

Quantitative approach to the Menschutkin reaction of benzylic systems

Soo-Dong Yoh,^{1*} Duk-Young Cheong¹ and Oh-Seuk Lee²

¹Department of Chemistry Education, Kyungpook National University, Taegu 702-701, Korea

²Department of Chemistry, Andong National University, Andong 760-749, Korea

Received 25 May 2002; revised 31 July 2002; accepted 15 August 2002

ABSTRACT: The quaternization reactions of substituted (Z)-benzyl (X)-benzenesulfonates with substituted (Y)-pyridines were investigated in acetonitrile at 35 °C. The magnitudes of the Hammett reaction constants ρ_X , ρ_Y and ρ_Z indicate that a stronger nucleophile leads to a lesser degree of bond breaking. In addition, a better leaving group is accompanied by a lesser degree of bond formation. Application of multi-Hammett interactions, $|\rho_{YZ}| > |\rho_{XY}| > |\rho_{XZ}|$, predicts that these Menschutkin-type reactions are dissociative S_N2 reactions. In particular, the reaction of strongly activated benzyl derivatives with tertiary amines in acetonitrile reveals a more advanced bond breaking like S_N1 reactions. The predicted mechanism for the benzylation of pyridines with benzylic systems is evident from More O'Ferrall–Jencks diagram and the semi-empirical MO calculations with the AM1 method. Copyright © 2002 John Wiley & Sons, Ltd.

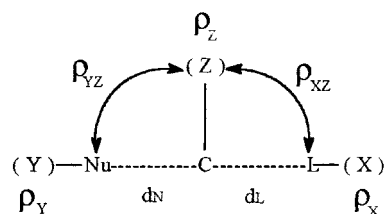
KEYWORDS: benzylic systems; Menschutkin reaction; S_N2 reactions; multi-Hammett interactions; semi-empirical MO; MOFJ diagram

INTRODUCTION

There has been considerable interest in determining the transition-state (TS) structure for S_N reactions using linear free energy relationships.^{1–3} The magnitudes of Hammett ρ values have commonly been used as a means of assessing relative bond tightness in the TS. However, it has often been pointed out that the efficiency of charge transmission among the reaction centers of the substrate, nucleophile and leaving group in bond formation or cleavage may differ for different reaction series. As a result, the magnitudes of ρ can at most serve as a relative measure of bond formation or cleavage within a particular family of closely related reactions.⁴ In contrast, already proposed is the correlation interaction coefficient (CIC), ρ_{ij} , which reflects the demand of the changing distance between the reaction centers of *i* and *j* in the TS.⁵ For example, a CIC with the three variables ρ_Z , ρ_X and ρ_Y for the reaction of substituted (Z)-benzyl (X)-benzenesulfonates with substituted (Y)-*N,N*-dimethylanilines in acetone is expressed by Scheme 1:^{6,7}

$$\log(k_{XYZ}/k_{000}) = \rho_X\sigma_X + \rho_Y\sigma_Y + \rho_Z\sigma_Z + \rho_{XY}\sigma_X\sigma_Y + \rho_{XZ}\sigma_X\sigma_Z + \rho_{YZ}\sigma_Y\sigma_Z$$

where nucleophilic displacement is promoted by facile bond formation with the nucleophile and facile bond fission with the leaving group, in addition to stabilization of the TS. In a detailed analysis of the mechanism, it is important to evaluate the contributions from three species: the substrate, nucleophile and leaving group. This is to establish overall stabilization of the TS. The magnitude of ρ_{XZ} reflects the requirement of bond cleavage between the centers of the leaving group (L) and the substrate (Z) for the formation of TS. A larger value of $|\rho_{XZ}|$ leads to a need for a greater degree of bond cleavage for TS formation (i.e. when the magnitude of ρ_{XZ} is large, C–L bond fission is not ready, hence the bond fission of C–L needs more progress for the formation of the TS). In the same sense, the magnitude of ρ_{YZ} reflects the requirement for bond formation between the centers of the nucleophile (Nu) and the substrate (Z); a larger value of $|\rho_{YZ}|$ needs a greater degree of bond formation for the formation of TS. Nevertheless, quantitative measurement of the CIC method is not complete in all reaction series.



Scheme 1

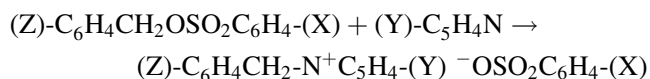
*Correspondence to: S.-D. Yoh, Department of Chemistry Education, Kyungpook National University, Taegu 702-701, Korea.

E-mail: sdyoh@knu.ac.kr

Contract/grant sponsor: KOSEF, Centre for Biofunctional Molecule.

Contract/grant sponsor: Brain Korea 21 Project.

In this paper, we present an example to demonstrate the degree of bond formation and bond fission by comparing them with the magnitude of ρ_{ij} and computational analysis. As a result, ρ_{ij} provides a quantitative measure of bond order in the TS of S_N reactions of substituted benzyl arenesulfonates with pyridines:



Z = 4-CH₃, H, 4-Br, 3-Br, 4-NO₂

X = 4-CH₃, H, 4-Cl, 3-NO₂

Y = 4-NH₂, 3, 4-CH₃, 3, 5-CH₃, 4-CH₃, H, 3-Cl, 3-CN

RESULTS AND DISCUSSION

The reaction rates were determined by monitoring the changes in conductance through the formation of salt from the reactions of substituted (Z)-benzyl (X)-benzenesulfonates with (Y)-pyridines in acetonitrile as described previously.⁸ The reactions, carried out with a large excess of pyridine, follow pseudo-first-order kinetics to at least 85% completion. The second-order rate constants are summarized in Table 1.

Rate enhancement with a more electron-donating

substituent in the substrate and nucleophile indicates that a positive charge developed on the benzylic carbon because the reaction center of the substrate is stabilized by electron-donating substituents in the TS. This is in harmony with the sign of ρ_Z in Table 2. A negative sign of ρ_Z indicates that the reaction center of the substrate has developed a positive charge and the TS is stabilized by electron-donating substituents on the substrate or nucleophile. In the leaving group, however, the attracting substituents facilitate the reaction rate as listed in Table 1. This is also illustrated by the negative ρ_Y value as shown in Table 3, which is consistent with an attack by the nucleophile at the benzylic carbon being helped by electron-attracting substituents of the leaving group.

The ρ_Y values can be regarded as relative measures of the degree of C—N bond formation in the transition state. The ρ_Y values vary widely from -2.43 to -1.85 as the substituent Z changes from 4-NO₂ to 4-CH₃ at the leaving group X = H. According to the above data, the order of bond formation is 4-NO₂ > 4-CH₃ for the benzylic substrate. This agrees with the prediction of the substituent effects on the S_N2 transition state.

The $|\rho_Y|$ values being used by pyridines as nucleophile are larger than that of *N,N*-dimethylanilines in this reaction.⁸ This probably causes the nucleophilic nitrogen atoms on the aromatic ring in the pyridine. The former is

Table 1. Second-order rate constants, $k_2 \times 10^4$ (1 mol⁻¹ s⁻¹), for the reactions of (Z)-benzyl (X)-benzenesulfonates with (Y)-pyridines in acetonitrile at 35 °C

(X)	(Y)	(Z)				
		4-CH ₃	H	4-Br	3-Br	4-NO ₂
<i>p</i> -CH ₃	4-NH ₂	424.4	254.3	209.9	140.0	116.9
	3,4-(CH ₃) ₂	91.44	48.22	39.14	24.70	16.40
	3,5-(CH ₃) ₂	78.20	39.59	30.78	19.07	13.31
	4-CH ₃	59.85	29.53	24.26	14.14	10.32
	H	37.29	17.78	12.98	9.583	5.049
	3-Cl	5.813	2.560	1.693	0.8355	0.4251
H	3-CN	2.042	1.132	0.5171	0.2818	0.1387
	4-NH ₂	675.7	468.9	408.8	295.2	212.2
	3,4-(CH ₃) ₂	169.4	86.98	70.69	46.82	29.40
	3,5-(CH ₃) ₂	144.2	77.00	57.21	38.92	24.32
	4-CH ₃	113.9	53.31	44.70	28.62	17.17
	H	68.22	32.66	24.90	15.13	8.952
<i>p</i> -Cl	3-Cl	9.400	4.230	3.300	2.100	0.7300
	3-CN	4.044	1.470	1.095	0.6136	0.2348
	4-NH ₂	1901	1024	950.2	629.4	486.9
	3,4-(CH ₃) ₂	495.4	244.1	190.4	120.8	79.50
	3,5-(CH ₃) ₂	464.1	206.9	153.4	97.30	63.43
	4-CH ₃	362.9	170.1	124.1	85.67	36.99
<i>m</i> -NO ₂	H	223.0	94.53	68.90	44.19	24.06
	3-Cl	38.92	13.90	9.802	5.373	2.426
	3-CN	10.86	4.356	2.927	1.587	0.6399
	4-NH ₂	10420	6582	5399	3632	2554
	3,4-(CH ₃) ₂	2909	1581	1359	823.3	514.9
	3,5-(CH ₃) ₂	2560	1265	1056	655.1	397.2
	4-CH ₃	1951	1002	819.0	526.1	286.8
	H	1144	608.1	533.2	291.8	153.1
	3-Cl	239.8	104.5	63.85	35.05	16.20
	3-CN	96.67	33.53	23.31	11.04	4.380

Table 2. Hammett ρ_Z values and interaction terms for the reaction of (Z)-benzyl (X)-benzenesulfonates with (Y)-pyridines in acetonitrile at 35 °C

(Y)	σ_{py}^a	ρ_Z				ρ_{ZX}
		(X) = 4-CH ₃	(X) = H	(X) = 4-Cl	(X) = 3-NO ₂	
4-NH ₂	-0.61	-0.550	-0.497	-0.560	-0.605	-0.09
3,4-(CH ₃) ₂	-0.18	-0.726	-0.733	-0.770	-0.758	-0.04
3,5-(CH ₃) ₂	-0.11	-0.750	-0.755	-0.833	-0.785	-0.05
4-CH ₃	-0.12	-0.742	-0.784	-0.957	-0.800	-0.07
H	0	-0.832	-0.869	-0.929	-0.857	-0.02
3-Cl	0.41	-1.13	-1.07	-1.23	-1.17	-0.09
3-CN	0.56	-1.21	-1.19	-1.20	-1.31	-0.13
ρ_{ZY}		-0.60	-0.58	-0.59	-0.62	

^a The σ_{py} values were taken from Ref. 9.**Table 3.** Hammett ρ_Y values and interaction terms for the reaction of (Z)-benzyl (X)-benzenesulfonates with (Y)-pyridines in acetonitrile at 35 °C

X	σ^a	ρ_Y					ρ_{YZ}
		(Z) = 4-CH ₃	(Z) = H	(Z) = 4-Br	(Z) = 3-Br	(Z) = 4-NO ₂	
<i>p</i> -CH ₃	-0.14	-1.88	-1.93	-2.12	-2.21	-2.41	-0.60
H	0	-1.85	-2.04	-2.09	-2.16	-2.43	-0.58
<i>p</i> -Br	0.24	-1.81	-1.94	-2.04	-2.12	-2.34	-0.56
<i>m</i> -NO ₂	0.71	-1.67	-1.85	-1.96	-2.07	-2.27	-0.62
ρ_{YX}		0.25	0.15	0.19	0.15	0.19	

^a The σ values were taken from Ref. 10.

-2.04 and the latter is -1.73. However, the relationship between bond formation and bond fission in the benzylic system cannot be explained clearly. Ballistereri *et al.*¹¹ reported Hammett ρ_Y values for the reactions of benzyl halides with substituted (Y)-anilines. The $|\rho_Y|$ value decreased from -1.46 to -0.87 when the leaving group changed from iodide to chloride. Furthermore, Westaway and Ali¹² reported that more nucleophilic assistance is required to displace a better leaving group given for the reaction of arylbenzyltrimethylammonium ions with (Y)-thiophenoxide ions. These results suggest that changing to a better leaving group leads to a product-like transition-state structure. However, Table 6 (see later) shows that the $|\rho_Y|$ values decrease gradually as the

leaving group changes from 4-CH₃ to 3-NO₂. This means that C—N bond formation decreases progressively with a better leaving moiety. This is in complete agreement with the result of previous work.^{7,8,13} In the case of the present benzyl system, the better leaving groups thus do not yield a 'product-like' transition state but rather a 'loose' one. This result agrees with the prediction of the More O'Ferrall diagram for the effects of leaving group variation in an S_N2 transition state.^{4,14} The variation of $|\rho_Y|$, $\Delta\rho_Y$, on changing the substituent of the substrate (Z) is larger than $\Delta\rho_X$ of ρ_X for leaving group (X), as shown in Tables 3 and 4. For example, the values of $\Delta\rho_Y$ (X = H) and $\Delta\rho_X$ (Y = H) are 0.55 and 0.15, respectively. This means that a larger value of $|\rho_{YZ}|$ requires a greater

Table 4. Hammett ρ_X values and interaction terms for the reaction of (Z)-benzyl (X)-benzenesulfonates with (Y)-pyridines in acetonitrile at 35 °C

Z	σ^a	ρ_X							ρ_{XZ}
		(Y) = 4-NH ₂	(Y) = 3,4-(CH ₃) ₂	(Y) = 3,5-(CH ₃) ₂	(Y) = 4-CH ₃	(Y) = H	(Y) = 3-Cl	(Y) = 3-CN	
4-CH ₃	-0.14	1.65	1.76	1.78	1.78	1.75	1.94	1.90	0.27
H	0	1.64	1.78	1.75	1.80	1.80	1.92	1.79	0.16
4-Br	0.24	1.63	1.81	1.80	1.79	1.89	1.84	1.92	0.16
3-Br	0.37	1.62	1.78	1.78	1.83	1.77	1.85	1.84	0.17
4-NO ₂	0.78	1.56	1.76	1.73	1.70	1.74	1.88	1.77	0.20
ρ_{XZ}		-0.09	-0.01	-0.04	-0.08	-0.03	-0.07	-0.14	

^a The σ values were taken from Ref. 10.

Table 5. Charges of atoms relevant to the reaction center in the transition state for the reaction of (Z)-substituted benzyl (X)-benzenesulfonates with pyridine^a

(Z)	Charge	(X)						
		4-CH ₃ O	4-CH ₃	3-CH ₃	H	4-Cl	3-Cl	4-NO ₂
4-CH ₃ O	N	-0.205	-0.205	-0.205	-0.205	-0.207	-0.208	-0.212
	C	0.315	0.315	0.316	0.316	0.316	0.316	0.314
	O	-1.087	-1.087	-1.087	-1.087	-1.093	-1.094	-1.096
4-CH ₃	N	-0.203	-0.203	-0.203	-0.203	-0.206	-0.207	-0.212
	C	0.315	0.315	0.316	0.316	0.319	0.319	0.322
	O	-1.078	-1.077	-1.078	-1.078	-1.085	-1.086	-1.089
3-CH ₃	N	-0.202	-0.202	-0.202	-0.202	-0.205	-0.206	-0.212
	C	0.315	0.315	0.315	0.315	0.318	0.319	0.324
	O	-1.073	-1.073	-1.073	-1.074	-1.076	-1.081	-1.086
H	N	-0.202	-0.202	-0.202	-0.202	-0.205	-0.206	-0.212
	C	0.313	0.313	0.314	0.314	0.317	0.318	0.324
	O	-1.072	-1.072	-1.072	-1.073	-1.075	-1.080	-1.085
4-Cl	N	-0.200	-0.201	-0.201	-0.201	-0.205	-0.205	-0.211
	C	0.308	0.309	0.309	0.310	0.314	0.315	0.322
	O	-1.066	-1.066	-1.066	-1.067	-1.074	-1.075	-1.080
3-Cl	N	-0.200	-0.200	-0.200	-0.201	-0.204	-0.205	-0.211
	C	0.307	0.308	0.308	0.308	0.313	0.314	0.322
	O	-1.063	-1.063	-1.063	-1.063	-1.070	-1.071	-1.076
4-NO ₂	N	-0.197	-0.198	-0.198	-0.198	-0.200	-0.201	-0.204
	C	0.292	0.293	0.293	0.294	0.297	0.298	0.301
	O	-1.052	-1.052	-1.052	-1.052	-1.052	-1.055	-1.050

^a The values for reactants and products, where (Z) = (X) = H, are N -0.161, C 0.065, O -0.703 and N -0.022, C -0.030, O -1.094, respectively.

degree of bond formation in the TS formation while varying the substituent of the substrate or nucleophile (i.e. the formation of the C—Nu bond progresses poorly in the TS). On the other hand, the smaller the value of $|\rho_{XZ}|$, the more the C—L bond fission progresses in the TS. This is reasonable since bond breaking has already progressed much further than bond formation in the TS of a dissociative S_N2 reaction, so further increases in bond breaking will be small.

These results also agreed with those of semi-empirical AM1 calculations. The charges of atoms relevant to the

reaction center, i.e. N of the nucleophile, benzylic C of the substrate and O of the leaving group in the transition state of the reaction between (Z)-benzyl (X)-benzenesulfonates and pyridine, are listed in Table 5. Distances between atoms and the reaction center in the transition state for these reactions are listed in Table 6.

In Table 5, when (Y) = H and (Z) changes from 4-NO₂ to 4-CH₃O, the charge values of C increase, but those of N and O decrease in all of the (X) substituents. In addition, when (X) = (Y) = H and (Z) changes from 4-NO₂ to 4-CH₃O, the C—N and C—O are bond lengths

Table 6. Distances (Å) between atoms and reaction center in the transition state for the reaction of (Z)-substituted benzyl (X)-benzenesulfonates with pyridine^a

(Z)	Distance	(X)						
		4-CH ₃ O	4-CH ₃	3-CH ₃	H	4-Cl	3-Cl	4-NO ₂
4-CH ₃ O	D(N—C)	2.045	2.045	2.047	2.048	2.067	2.070	2.101
	D(C—O)	2.234	2.235	2.238	2.240	2.266	2.271	2.323
4-CH ₃	D(N—C)	2.024	2.025	2.027	2.028	2.049	2.053	2.090
	D(C—O)	2.181	2.183	2.185	2.187	2.210	2.216	2.263
3-CH ₃	D(N—C)	2.013	2.014	2.016	2.018	2.034	2.043	2.081
	D(C—O)	2.158	2.160	2.162	2.164	2.182	2.191	2.236
H	D(N—C)	2.008	2.010	2.012	2.013	2.029	2.039	2.077
	D(C—O)	2.152	2.154	2.157	2.158	2.175	2.185	2.228
4-Cl	D(N—C)	1.986	1.988	1.991	1.992	2.014	2.019	2.060
	D(C—O)	2.119	2.120	2.123	2.124	2.144	2.150	2.195
3-Cl	D(N—C)	1.979	1.980	1.983	1.984	2.005	2.010	2.050
	D(C—O)	2.104	2.106	2.108	2.109	2.127	2.133	2.173
4-NO ₂	D(N—C)	1.924	1.925	1.927	1.928	1.937	1.944	1.966
	D(C—O)	2.022	2.023	2.024	2.024	2.028	2.031	2.049

^a The values for reactants and products, where (Z) = (X) = H, are D(N—C) 4.038, D(C—O) 1.411 and D(N—C) 1.474, D(C—O) 3.107, respectively.

Table 7. Hammett and Brønsted constants for the reaction of substituted (Z)-benzyl (X)-benzenesulfonates with substituted (Y)-pyridines in acetonitrile at 35 °C

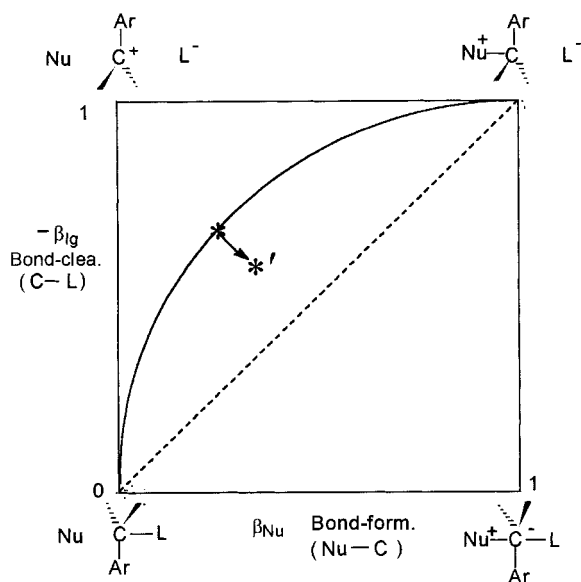
(Z)	ρ_Y^a	β_{Nu}^a	ρ_X^b	β_{Lg}^b
4-CH ₃	-1.85	0.25	1.87	-0.62
H	-2.04	0.27	1.76	-0.59
4-Br	-2.09	0.28	1.85	-0.61
3-Br	-2.16	0.29	1.72	-0.58
4-NO ₂	-2.43	0.33	1.70	-0.57

^a The ρ and β values are evaluated for (X) = H and pK_{as} were taken from Ref. 15.

^b The ρ and β values are evaluated for (Y) = H and pK_{as} were taken from Ref. 16.

longer, as shown in Table 6. These results agree well with the experimental results for the reaction of (Z)-benzyl (X)-benzenesulfonates with (Y)-pyridine in acetonitrile. The parameter of nucleophilic participation, $|\rho_Y|$, decreases but the facility of the leaving moiety, $|\rho_X|$, increases with electron-donating substituents in the substrate, as shown in Tables 3 and 4. These results show that the more electron-donating substituents in the substrate, the weaker is bond formation between the nucleophile and reaction center, but the looser it is between the leaving group and substrate. When (Z) = 4-CH₃O, the nucleophilic attack is less advanced. However, bond breaking progresses greatly. Therefore, its TS stands like an S_N1 mechanism.

Table 7 shows that the value of $|\beta_{Lg}|$ is about twice that of β_{Nu} and the More O'Ferrall–Jencks diagram (Fig. 1) for this reaction also is above that for a concerted S_N2

**Figure 1.** MOFJ diagram based on structure-reactive coefficient for the reaction of substituted (Z)-benzyl (X)-benzenesulfonates with (Y)-pyridines in acetonitrile. The energy contours are not shown. The transition state * moves toward *' with the lowering of the energy of the TS when the substituent (Z) changed from 4-CH₃ to 4-NO₂

reaction. This agrees with the above-mentioned CIC treatment and the reaction of substituted (Z)-benzyl (X)-benzenesulfonates with (Y)-pyridines in acetonitrile will lead to a dissociative S_N2 mechanism.

The magnitude of ρ_{ij} dependent on the changes in distance between the reaction centers of i and j , which can express the sensitivity of $\rho_i\sigma_j$ (or $\rho_j\sigma_i$) (i.e. ρ_{XZ} and ρ_{YZ} indicate the degrees of C_a-L bond fission and $Nu-C_a$ bond formation, respectively). The sign of ρ_Z is negative in Table 2, indicating that the reaction center of the substrate has developed a positive charge and thus a greater degree of bond breaking than bond formation in the TS for the reaction series. In Tables 2–4, the magnitude of $|\rho_{XZ}|$ is smaller than that of $|\rho_{YZ}|$. The change in the substituent of substrates indicates that the leaving moiety is already away from the reaction center of the substrate, so the variation in the distance from the reaction center is small, but is large in the case of ρ_{YZ} . Therefore, from the sign of ρ_Z and the comparison of ρ_{ij} ($|\rho_{YZ}| > |\rho_{XZ}|$), this reaction will lead to a dissociative S_N2 mechanism:

$$\log(k_{XYZ}/k_{000}) = 1.8\sigma_X - 2.0\sigma_Y - 0.86\sigma_Z + 0.15\sigma_X\sigma_Y \\ - 0.58\sigma_Y\sigma_Z - 0.02\sigma_X\sigma_Z + 0.04\sigma_X\sigma_Y\sigma_Z$$

EXPERIMENTAL

Materials. Purification of acetonitrile, substrate preparation and product analysis have been described previously.⁵ Pyridines were commercially available and further purified by distillation or recrystallization before use.

Kinetic measurements. The reaction rates of substituted (Z)-benzyl (X)-benzenesulfonates with (Y)-pyridines in acetonitrile at 35 °C were measured by a conductimetric method.⁸ Conductance measurements were performed in a cell with platinum electrodes and conductivity readings were carried out by using a conductivity meter (CM-60S, equipped with an interval time unit and printer; TOA Electric).

The typical procedure for kinetic measurements is as follows. A 50 ml volume of a stock solution of pyridine (0.12 M) in acetonitrile, which was prepared at 35 °C, was equilibrated in the reaction cell at 35.0 ± 0.02 °C in a thermostated bath for 30 min and then 10 ml of benzyl ester solution (ca 0.003 M) were added. The resulting solution of ester and pyridine in the cell was shaken thoroughly. The reactions were generally followed by taking at least 80 points at appropriate time intervals for 2.5 half-lives and the infinity reading was taken after eight half-lives. All kinetic runs were under pseudo-first-order conditions with 0.01–0.30 M final concentrations of pyridine, which were 20–600 times larger than that of the

substrate. The pseudo-first-order rate constants were determined by a least-squares computer program. Duplicate kinetic runs showed that the rate constant was reproducible to within $\pm 2.0\%$. The precision of the fit to pseudo-first-order kinetics was generally satisfactory, with a correlation coefficient >0.99995 over three half-lives of the reaction. Second-order rate constants, k_2 , were determined by dividing k_{obs} by the initial amine concentration.

Calculations. All calculations were performed with the AM1 method by using MOPAC93.¹⁷ Transition states were located by using the eigenvector following procedure¹⁸ and characterized by confirming the presence of only one negative eigenvalue in the Hessian matrix.

Acknowledgements

This work was supported by the KOSEF through the Center for Biofunctional Molecules and partly financially supported by the Brain Korea 21 Project.

REFERENCES

1. Chapman NB, Shorter J. *Advances in Linear Free Energy Relationships*. Plenum Press: London, 1972; chapter 1.
2. Chapman NB, Shorter J. *Correlation Analysis in Chemistry*. Plenum Press: London, 1978; chapter 4.
3. Lowry TH, Richardson KS. *Mechanism and Theory in Organic Chemistry* (3rd edn). Harper and Row: New York, 1987; 143.
4. Jencks WP. *Chem. Rev.* 1985; **85**: 511.
5. (a) Yoh S-D, Cheong DY. *J. Phys. Org. Chem.* 1996; **9**: 701; (b) Yoh S-D, Park HY, Cheong DY, Park JH, Lee YD, Howang KT. *J. Phys. Org. Chem.* 1999; **12**: 319.
6. (a) Yoh S-D. PhD Dissertation, Osaka University, 1973; 6(b) Yoh S-D, Sawada M, Yukawa Y. In Abstracts of the 28th Spring Meeting of the Chemical Society of Japan, Tokyo, 1974; 1128; 6(c) Tsuno Y, Fujio M, Yoh S-D, Sawada M, Yukawa Y. In Abstracts of the 25th Symposium on Reaction Mechanisms, Chemical Society of Japan, Tokyo, 1974; 119; 6(d) Yoh S-D. *J. Korean Chem. Soc.* 1975; **19**: 449; (e) Yoh S-D, Tsuno Y, Yukawa Y. *J. Korean Chem. Soc.* 1984; **28**: 433; (f) Yoh S-D, Cheong DY, Park JH, Kim SH, Howang KT. *Bull. Korean Chem. Soc.* 1998; **19**: 434.
7. Yoh S-D, Tsuno Y, Fujio M, Sawada M, Yukawa Y. *J. Chem. Soc., Perkin Trans. 2* 1989; 7.
8. (a) Kim SH, Yoh S-D, Fujio M, Imahori H, Mishima M, Tsuno Y. *Bull. Korean Chem. Soc.* 1995; **16**: 760; (b) Kim SH, Yoh S-D, Lim C, Mishima M, Fujio M, Tsuno Y. *J. Phys. Org. Chem.* 1998; **11**: 254.
9. Cheong DY, Kweon JM, Yoh S-D, Park S, Lee OS. *J. Korean Chem. Soc.* 1995; **16**: 604.
10. Isaacs NS. *Physical Organic Chemistry* (2nd edn). Longman: Harlow, 1995; 151.
11. Ballistereri FP, Maccaron E, Mamo A. *J. Org. Chem.* 1976; **41**: 3364.
12. Westaway KC, Ali SF. *Can. J. Chem.* 1979; **57**: 1354.
13. (a) Cheong DY, Kim SH, Lee MH, Yoh S-D, Fujio M, Tsuno Y. *J. Korean Chem. Soc.* 1995; **39**: 643; (b) Tsuji Y, Saeki Y, Yatsugi K, Kim SG, Fujio M, Tsuno Y. *Mem. Fac. Sci. Kyushu Univ. Ser. C* 1992; **18**: 267.
14. (a) More O'Ferrall RA. *J. Chem. Soc.* 1970; 274; (b) Harris JM, Shafer SG, Moffatt JR, Becker AR. *J. Am. Chem. Soc.* 1979; **101**: 3295.
15. Coatzee JF, Padmanabham GR. *J. Am. Chem. Soc.* 1965; **87**: 5005.
16. Hofman RV, Shankweiler JM. *J. Am. Chem. Soc.* 1986; **108**: 5536.
17. Stewart JJP. MOPAC93. Fujitsu: Tokyo, 1993.
18. (a) Cerjan CJ, Miller WH. *J. Chem. Phys.* 1981; **75**: 2800; (b) Banerjee A, Adams A, Simons J, Shepard R. *J. Phys. Chem.* 1985; **89**: 52.