trans geometry.

Recently, Bergman and his coworkers reported an insertion of CO into an Ir≡N bond in Cp*Ir(≡N'Bu), (Cp*=C₅(CH₃)₅), which is the first carbonylation of a terminal imido ligand to give an isocyanate complex.[10] The results of above studies prompted us to investigate the possibility of insertion of CO into Re-nitrene bonds in our compounds. No reactions of compound II or III with CO (up to 6 atm) have been observed.

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Supplementary Material Available. Tables of bond distances and bond angles, anisotropic thermal parameters, positional parameters for hydrogen atoms (6 pages); listings of observed and calculated structure factors (10 pages). Supplementary materials are available from one of the authors (S. W. Lee) upon request.

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Kinetics and Mechanism of Aminolysis of Phenyl Benzoates in Acetonitrile

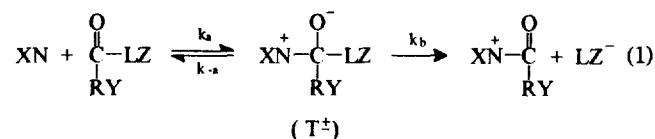Han Joong Koh, Ho Chan Lee, Hai Whang Lee, and Ikchoon Lee

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The kinetics and mechanism of the reactions of phenyl benzoates with benzylamines and pyrrolidine are investigated in acetonitrile. The variations of ρ_X ($\rho_{XY}>0$) and ρ_Z ($\rho_{YZ}<0$) with respect to the substituent in the substrate (σ_Y) indicate that the reactions proceed through a tetrahedral intermediate, $T^{\pm}$, with its breakdown in the rate determining step. The large magnitudes of ρ_Z, ρ_{XY} and ρ_{YZ} as well as the effects of secondary kinetic isotope effects involving deuterated nucleophiles are also in line with the proposed mechanism.

Introduction

The mechanism of ester aminolysis has been extensively studied. The nucleophilic reactions of a series of structurally similar amines with various esters exhibit curved Brönsted-type plots (for $\beta_{nuc}(\beta_X)$) when the basicity of the leaving group is relatively low.[1] The nonlinear plots have been interpreted in terms of a tetrahedral intermediate, $T^{\pm}$, along the reaction path (eq. 1 where X, Y and Z represent substituents in the nucleophile, substrate, and leaving group, respectively) and a change in the rate-limiting step from breakdown to products (k_b) of $T^{\pm}$ to its formation (k_a) as the amine becomes more basic.[1]

$$XN + \underset{RY}{\overset{O}{\underset{|}{\overset{\parallel}{C}}}}-LZ \underset{k_{-a}}{\overset{k_a}{\rightleftharpoons}} XN\overset{+}{-}\underset{RY}{\overset{O^-}{\underset{|}{\overset{|}{C}}}}-LZ \overset{k_b}{\longrightarrow} XN\overset{+}{-}\underset{RY}{\overset{O}{\underset{|}{\overset{\parallel}{C}}}} + LZ^- \quad (1)$$

$$(T^{\pm})$$

In contrast to the generally accepted view of the past 20-30 years that the nucleophilic substitution reactions at a carbonyl group involve almost invariably the tetrahedral intermediate, it has been shown recently that some acyl transfer reactions can involve a concerted mechanism.[2] Most of these studies are, however, carried out in protic solvents, typically in aqueous solution. Recent results of aminolysis studies of esters[3] and acyl halides[4] have shown that the similar mecha-

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Substrate
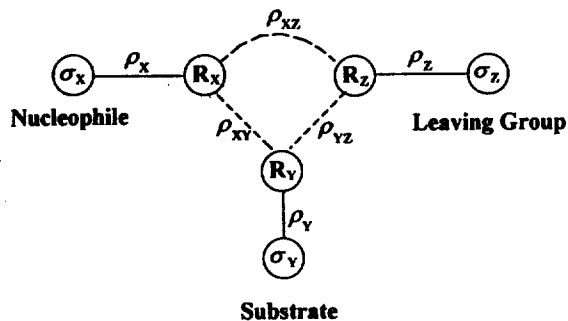
Scheme 1.

nism involving the tetrahedral intermediate also applies in aprotic solvents like acetonitrile, dioxane etc.
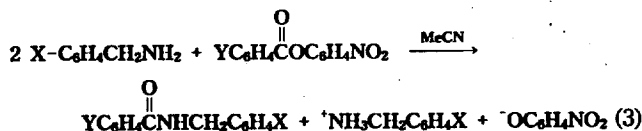
In our developing works of the cross-interaction constants, ρ_{ij} (or β_{ij}) in eq. 2 where i, j=X, Y or Z in Scheme 1, as a mechanistic tool for organic reactions

$$\log(k_{ij}/k_{HH}) = \rho_i\sigma_i + \rho_j\sigma_j + \rho_{ij}\sigma_i\sigma_j \qquad (2a)$$

$$\log(k_{ij}/k_{HH}) = \beta_i \cdot pK_i + \beta_j \cdot pK_j + \beta_{ij} \cdot pK_i \cdot pK_j \qquad (2b)$$

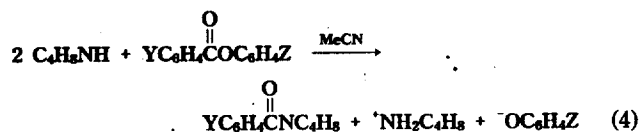in solution,[5] we arrived at the conclusion that[6,7]: The signs of ρ_{XY} (>0) and ρ_{YZ} (<0) for the stepwise carbonyl addition reactions involving the rate-limiting breakdown of the tetrahedral intermediate, $T^{\pm}$, are exactly opposite to those (ρ_{XY}<0 and ρ_{YZ}>0) for the concerted nucleophilic displacement mechanism.

We now report a study of the aminolysis of phenyl benzoates by primary amines, benzylamines, and by a secondary amine, pyrrolidine, in acetonitrile solution, eqs. 3 and 4. Our purpose in this study is to apply the mechanistic criteria based on the sign of ρ_{XY} and ρ_{YZ} to the ester aminolysis reactions in aprotic solvent to show general applicability of the criteria.

$$2\ X\text{-}C_6H_4CH_2NH_2 + YC_6H_4\overset{O}{\overset{\|}{C}}OC_6H_4NO_2 \xrightarrow{MeCN}$$

$$YC_6H_4\overset{O}{\overset{\|}{C}}NHCH_2C_6H_4X + {}^+NH_3CH_2C_6H_4X + {}^-OC_6H_4NO_2 \quad (3)$$

X = p-CH₃O, p-CH₃, H or p-Cl

Y = p-CH₃, H, p-Cl, m-Cl or p-NO₂ .

$$2\ C_4H_8NH + YC_6H_4\overset{O}{\overset{\|}{C}}OC_6H_4Z \xrightarrow{MeCN}$$

$$YC_6H_4\overset{O}{\overset{\|}{C}}NC_4H_8 + {}^+NH_2C_4H_8 + {}^-OC_6H_4Z \quad (4)$$

Y = H, p-Cl or p-NO₂

Z = H, p-Cl, p-CN, m-NO₂ or p-NO₂

Results and Discussion

The second-order rate constants, k_2, for the reactions of p-nitrophenyl benzoates with benzylamines were obtained from k_{obsd} vs [Nu] plots with more than four nucleophile

Table 1. Second-order rate constants[a], ($k_2 \times 10^2$ dm³mol⁻¹s⁻¹), for reactions of p-nitrophenyl Y-benzoates with X-benzylamines in MeCN at 55.0, 45.0 and 35.0 °C, and ρx, ρy, βx and ρxy values

T/°C	X	Y					
		p-CH₃	H	*p*-Cl	*m*-Cl	*p*-NO₂	ργ[b]
55.0	*p*-CH₃O	2.05	3.02	5.04	7.02	17.4	0.98
	p-CH₃	1.82	2.75	4.57	6.31	15.8	0.99
	H	1.40	2.29	3.84	5.01	14.7	1.06
	p-Cl	0.955	1.62	2.70	3.96	12.6	1.16
	ρx[c]	−0.68	−0.55	−0.54	−0.51	−0.27	ρxy[e]=
	βx[d]	0.70	0.58	0.58	0.50	0.25	0.38
45.0	*p*-CH₃O	1.37	2.01	3.45	4.75	12.2	1.00
	p-CH₃	1.20	1.81	3.08	4.30	11.5	1.03
	H	0.917	1.48	2.55	3.44	10.1	1.08
	p-Cl	0.616	1.02	1.81	2.73	8.59	1.20
	ρx[c]	−0.71	−0.60	−0.56	−0.49	−0.31	ρxy[e]=
	βx[d]	0.72	0.63	0.58	0.49	0.32	0.39
35.0	*p*-CH₃O	0.715	1.06	1.89	2.59	6.85	1.04
	p-CH₃	0.582	0.877	1.58	2.36	6.38	1.10
	H	0.432	0.667	1.25	1.87	5.45	1.16
	p-Cl	0.297	0.493	0.910	1.50	4.57	1.26
	ρx[c]	−0.76	−0.68	−0.63	−0.49	−0.36	ρxy[e]=
	βx[d]	0.73	0.62	0.60	0.49	0.36	0.42

[a] No detectable k_3 term. [b] Correlation coefficients were better than 0.999 in all cases. [c] Correlation coefficients were better than 0.992 in all cases. [d] Correlation coefficients were better than 0.992 in all cases. X=p-CH₃O is excluded from the Brönsted plot for β_X (benzylamine) due to unreliable pK_a value listed. [e] Correlation coefficients were better than 0.992 in all cases.

concentrations, [Nu]. The general rate law for these reactions is given by eq. 5,

$$k_{obsd} = k_2[Nu] \qquad (5)$$

where the rate constant in the absence of amine is zero. The k_2 values observed at three temperatures are summarized in Table 1 together with the Hammett (ρ_X and ρ_Y) and Brönsted coefficients (β_X). The ρ_{XY} values determined by subjecting the rate constants, k_2, to multiple regression analysis using eq. 2a with i, j,=X, Y, are also included in the Table. We note that the magnitude of $\rho_X(\rho_{nuc})$ values is relatively low (ρ_X= −0.36−−0.76 at 35.0 °C), especially for Y=p-NO₂[†]. In terms of the mechanism involving rate-limiting breakdown of a zwitterionic tetrahedral intermediate, $T^{\pm}$, in eq. 1 where XN=XC₆H₄CH₂NH₂, RY=C₆H₄Y and LZ=OC₆H₄NO₂ for the reactions in Table 1, the trend of change in ρ_X with substituent Y is reasonable; electron with-

[†] If we allow for the fall off factor of 2.8 for a non-conjugating intervening group, CH₂[8] in benzylamine (relative to aniline), ρ_X ranges *ca.* 1.0-2.1, which is still relatively small for a reaction involving an addition intermediate formation in protic solvents (|ρ_X|≥3.0).[6]
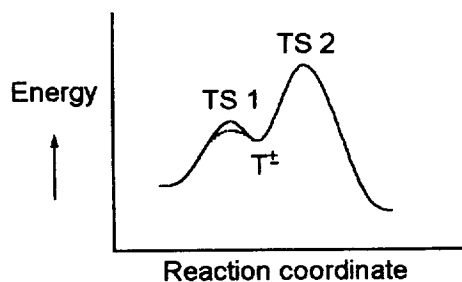
Figure 1. Schematic energy profile along the reaction coordinate for the partitioning of $T^{\pm}$ with $E(TS1) < E(TS2)$ required when $\delta(k_{-a}/k_b) > 0$.

drawal from the nonleaving group ($\delta \rho_Y > 0$ in RY, Table 1) favors amine expulsion ($\delta \rho_X > 0$ or $\delta |\rho_X| < 0$, Table 1) from $T^{\pm}$ (TS1) relative to p-nitrophenoxide release (TS2), *i.e.*, k_{-a}/k_b in eq. 1 increases as RY becomes more electron withdrawing,[1b,e,f] leading to a lower barrier for TS1 with k_b (TS2) as the rate-determining step. The relatively smaller magnitude of $\rho_X(\rho_{nuc})$ found could be due to a less polar solvent used (MeCN) in this work, which should also increase k_{-a} and have little or no effect on $k_b^{(1e)}$(*vide infra*).

Applying the steady-state treatment to $T^{\pm}$ gives $k_2 = k_a k_b/(k_{-a} + k_b)$ where k_2 is the macroscopic rate constant defined in eq. 5. For the rate-limiting breakdown of $T^{\pm}$, $k_2 \cong K k_b$ where $K = k_a/k_{-a}$.

TS 1 (for k_a in eq 1)   TS 2 (for k_b in eq 1)
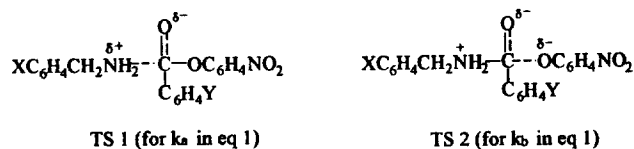
The relatively smaller magnitude of ρ_X (and also β_X) in a less polar solvent (MeCN versus aqueous solution) and for a stronger electron-withdrawing Y substituent in RY, for which k_{-a}/k_b increases to a greater value ($\delta(k_{-a}/k_b) > 0$), can be rationalized with these relations, $k_2 = K k_b$ and $K = k_a/k_{-a}$. The observed ρ_X value listed in Table 1 is in fact a complex quantity.

$$\rho_{X(obsd)} = \frac{\partial \log k_2}{\partial \sigma_X} = \frac{\partial \log K}{\partial \sigma_X} + \frac{\partial \log k_b}{\partial \sigma_X}$$
$$= \frac{\partial \log k_a}{\partial \sigma_X} - \frac{\partial \log k_{-a}}{\partial \sigma_X} + \frac{\partial \log k_b}{\partial \sigma_X}$$
$$= \rho_X(k_a) - \rho_X(k_{-a}) + \rho_X(k_b) \qquad (6)$$
$$= (-) \ - \ (+) \ + (-)$$

Consideration of the effect of σ_X on the three rate constants leads to $\rho_X(k_a) < 0$, $\rho_X(k_{-a}) > 0$ and $\rho_X(k_b) < 0$. The last term will be relatively small, because this term reflects the effect of substituent in the amine (σ_X) on the rate of leaving group expulsion, k_b, from the intermediate, $T^{\pm}$ (a secondary effect). Eq. 6 asserts that the observed ρ_X values in the rate-limiting breakdown of $T^{\pm}$ should be large negative in general since all three terms in eq. 6 are contributing additively to the negative $\rho_{X(obsd)}$ value. When, however, k_{-a}/k_b increases, especially in a less polar solvent,[1e] the greater rate increase in k_{-a} relative to k_b results in a greater decrease in the magnitude of $\rho_X(k_{-a})$ relative to $\rho_X(k_b)$; this is expected from

the reactivity-selectivity relations[9] found in Table 1, *i.e.*, the rate increase is always accompanied by a decrease in the selectivity, ρ_X and ρ_Y[*]. The relatively large decrease in ρ_X (k_{-a}) with very little effect on $\rho_X(k_b)$ should result in a smaller negative $\rho_{X(obsd)}$ value ($\delta \rho_X > 0$), as we have found in Table 1, for the less polar solvent, MeCN, as well as for RY with the more electron-withdrawing substituent ($\delta \rho_Y > 0$); this latter is really a necessary condition (a positive ρ_{XY} value, $\rho_{XY} = \partial \rho_X / \partial \rho_Y > 0$) for the rate-limiting breakdown of $T^{\pm}$.[6] Similar argument leads to the generally large $\beta_X(\beta_{nuc})$ values for the reactions proceeding by the rate-limiting breakdown of $T^{\pm}$, but the magnitude decreases to smaller $\beta_X(\beta_{nuc})$ values in a less polar solvent (MeCN) and for the reactions involving with a stronger electron withdrawing Y substituent, when we differentiate log k_2 with respect to $pK_a(X)$ instead of σ_X in eq. 6 (Table 1).

For these reactions, the sign of ρ_{XY} was found to be positive[6] (Table 1). Thus

$$\rho_{XY} = \frac{\partial^2 \log k_2}{\partial \sigma_X \partial \sigma_Y} = \frac{\partial^2 \log K}{\partial \sigma_X \cdot \partial \sigma_Y} + \frac{\partial^2 \log k_b}{\partial \sigma_X \cdot \partial \sigma_Y} > 0 \qquad (7)$$

Since in the rate-determining step, k_b, the change in the intensity of interaction between substituents X and Y is insignificant,[10] *i.e.*, $\partial^2 \log k_b / \partial \sigma_X \partial \sigma_Y \cong 0$, eq. 7 can be simplified to eq. 8. This shows that the ρ_{XY} value calculated with k_2

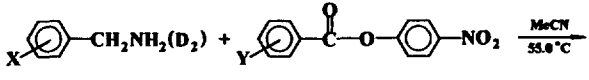$$\rho_{XY} = \frac{\partial^2 \log K}{\partial \sigma_X \cdot \partial \sigma_Y} = \rho'_{XY} \qquad (8)$$

corresponds to the ρ_{XY} value calculated with K, ρ'_{XY}.[10] In the equilibrium step, *i.e.*, for the change involved in the two separated reactants forming an intermediate (a covalent complex), the change in the intensity of interaction is equal to that within a covalent-bonded complex and hence should be very large; for the separated reactants the interaction between X and Y is zero, $\rho^o_{XY} = 0$, and ρ'_{XY} becomes equal to that within a covalent-bonded system, ρ^{cov}_{XY}.[10]

$$\rho'_{XY} = \rho^{cov}_{XY} - \rho^o_{XY} = \rho^{cov}_{XY} \qquad (9)$$

This is why the ρ_{XY} values are relatively large in Table 1 (where compared to the ρ_{XY} values obtained for the reactions with anilines the ρ_{XY} values in Table 1 should become larger ($\rho_{XY} \geq 1.0$) when the fall-off factor of *ca.* 2.8 for the nucleophile, benzylamine *vs* aniline, is taken into consideration).[8] Again the positive ρ'_{XY} value (ρ_{XY} in Table 1) is consistent with the rate-limiting breakdown of $T^{\pm}$. Jencks *et al.*[1b], and Castro *et al.*[1e,f], have shown that in the partitioning of the tetrahedral intermediate, $T^{\pm}$, in eq. 1 leaving group expulsion is favored, or conversely amine expulsion is disfavored ($\delta \rho_X < 0$), from $T^{\pm}$ as the group that remains behind (RY) becomes more electron donating ($\delta \sigma_Y < 0$), leading to $\partial \rho_X / \partial \sigma_Y = \rho_{XY} > 0$. Reference to Table 1 reveals that the variation of ρ_X with respect to σ_Y is in the right direction.

*Available experimental results indicated that in the nucleophilic substitution reactions of carbonyl compounds, the reactivity-selectivity principle (RSP),[9] *i.e.*, a greater reactivity leading to a smaller selectivity, holds in general. In addition to the results in this work, references 1i, 2a, 3, 7 and the following papers support this contention: Lee, I.; Shim, C. S.; Lee, H. W. *J. Chem. Res.*, **1992**, (S) 90. Castro, E. A.; Salas, M. Santos, J. G. *J. Org. Chem.*, **1994**, *59*, 30.

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Table 2. The kinetic isotope effects (k_H/k_D) for the reactions of p-nitrophenyl Y-benzoates with deuterated X-benzylamines $(XC_6H_4CH_2ND_2)$ in Acetonitrile at 55.0 ℃. (No detectable k_3 term is found for this reaction.)

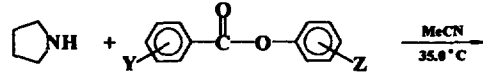| X	Y	$k_2(H)(\times 10^2 M^{-1}s^{-1})$	$k_2(D)(\times 10^2 M^{-1}s^{-1})$	k_H/k_D
p-CH$_3$O	p-CH$_3$	2.05$_{(\pm 0.3)}$[a]	1.95$_{(\pm 0.4)}$	1.05$_{(\pm 0.008)}$[b]
p-CH$_3$O	p-NO$_2$	17.4$_{(\pm 0.9)}$	16.9$_{(\pm 0.5)}$	1.03$_{(\pm 0.009)}$
p-Cl	p-CH$_3$	0.955$_{(\pm 0.004)}$	0.866$_{(\pm 0.006)}$	1.10$_{(\pm 0.006)}$
p-Cl	p-NO$_2$	12.6$_{(\pm 0.06)}$	11.8$_{(\pm 0.05)}$	1.07$_{(\pm 0.009)}$

[a] Standard deviation. [b] Standard error.[14]

For a rate-limiting breakdown of T$^{\pm}$, the $\beta_X(\beta_{nuc})$ value has been found to be large, $\beta_X \cong 1.0$, for the reactions in protic solvents[1] (*vide supra*). Although the β_X values in Table 1 are low ($\beta_X = 0.36$-0.73 at 35.0 ℃ obtained by pK_a values in water not in MeCN) the direct comparison of the β_X values with those reported in the aqueous solution may not be justified, since the solvent effect and especially the use of pK_a in water invalidate such a comparison.

The magnitude of ρ_Y in Table 1 (1.04-1.26 at 35.0 ℃) is similar to those of Menger *et al.*,[3] for the reactions of phenyl benzoates with pyrrolidine in acetonitrile at 25.0 ℃ ($\rho_Y = 1.01$-1.4).

It is notable that the temperature coefficient of both ρ_X and ρ_{XY} are *ca.* 6% decrease per 10° rise. This decrease in the size of ρ_{XY} is an indication that the degree of bond-making decreases *i.e.*, becomes looser as the temperature is raised.

The secondary kinetic isotope effects, k_H/k_D, involving deuterated benzylamine nucleophiles[11] are shown in Table 2. The k_H/k_D values are all near unity ranging 1.03 to 1.07. The magnitude of k_H/k_D is again similar to that reported by Menger *et al.* (0.93-1.09)[3] for the reactions of p-nitrophenyl acetate with deuterated primary and secondary amines in acetonitrile and chlorobenzene at 25.0 ℃. Although k_H/k_D in Table 2 differs little between different substituents X and Y, there is a distinctive trend of change : the k_H/k_D values are greater for electron-donating Y (Y=CH$_3$) and electron-withdrawing X (X=p-Cl). This is consistent with the rate-determining k_b step, since a stronger electron-donating Y ($\delta\sigma_Y < 0$) and an electron-withdrawing X ($\delta\sigma_X > 0$) in the intermediate, T$^{\pm}$, should lead to a greater degree of C-O bond

Table 4. The second order, k_2, and third-order rate constats, k_3, for the reaction of Z-phenyl Y-benzoates with pyrrolidine in acetonitrile at 35.0 ℃

$$k_{obsd} = k_2[Nu] + k_3[Nu]^2$$

Y	Z	H	p-Cl	p-CN	m-NO$_2$	p-NO$_2$	ρ_Z[a]
	k_2, M^{-1}s^{-1}						
H		2.01×10^{-5}	1.04×10^{-3}	1.57	5.04	16.0	7.57
p-Cl		3.55×10^{-5}	1.74×10^{-3}	3.95	6.36	24.2	7.51
p-NO$_2$		15.8×10^{-5}	7.76×10^{-3}	11.7	23.4	72.6	7.23
ρ_Y[b]		1.16	1.13	1.07	0.89	0.85	ρ_{YZ}[c] = -0.35
	k_3, M^{-2}s^{-1}						
H		7.94×10^{-5}	8.36×10^{-3}	55.7	No detectable		8.85
p-Cl		3.24×10^{-4}	2.05×10^{-2}	56.1	k_3 term		7.94
p-NO$_2$		2.19×10^{-2}	3.61×10^{-1}	59.0			5.11
ρ_Y[b]		3.17	1.94	0.03			ρ_{YZ}[c] = -4.85

[a] Correlation coefficients were better than 0.999 in all cases. [b] Correlation coefficients were better than 0.982 in all cases. [c] Correlation coefficients were better than 0.999 in all cases.

cleavage in the TS ($\delta\rho_Z > 0$); these changes are in line with the signs of $\rho_{YZ} = \partial\rho_Z/\partial\sigma_Y$ (<0) and $\rho_{XZ} = \partial\rho_Z/\partial\sigma_X$ (>0).[5] A greater degree of bond cleavage should lead to a greater β-secondary deuterium isotope effect due to a greater σ_{ND} hyperconjugation toward the empty p orbital forming as the C-O bond cleavage takes place.[7]

The relatively low activation parameters, $\Delta H^{\ne}$ and $\Delta S^{\ne}$, in Table 3 are also in accord with the mechanism proposed. Castro *et al.*[1f&4], have shown that for the rate-limiting k_b step, relatively low $\Delta H^{\ne}$ and $\Delta S^{\ne}$ (large negative) are values one expected.

The k_2 and k_3 values from eq. 5 for the reactions of Z-phenyl Y-benzoates with pyrrolidine nucleophile are collected in Table 4.

We have varied the pyrrolidine concentrations up to 0.5 mole·dm^{-3} and the k_{obsd}/[Nu] plots versus [Nu] gave straight lines with intercept, k_2, and slope, k_3, as required from eq. 5 for the relatively weak nucleofuge, Z=H, p-Cl

Table 3. Activation parameters, $\Delta H^{\ne}$ (kcal·mol^{-1}) and $\Delta S^{\ne a}$ (cal·deg^{-1} mol^{-1}) for reactions of p-nitrophenyl Y-benzoates with X-benzylamines in acetonitrile

X \ Y	p-CH$_3$		H		p-Cl		m-Cl		p-NO$_2$	
	$\Delta H^{\ne}$	$-\Delta S^{\ne}$	$\Delta H^{\ne}$	$-\Delta S^{\ne}$	$\Delta H^{\ne}$	$-\Delta S^{\ne}$	$\Delta H^{\ne}$	$-\Delta S^{\ne}$	$\Delta H^{\ne}$	$-\Delta S^{\ne}$
p-CH$_3$O	10.0	38.1	9.95	37.5	9.28	38.4	9.45	37.2	8.79	37.3
p-CH$_3$	10.9	35.8	10.9	34.9	10.1	36.1	9.31	37.8	8.54	38.2
H	11.3	35.3	11.8	32.6	10.7	34.8	9.33	38.2	9.40	35.9
p-Cl	11.2	36.3	11.4	34.6	10.4	36.5	9.18	39.1	9.62	33.6

[a] Calculated values at 35.0 ℃.

Table 5. The second-order rate constants, k_2 ($M^{-1}s^{-1}$), for the aminolysis of p-nitrophenyl Y-benzoates in acetonitrile at 35.0 ℃

Nucleophile + [structure: Y—⌬—C(=O)—O—⌬—NO₂] $\xrightarrow[35.0\,°C]{MeCN}$

Nucleophile	Y			
	pK_a	H	p-Cl	p-NO₂
p-Methylbenzylamine	9.54[a]	0.877×10^{-2}	1.58×10^{-2}	6.38×10^{-2}
p-Methoxybenzylamine	9.51[a]	1.06×10^{-2}	1.89×10^{-2}	6.85×10^{-2}
Benzylamine	9.38[a]	0.667×10^{-2}	1.25×10^{-2}	5.45×10^{-2}
p-Chlorobenzylamine	9.14[a]	0.493×10^{-2}	0.910×10^{-2}	4.57×10^{-2}
piperazine	9.83[b]	0.399	0.520	1.28
piperidine	11.1[b]	0.644	0.974	1.17
pyrrolidine	11.3[b]	16.0	24.2	72.6

[a] Blackwell, L. F. *J. Chem. Soc.* **1964**, 3588. [b] *CRC Handbook of Chemistry and Physics*; 74TH ed., CRC Press, Inc., Florida, 1993; pp 8-44.

and p-CN. For a stronger nucleofuge, $Z=m$-NO₂ and p-NO₂, however, no detectable k_3 term was obtained.

We note in Table 4 that the ρ_Z values for both k_2 and k_3 steps are very large as reported by Menger *et al.*,[3] for the reactions of Z-phenyl acetates. Strikingly, changes in ρ_Y with substituent in the leaving group (Z) is large for both steps and the cross-interaction constants, ρ_{YZ}, are relatively large negative. An electron-withdrawing substituent in the leaving group ($\delta\sigma_Z>0$) should shift the equilibrium, eq. 1, to the right, since the anion product, LZ⁻, is stabilized. As a result, the second barrier (TS2) is lowered and accelerates the second step, k_b, leading to a large ρ_Z value. The use of the relation $k_2=Kk_b$ should lead to a similar three term equation with eq. 6 and the three component ρ_Z values will augment to give a large observed ρ_Z value (Table 4). The effect of substituent, Z, on the aminolysis rates should be large, particularly since the anionic oxygen is poorly solvated in acetonitrile. Thus the unusually large ρ values observed in Table 4 support the mechanism in which breakdown of $T^{\pm}$ is rate-limiting.

The negative sign of ρ_{YZ} is in accord with the rate-limiting breakdown of $T^{\pm}$[6]: It requires that a stronger electron-withdrawing substituent in RY (*i.e.*, $\delta\sigma_Y>0$) should lead to a smaller ρ_Z value ($\delta\rho_Z<0$) *i.e.*, $\rho_{YZ}=\partial\rho_Z\partial\sigma_Y<0$. This is again consistent with the experimental results by Jencks *et al.*[1b] and also by Castro *et al.*[1e,f] that in the partitioning of $T^{\pm}$ amine expulsion is favored, or conversely leaving group expulsion is disfavored ($\delta\rho_Z<0$), as the group that remains behind (RY) becomes more electron withdrawing ($\delta\sigma_Y>0$) leading to $\partial\rho_Z/\partial\sigma_Y=\rho_{YZ}<0$; thus our results in both Tables 1 and 4 are consistent with their experimental conclusions regarding the effect of the nonleaving group in the mechanism involving rate-limiting breakdown of $T^{\pm}$, $\rho_{XY}=\partial\rho_X/\partial\sigma_Y>0$, $\rho_{YZ}=\partial\rho_Z/\partial\sigma_Y<0$.

In order to investigate the effects of primary and secondary amine nucleophiles on the Brönsted β_X value, we have determined k_2 values for the reactions of p-nitrophenyl Y-benzoates with three secondary amines as shown in Table
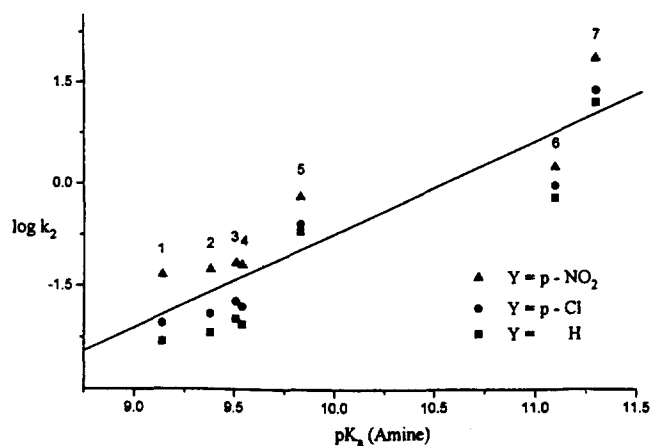

Figure 2. Brönsted-type plots for the reactions of p-nitrophenyl Y-benzoates with X-benzylamines, (1-4; X=p-Cl, H, p-CH₃ and p-CH₃O), piperazine (5), piperidine (6) and pyrrolidine (7) in acetonitrile at 35.0 ℃, (for k_2).

5. The plot of log k_2 (Table 5) versus pK_a is presented in Figure 2.

The overall linearity is poor ($r=0.867$) with $\beta_X=1.28$. The large scatter probably results from the different kind of amines[12] as well as from the use of pK_a in water, not the pK_a value in acetonitrile used in this work. However the large β_X value with a poor linearity is quite similar to those reported for the similar reactions in aprotic solvent; for p-nitrophenyl 3,5-dinitrobenzoate in acetonitrile a plot of logk_2 versus pK_a (water) for the primary amines gave a slope of ca. 2.5,[13] while for benzoyl fluoride in dioxane with primary amines gave a slope ≤1.0.[4]

Conclusions

The variations of ρ_X ($\rho_{XY}>0$) and ρ_Z ($\rho_{YZ}<0$) with changes in the substituent in the substrate (σ_Y) are consistent with the experimentally observed trends in the literature for the rate-limiting breakdown of the tetrahedral intermediate. The relatively greater magnitudes of ρ_Z, ρ_{XY} and ρ_{YZ} and the secondary kinetic isotope effects involving deuterated nucleophiles are also in line with the proposed mechanism.

Experimental

Materials. Acetonitrile was distilled twice over phosphorus pentoxide and again over anhydrous potassium carbonate using a 30 cm vigreux column. Preparation of deuterated benzylamines was described previously[3,11c]. Since the content of deuterium in the deuterated benzylamines is greater than 98% determined from the analysis of NMR spectra, no corrections were made to the kinetic isotope effect. Phenyl benzoates were prepared by the reactions of equimolar amounts of the substituted benzoyl chlorides with substituted phenol in dry pyridine. The reaction mixtures were heated, allowed to stand for several hours, and poured into five to tenfold excess of cool water. Final products were obtained by the filtration and recrystallized twice using acetone, methanol, as a mixture of the two solvents.[3]

Kinetic procedures. Rates were measured conducti-

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metrically at 35.0, 45.0 and 55.0 ℃ in acetonitrile. The conductivity bridge used in this work was a self-made computer interface automatic A/D converter conductivity bridge. Pseudo-first order rate constants, k_{obs}, were determined by the Guggenheim method[15] with a large excess of amine; [phenyl benzoate] $= 5.0 \times 10^{-4}$ mol dm^{-3} and [amine] $= 0.03$-0.40 mol dm^{-3}. Aminolyses of phenyl benzoates in aprotic solvent under pseudo-first order conditions obey a two-term rate law, eq. (5). The rate constants, k_2 and k_3, were determined from the intercepts and the slopes of the plot of $k_{obs}/$[amine] vs [amine], respectively. In a few cases the k_3 term was not observed. The k_2 and k_3 values in Tables 1 and 4 are the averages of more than triplicate runs and were reproducible to within ± 3%.

Products analysis. p-Nitrophenyl p-methylbenzoate was reacted with excess p-methyl benzylamine with stirring for more than 15 half-lives at 35.0 ℃ in acetonitrile, and the products were isolated by evaporating the solvent under reduced pressure. The TLC analysis of the product mixture gave three spots (silica gel, glass plate, 10% ethyl acetate/n-hexane).

Rf values. 0.35 (p-CH$_3$C$_6$H$_4$CONHCH$_2$C$_6$H$_4$-p-CH$_3$), 0.65 (p-CH$_3$C$_6$H$_4$CH$_2$NH$_2$), 0.02 (p-CH$_3$C$_6$H$_4$CH$_2$NH$_3$$^+$ $^-$OC$_6$H$_4$-p-NO$_2$).

The product mixture was treated with column chromatography (silica gel, 10% ethyl acetate/n-hexane). Analysis of the product, p-CH$_3$C$_6$H$_4$CONHCH$_2$C$_6$H$_4$-p-CH$_3$, gave the following results.

p-CH$_3$C$_6$H$_4$CONHCH$_2$C$_6$H$_4$-p-CH$_3$: mp 130-131 ℃.; IR (KBr), 3300 (NH), 1660 (C=O).; NMR (CDCl$_3$), 7.1-7.6 (8H, m, phenyl), 6.5 (1H, s, NH), 4.6 (2H, d, CH$_2$), 2.4 (3H, s, CH$_3$ (benzoyl)), 2.2 (3H, s, CH$_3$ (benzyl)).

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