Y-benzyl (**III**)<sup>5</sup> arennesulphonates with anilines,  $\text{XC}_6\text{H}_4\text{NH}_2$ . The magnitude of  $\rho_{XY}$  is known to increase with increasing degree of bond formation.<sup>2</sup> The parallel changes in  $|\rho_X|$  and  $|\rho_{XY}|$  in fast correctly reflect that a greater  $|\rho_X|$  corresponds to a lighter TS for a more electron-withdrawing Y substituent within the series of reactions.

In this paper, we show that for an associative  $S_N2$

reaction series, in which negative charge develops at  $\text{C}_\alpha$  in the TS with  $\rho_Y > 0$ , an inverse proportionality between  $|\rho_X|$  and the extent of bond making is obtained, in contrast to a proportionality between  $|\rho_X|$  and the extent of bond making in the TS for a disassociative  $S_N2$  reaction series, in which positive charge develops at the reaction centre,  $\text{C}_\alpha$ , in the TS with  $\rho_Y < 0$ . Hence care should be exercised in the interpretation of the magnitude of  $\rho_X$  as a measure of bond formation within a series of  $S_N2$  reactions.

The secondary  $\alpha$ -deuterium kinetic isotope effect (SDKIE) involving deuterated aniline nucleophile,  $\text{XC}_6\text{H}_4\text{NH}_2(\text{D}_2)$ ,  $k_{\text{H}}/k_{\text{D}}$ , has been shown to be useful in determining the relative extent of bond making in the  $S_N2$  TS.<sup>6</sup> As a nucleophile,  $\text{XC}_6\text{H}_4\text{NH}_2(\text{D}_2)$ , attacks the reaction centre,  $\text{C}_\alpha$ , the two N-H(D) vibrations, both bending and stretching modes,<sup>7</sup> are sterically hindered and force constants (and hence vibrational frequencies) increase in the TS.<sup>8</sup> This results in an inverse type of SDKIE,  $k_{\text{H}}/k_{\text{D}} < 1.0$ ,<sup>8</sup> in all normal  $S_N2$ -type



reactions, and the size of the inverse SDKIE values reflect the degree of steric hindrance and hence the degree of bond formation; the smaller the SDKIE value, the greater is the extent of bond formation.

We have determined the SDKIE values for the reaction of Y-benzoyl chlorides with deuterated anilines,  $\text{XC}_6\text{H}_4\text{NH}_2(\text{D}_2)$ , in acetonitrile at  $25.0^\circ\text{C}$ . The results are summarized in Tables 1 and 2.

Table 2 reveals that the  $k_{\text{H}}/k_{\text{D}}$  value becomes systematically smaller, and hence the degree of bond formation becomes systematically greater in the TS, with a weaker nucleophile (e.g.  $\text{X} = p\text{-NO}_2$ ) and with a more electron-donating substituent in the substrate (e.g.  $\text{Y} = p\text{-CH}_3$ ) exhibiting the smallest value ( $k_{\text{H}}/k_{\text{D}} = 0.82$ ) for the reactants with  $\text{X} = p\text{-NO}_2$  and  $\text{Y} = p\text{-CH}_3$ . These trends indicate that the extent of bond making is the greater the weaker is the nucleophile and the stronger is the electron-donating power of the

substituent (Y) in the substrate. The former trend is consistent with that expected from the More O'Ferrall-Jencks diagram,<sup>9</sup> but the latter trend is contrary to the putative proportionality between  $|\rho_{\text{X}}|$  and the extent of bond making;  $|\rho_{\text{X}}|$  in fact decreases, in contrast to an increase expected from the proportionality, as the degree of bond formation increases, i.e. the inverse SDKIE decreases, with increase in electron-donating power of substituent Y.

The decrease in the  $|\rho_{\text{X}}|$  value with a more electron-donating Y appears to result from an accumulation of negative charge at  $\text{C}_\alpha$  in the TS<sup>10</sup> ( $\rho_{\text{Y}} > 0$ ) due to a relatively strong electronegative, or electron-attracting, carbonyl oxygen atom in benzoyl chlorides. The accumulation of negative charge at the  $\text{C}_\alpha\text{-O}$  moiety leads to an inefficient charge transfer from the nucleophile even at a closer  $\text{N}-\text{C}_\alpha$  distance. Indeed, the inefficient charge transfer requires a closer approach of the

Table 1. Second-order rate constants,  $k_2$  ( $\text{dm}^3 \text{mol}^{-1} \text{s}^{-1}$ ), for the reactions of Y-benzoyl chlorides with deuterated X-anilines in acetonitrile at  $25.0^\circ\text{C}$

		$\text{XC}_6\text{H}_4\text{NH}_2(\text{D}_2) + \text{YC}_6\text{H}_4\text{COCl} \xrightarrow[25.0^\circ\text{C}]{\text{MeCN}}$						
		Y						
X		<i>p</i> -CH <sub>3</sub>	H	<i>p</i> -Cl	<i>m</i> -Cl	<i>p</i> -CN	<i>p</i> -NO <sub>2</sub>	<i>m,m</i> -(NO <sub>2</sub> ) <sub>2</sub>
<i>p</i> -CH <sub>3</sub> O	H <sup>a</sup>	23.9	65.2	186	401			
	D <sup>b</sup>	$\pm 0.1^c$	$\pm 0.2$	$\pm 1$	$\pm 4$			
<i>p</i> -CH <sub>3</sub>	H	26.4	71.8	202	432			
	D	$\pm 0.2$	$\pm 0.1$	$\pm 2$	$\pm 2$			
H	H	15.3	38.7	110	233			
	D	$\pm 0.1$	$\pm 0.2$	$\pm 1$	$\pm 2$			
<i>p</i> -Cl	H	17.0	42.8	120	253			
	D	$\pm 0.2$	$\pm 0.2$	$\pm 1$	$\pm 1$			
<i>m</i> -Cl	H	6.03	14.0	34.5	63.1	238	386	
	D	$\pm 0.01$	$\pm 0.2$	$\pm 0.2$	$\pm 0.3$	$\pm 2$	$\pm 2$	
<i>p</i> -NO <sub>2</sub>	H	6.73	15.6	38.0	68.8	256	408	
	D	$\pm 0.01$	$\pm 0.1$	$\pm 0.1$	$\pm 0.2$	$\pm 2$	$\pm 2$	
<i>m</i> -NO <sub>2</sub>	H	2.01	4.28	10.6	20.2	63.4	107	
	D	$\pm 0.01$	$\pm 0.03$	$\pm 0.2$	$\pm 0.3$	$\pm 0.3$	$\pm 2$	
<i>p</i> -CH <sub>3</sub>	H	2.26	4.78	11.7	22.2	68.9	114	
	D	$\pm 0.02$	$\pm 0.01$	$\pm 0.1$	$\pm 0.1$	$\pm 0.2$	$\pm 1$	
<i>m</i> -Cl	H	1.08	2.37	5.13	8.96	27.4	42.2	
	D	$\pm 0.01$	$\pm 0.02$	$\pm 0.01$	$\pm 0.03$	$\pm 0.2$	$\pm 0.2$	
<i>p</i> -NO <sub>2</sub>	H	1.22	2.66	5.67	9.85	30.0	45.6	
	D	$\pm 0.01$	$\pm 0.01$	$\pm 0.01$	$\pm 0.01$	$\pm 0.1$	$\pm 0.1$	
<i>m</i> -NO <sub>2</sub>	H	0.204	0.397	0.706	1.17	2.71	4.01	25.5
	D	$\pm 0.002$	$\pm 0.004$	$\pm 0.004$	$\pm 0.01$	$\pm 0.03$	$\pm 0.03$	$\pm 0.3$
<i>p</i> -NO <sub>2</sub>	H	0.244	0.474	0.814	1.33	3.05	4.49	27.6
	D	$\pm 0.002$	$\pm 0.001$	$\pm 0.001$	$\pm 0.01$	$\pm 0.01$	$\pm 0.01$	$\pm 0.1$
<i>p</i> -NO <sub>2</sub>	H	0.150	0.248	0.482	0.789	1.73	2.52	15.4
	D	$\pm 0.001$	$\pm 0.002$	$\pm 0.003$	$\pm 0.001$	$\pm 0.02$	$\pm 0.02$	$\pm 0.2$
<i>p</i> -NO <sub>2</sub>	H	0.183	0.301	0.572	0.914	1.97	2.87	17.2
	D	$\pm 0.001$	$\pm 0.002$	$\pm 0.002$	$\pm 0.001$	$\pm 0.01$	$\pm 0.01$	$\pm 0.1$

<sup>a</sup> With  $\text{XC}_6\text{H}_4\text{NH}_2$ .

<sup>b</sup> With  $\text{XC}_6\text{H}_4\text{ND}_2$ .

<sup>c</sup> Standard deviation.

Table 2. Kinetic isotope effects ( $k_H/k_D$ ) and Hammett reaction constants for the reaction of Y-benzoyl chlorides with deuterated X-anilines in acetonitrile at 25.0 °C
$$\text{XC}_6\text{H}_4\text{NH}_2(\text{D}_2) + \text{YC}_6\text{H}_4\text{COCl} \xrightarrow[25.0^\circ\text{C}]{\text{MeCN}}$$

X	Y							$\rho_Y^b$
	<i>p</i> -CH <sub>3</sub>	H	<i>p</i> -Cl	<i>m</i> -Cl	<i>p</i> -CN	<i>p</i> -NO <sub>2</sub>	<i>m,m</i> -(NO <sub>2</sub> ) <sub>2</sub>	
<i>p</i> -CH <sub>3</sub> O	0.905 ± 0.008 <sup>a</sup>	0.908 ± 0.008	0.921 ± 0.010	0.928 ± 0.010				2.23 (2.21) <sup>c</sup>
<i>p</i> -CH <sub>3</sub>	0.900 ± 0.012	0.904 ± 0.006	0.917 ± 0.011	0.921 ± 0.009				2.16 (2.14)
H	0.896 ± 0.003	0.897 ± 0.013	0.908 ± 0.008	0.917 ± 0.004	0.930 ± 0.010	0.946 ± 0.007		1.89 (1.87)
<i>p</i> -Cl	0.889 ± 0.009	0.895 ± 0.007	0.906 ± 0.010	0.910 ± 0.009	0.920 ± 0.005	0.939 ± 0.012		1.81 (1.79)
<i>m</i> -Cl	0.885 ± 0.010	0.891 ± 0.008	0.905 ± 0.004	0.910 ± 0.002	0.913 ± 0.007	0.925 ± 0.009		1.66 (1.64)
<i>m</i> -NO <sub>2</sub>	0.833 ± 0.010	0.838 ± 0.009	0.867 ± 0.005	0.880 ± 0.010	0.889 ± 0.010	0.893 ± 0.007	0.924 ± 0.011	1.31 (1.28)
<i>p</i> -NO <sub>2</sub>	0.820 ± 0.012	0.824 ± 0.009	0.843 ± 0.006	0.863 ± 0.001	0.878 ± 0.010	0.878 ± 0.008	0.895 ± 0.012	1.24 (1.24)
$\rho_X^b$	-2.11 (-2.07) <sup>c</sup>	-2.28 (-2.24)	-2.46 (-2.43)	-2.57 (-2.54)	-2.77 (-2.74)	-2.84 (-2.80)	-3.22 (-3.02)	

<sup>a</sup> Standard error =  $1/k_D[(\Delta k_H)^2 + (k_H/k_D)^2(\Delta k_D)^2]^{1/2}$ .

<sup>b</sup> The  $\sigma$  values were taken from *Handbook of Organic Chemistry*, McGraw-Hill, New York (1987), Table 7-1. The correlation coefficients were better than 0.998 in all cases.

<sup>c</sup>  $\rho_X$  and  $\rho_Y$  values are for reactions with  $\text{XC}_6\text{H}_4\text{ND}_2$ .

nucleophile in the TS.<sup>10</sup> Hence the inverse proportionality between  $|\rho_X|$  and the extent of bond making is intimately related to the negative charge accumulation in the TS for an associative  $S_N2$  reaction series in which bond formation is ahead of bond cleavage ( $\rho_Y > 0$ ) with a relatively tight TS.

The selectivity plots,  $\log(k_H/k_D)$  vs  $\sigma_Y$ , give positive slopes,<sup>11</sup> indicating that the reactions proceed via the  $S_N2$  mechanism.<sup>12</sup> It is also interesting to note that the least reactive reactant pair with  $X = p\text{-NO}_2$  and  $Y = p\text{-CH}_3$  has the least SDKIE value, i.e. the most selective, in line with the reactivity-selectivity principle (RSP).<sup>13</sup> The magnitude of the first-order selectivity parameters,  $\rho_X$  and  $\rho_Y$ , is smaller for the more reactive processes with  $\text{XC}_6\text{H}_4\text{ND}_2$  rather than with  $\text{XC}_6\text{H}_4\text{NH}_2$ , which is again consistent with the RSP. The cross-interaction constant,  $\rho_{XY}$ , is however, identical for the two reaction series with  $\text{XC}_6\text{H}_4\text{NH}_2$  and  $\text{XC}_6\text{H}_4\text{ND}_2$  (for both series,  $\rho_{XY} = -0.85$  with  $r = 0.999$ ), demonstrating that the TS structure, i.e. the degree of bond formation, is not affected by the isotopic substitution ( $-\text{NH}_2 \rightarrow -\text{ND}_2$ ).<sup>14</sup> Experimental procedures were as described previously.<sup>6,15</sup>

#### ACKNOWLEDGEMENT

We thank Inha University for support of this and a postdoctoral fellowship to H. J. Koh.

#### REFERENCES

1. K. C. Westaway and S. F. Ali, *Can. J. Chem.* **57**, 1354 (1979).
2. (a) I. Lee, *Chem. Soc. Rev.* **19**, 317 (1991); (b) I. Lee, *Adv. Phys. Org. Chem.* **27**, 57 (1992).
3. I. Lee, H. Y. Kim, H. K. Kang and H. W. Lee, *J. Org. Chem.* **53**, 2678 (1988).
4. I. Lee, Y. H. Choi, H. W. Lee and B. C. Lee, *J. Chem. Soc., Perkin Trans. 2* 1537 (1988).
5. I. Lee, S. C. Sohn, Y. J. Oh and B. C. Lee, *Tetrahedron* **42**, 4718 (1986).
6. (a) I. Lee, H. J. Koh and H. W. Lee, *J. Chem. Res (S)*, 282 (1990); (b) I. Lee, H. J. Koh, B.-S. Lee, D. S. Sohn and B. C. Lee, *J. Chem. Soc., Perkin Trans. 2* 1741 (1991).
7. (a) H. Yamataka, T. Ando, S. Nagase, M. Hanamusa and K. Morokuma, *J. Org. Chem.* **49**, 631 (1984); (b) X. G. Zhao, S. C. Tucker and D. G. Truhlar, *J. Am. Chem. Soc.*, **113**, 826 (1991).
8. T. H. Lowry and K. S. Richardson, *Mechanism and Theory in Organic Chemistry*, 3rd ed., p. 238. Harper and Row, New York (1987).
9. (a) R. A. More O'Ferrall, *J. Chem. Soc. B* 274 (1970); (b) W. P. Jencks, *Chem. Rev.* **72**, 705 (1972).
10. I. Lee, W. H. Lee, H. W. Lee and T. W. Bentley, *J. Chem. Soc., Perkin Trans. 2* 141 (1993).
11. I. Lee, H. J. Koh, Y. S. Park and H. W. Lee, *J. Chem. Soc., Perkin Trans. 2* 1575 (1993).
12. (a) I. Lee, I. S. Koo, S. C. Sohn and H. W. Lee, *Bull. Korean Chem. Soc.* **3**, 92 (1982); (b) J. H. Kim, I. Lee,

- S. C. Sohn and T. S. Uhm, *J. Korean Chem. Soc.* **27**, 95 (1983); (c) J. H. Kim, T. S. Uhm, I. Lee and I. S. Koo, *J. Korean Chem. Soc.* **29**, 15 (1985).
13. (a) A. Pross, *Adv. Phys. Org. Chem.* **14**, 69 (1977); (b) E. Bunce and H. Wilson, *J. Chem. Educ.* **64**, 475 (1987).
14. N. S. Isaacs, *Physical Organic Chemistry*, Chapt. 7. Longman, Harlow (1987).
15. I. Lee, C. S. Shim, S. Y. Chung, H. Y. Kim and H. W. Lee, *J. Chem. Soc., Perkin Trans. 2* 1919 (1988).