*trans* geometry.

Recently, Bergman and his coworkers reported an insertion of CO into an Ir≡N bond in Cp*Ir(≡N$^t$Bu), (Cp* = $C_5(CH_3)_5$), 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

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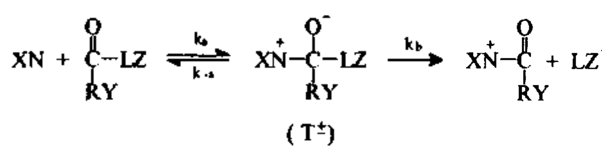
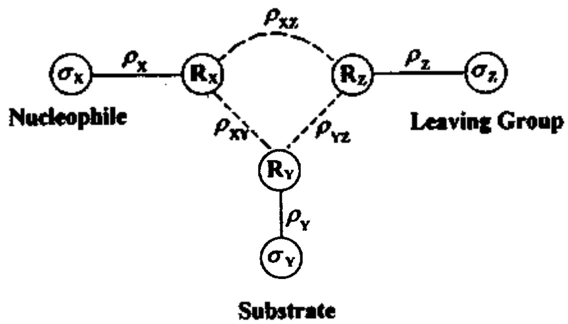
The kinetics and mechanism of the reactions of phenyl benzoates with benzylamines and pyrrolidine are investigated in acetonitrile. The variations of $\rho_X$ ($\rho_{XY}>0$) and $\rho_Z$ ($\rho_{YZ}<0$) with respect to the substituent in the substrate ($\sigma_Y$) indicate that the reactions proceed through a tetrahedral intermediate, $T^{\pm}$, with its breakdown in the rate determining step. The large magnitudes of $\rho_Z$, $\rho_{XY}$ and $\rho_{YZ}$ 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]


(1)

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-




**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, $\rho_{ij}$ (or $\beta_{ij}$) in eq. 2 where $i$, $j$=X, Y or Z in Scheme 1, as a mechanistic tool for organic reactions

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

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

in solution,[5] we arrived at the conclusion that[6,7]: The signs of $\rho_{XY}$ (>0) and $\rho_{YZ}$ (<0) for the stepwise carbonyl addition reactions involving the rate-limiting breakdown of the tetrahedral intermediate, $T^{\pm}$, are exactly opposite to those ($\rho_{XY}$<0 and $\rho_{YZ}$>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 $\rho_{XY}$ and $\rho_{YZ}$ 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-$CH_3O$, p-$CH_3$, H or p-Cl
Y = p-$CH_3$, H, p-Cl, m-Cl or p-$NO_2$ .

$$2\ C_4H_8NH + YC_6H_4\overset{O}{\overset{\|}{C}}OC_6H_4Z \xrightarrow{MeCN} YC_6H_4\overset{O}{\overset{\|}{C}}NC_4H_8 + {}^{+}NH_2C_4H_8 + {}^{-}OC_6H_4Z \quad (4)$$

Y = H, p-Cl or p-$NO_2$
Z = H, p-Cl, p-CN, m-$NO_2$ or p-$NO_2$

## 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], ($k_2\times10^2$ dm$^3$mol$^{-1}$s$^{-1}$), for reactions of $p$-nitrophenyl Y-benzoates with X-benzylamines in MeCN at 55.0, 45.0 and 35.0 ℃, and $\rho_X$, $\rho_Y$, $\beta_X$ and $\rho_{XY}$ values

| T/℃ | X | Y: $p$-$CH_3$ | H | $p$-Cl | $m$-Cl | $p$-$NO_2$ | $\rho_Y$[b] |
|---|---|---|---|---|---|---|---|
| 55.0 | $p$-$CH_3O$ | 2.05 | 3.02 | 5.04 | 7.02 | 17.4 | 0.98 |
| | $p$-$CH_3$ | 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 |
| | $\rho_X$[c] | −0.68 | −0.55 | −0.54 | −0.51 | −0.27 | $\rho_{XY}$[e]= |
| | $\beta_X$[d] | 0.70 | 0.58 | 0.58 | 0.50 | 0.25 | 0.38 |
| 45.0 | $p$-$CH_3O$ | 1.37 | 2.01 | 3.45 | 4.75 | 12.2 | 1.00 |
| | $p$-$CH_3$ | 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 |
| | $\rho_X$[c] | −0.71 | −0.60 | −0.56 | −0.49 | −0.31 | $\rho_{XY}$[e]= |
| | $\beta_X$[d] | 0.72 | 0.63 | 0.58 | 0.49 | 0.32 | 0.39 |
| 35.0 | $p$-$CH_3O$ | 0.715 | 1.06 | 1.89 | 2.59 | 6.85 | 1.04 |
| | $p$-$CH_3$ | 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 |
| | $\rho_X$[c] | −0.76 | −0.68 | −0.63 | −0.49 | −0.36 | $\rho_{XY}$[e]= |
| | $\beta_X$[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=$p$-$CH_3O$ is excluded from the Brönsted plot for $\beta_X$ (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,

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

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 ($\rho_X$ and $\rho_Y$) and Brönsted coefficients ($\beta_X$). The $\rho_{XY}$ 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 ($\rho_X$=−0.36-−0.76 at 35.0 ℃), especially for Y=$p$-$NO_2$†. In terms of the mechanism involving rate-limiting breakdown of a zwitterionic tetrahedral intermediate, $T^{\pm}$, in eq. 1 where XN=$XC_6H_4CH_2NH_2$, RY=$C_6H_4Y$ and LZ=$OC_6H_4NO_2$ for the reactions in Table 1, the trend of change in $\rho_X$ with substituent Y is reasonable; electron with-

†If we allow for the fall off factor of 2.8 for a non-conjugating intervening group, $CH_2$[8] in benzylamine (relative to aniline), $\rho_X$ ranges $ca.$ 1.0-2.1, which is still relatively small for a reaction involving an addition intermediate formation in protic solvents ($|\rho_X|\geq3.0$).[6]

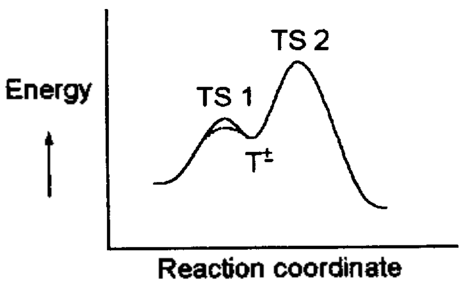
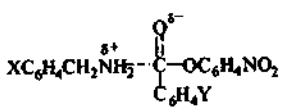


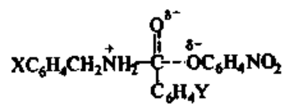

**Figure 1.** Schematic energy profile along the reaction coordinate for the partitioning of $T^{\pm}$ with E(TS1)<E(TS2) required when $\delta(k_{-a}/k_b)>0$.

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 $k_2=k_ak_b/(k_{-a}+k_b)$ where $k_2$ is the macroscopic rate constant defined in eq. 5. For the rate-limiting breakdown of $T^{\pm}$, $k_2 \cong Kk_b$ 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 $\rho_X$ (and also $\beta_X$) 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, $k_2=Kk_b$ and $K=k_a/k_{-a}$. The observed $\rho_X$ value listed in Table 1 is in fact a complex quantity.

$$\begin{aligned}\rho_{X(obsd)} &= \frac{\partial \log k_2}{\partial \sigma_X} = \frac{\partial \log K}{\partial \sigma_X} + \frac{\partial \log k_b}{\partial \sigma_X} \\ &= \frac{\partial \log k_a}{\partial \sigma_X} - \frac{\partial \log k_{-a}}{\partial \sigma_X} + \frac{\partial \log k_b}{\partial \sigma_X} \\ &= \rho_X(k_a) - \rho_X(k_{-a}) + \rho_X(k_b) \\ &= (-) \; - \; (+) \; + (-)\end{aligned} \tag{6}$$

Consideration of the effect of $\sigma_X$ 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 ($\sigma_X$) on the rate of leaving group expulsion, $k_b$, from the intermediate, $T^{\pm}$ (a secondary effect). Eq. 6 asserts that the observed $\rho_X$ 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, $\rho_X$ and $\rho_Y$[*]. The relatively large decrease in $\rho_X(k_{-a})$ 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 $\rho_{XY}$ 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 $\sigma_X$ in eq. 6 (Table 1).

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

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

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 $\rho_{XY}$ value calculated with $k_2$

$$\rho_{XY} = \frac{\partial^2 \log K}{\partial \sigma_X \cdot \partial \sigma_Y} = \rho^e_{XY} \tag{8}$$

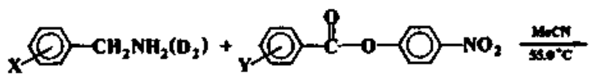
corresponds to the $\rho_{XY}$ value calculated with $K$, $\rho^e_{XY}$.[10] In the equilibrium step, *i.e.*, for the change involved in the two separated reactants forming an intermediate (a covalent complex), the change in the intensity of interaction is equal to that within a covalent-bonded complex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

$$\rho^e_{XY} = \rho^{cov}_{XY} - \rho^o_{XY} = \rho^{cov}_{XY} \tag{9}$$

This is why the $\rho_{XY}$ values are relatively large in Table 1 (where compared to the $\rho_{XY}$ values obtained for the reactions with anilines the $\rho_{XY}$ values in Table 1 should become larger ($\rho_{XY} \geqq 1.0$) when the fall-off factor of *ca.* 2.8 for the nucleophile, benzylamine *vs* aniline, is taken into consideration).[8] Again the positive $\rho^e_{XY}$ value ($\rho_{XY}$ 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 $\rho_X$ with respect to $\sigma_Y$ 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.

**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)(×10$^2$M$^{-1}$s$^{-1}$) | $k_2$(D)(×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 $\beta_X$ 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 $\beta_X$ 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.

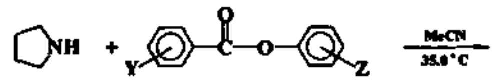
The magnitude of $\rho_Y$ in Table 1 (1.04-1.26 at 35.0 ℃) is similar to those of Menger *et al.*,[3] for the reactions of phenyl benzoates with pyrrolidine in acetonitrile at 25.0 ℃ ($\rho_Y$=1.01-1.4).

It is notable that the temperature coefficient of both $\rho_X$ and $\rho_{XY}$ are *ca.* 6% decrease per 10° rise. This decrease in the size of $\rho_{XY}$ 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 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).[6] A greater degree of bond cleavage should lead to a greater β-secondary deuterium isotope effect due to a greater $\sigma_{ND}$ hyperconjugation toward the empty p orbital forming as the C-O bond cleavage takes place.[7]

**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 ℃

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



| Y \ Z | H | $p$-Cl | $p$-CN | $m$-NO$_2$ | $p$-NO$_2$ | $\rho_Z{}^a$ |
|---|---|---|---|---|---|---|
| | $k_2$, 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 |
| $\rho_Y{}^b$ | 1.16 | 1.13 | 1.07 | 0.89 | 0.85 | $\rho_{YZ}{}^c$= −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 |
| $\rho_Y{}^b$ | 3.17 | 1.94 | 0.03 | | | $\rho_{YZ}{}^c$= −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.

The relatively low activation parameters, $\Delta H^*$ and $\Delta S^*$, in Table 3 are also in accord with the mechanism proposed. Castro *et al.*[1(a,d)], have shown that for the rate-limiting $k_b$ step, relatively low $\Delta H^*$ and $\Delta S^*$ (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.

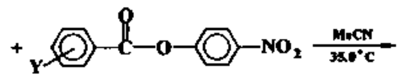
We have varied the pyrrolidine concentrations up to 0.5 mole·dm$^{-3}$ and the $k_{obsd}$/[Nu] plots versus [Nu] gave straight lines with intercept, $k_2$, and slope, $k_3$, as required from eq. 5 for the relatively weak nucleofuge, Z=H, $p$-Cl

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

| Y | $p$-CH$_3$ | | H | | $p$-Cl | | $m$-Cl | | $p$-NO$_2$ | |
|---|---|---|---|---|---|---|---|---|---|---|
| X | $\Delta H^*$ | $-\Delta S^*$ | $\Delta H^*$ | $-\Delta S^*$ | $\Delta H^*$ | $-\Delta S^*$ | $\Delta H^*$ | $-\Delta S^*$ | $\Delta H^*$ | $-\Delta S^*$ |
| $p$-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 | Y | | | |
|---|---|---|---|---|
| | $pK_a$ | H | *p*-Cl | *p*-$NO_2$ |
| *p*-Methylbenzylamine | 9.54[a] | $0.877\times10^{-2}$ | $1.58\times10^{-2}$ | $6.38\times10^{-2}$ |
| *p*-Methoxybenzylamine | 9.51[a] | $1.06\times10^{-2}$ | $1.89\times10^{-2}$ | $6.85\times10^{-2}$ |
| Benzylamine | 9.38[a] | $0.667\times10^{-2}$ | $1.25\times10^{-2}$ | $5.45\times10^{-2}$ |
| *p*-Chlorobenzylamine | 9.14[a] | $0.493\times10^{-2}$ | $0.910\times10^{-2}$ | $4.57\times10^{-2}$ |
| 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*-$NO_2$ and *p*-$NO_2$, however, no detectable $k_3$ term was obtained.

We note in Table 4 that the $\rho_Z$ 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 $\rho_Y$ with substituent in the leaving group (Z) is large for both steps and the cross-interaction constants, $\rho_{YZ}$, 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 $\rho_Z$ 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 $\rho_Z$ values will augment to give a large observed $\rho_Z$ 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 $\rho_{YZ}$ 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 $\rho_Z$ 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 $\beta_X$ value, we have determined $k_2$ values for the reactions of *p*-nitrophenyl Y-benzoates with three secondary amines as shown in Table 5. The plot of log $k_2$ (Table 5) versus $pK_a$ is presented in Figure 2.

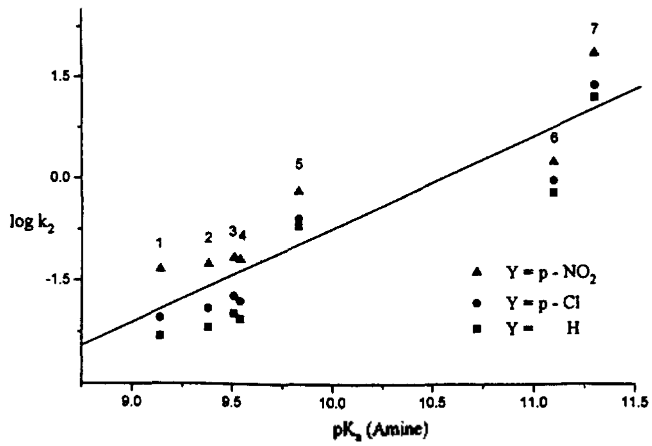



**Figure 2.** Brönsted-type plots for the reactions of *p*-nitrophenyl Y-benzoates with X-benzylamines, (1-4; X=*p*-Cl, H, *p*-$CH_3$ and *p*-$CH_3O$), piperazine (5), piperidine (6) and pyrrolidine (7) in acetonitrile at 35.0 ℃, (for $k_2$).

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 $\beta_X$ 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 log$k_2$ 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 $\lesssim1.0$.[4]

## Conclusions

The variations of $\rho_X$ ($\rho_{XY}>0$) and $\rho_Z$ ($\rho_{YZ}<0$) with changes in the substituent in the substrate ($\sigma_Y$) are consistent with the experimentally observed trends in the literature for the rate-limiting breakdown of the tetrahedral intermediate. The relatively greater magnitudes of $\rho_Z$, $\rho_{XY}$ and $\rho_{YZ}$ 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 conductimetrically 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]$=5.0\times10^{-4}$ 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*-$CH_3C_6H_4CONHCH_2C_6H_4$-*p*-$CH_3$), 0.65 (*p*-$CH_3C_6H_4CH_2NH_2$), 0.02 (*p*-$CH_3C_6H_4CH_2NH_3^{+}\,{}^{-}OC_6H_4$-*p*-$NO_2$).

The product mixture was treated with column chromatography (silica gel, 10% ethyl acetate/n-hexane). Analysis of the product, *p*-$CH_3C_6H_4CONHCH_2C_6H_4$-*p*-$CH_3$, gave the following results.

*p*-$CH_3C_6H_4CONHCH_2C_6H_4$-*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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