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Aminolysis of 2,4-Dinitrophenyl X-Substituted Benzoates and Y-Substituted Phenyl Benzoates in MeCN: Effect of the Reaction Medium on Rate and Mechanism

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Abstract: Second-order rate constants (k_N) have been determined spectrophotometrically for the reactions of 2,4-dinitrophenyl X-substituted benzoates (**1a–f**) and Y-substituted phenyl benzoates (**2a–h**) with a series of alicyclic secondary amines in MeCN at 25.0 ± 0.1 °C. The k_N values are only slightly larger in MeCN than in H_2O, although the amines studied are approximately 8 pK_a units more basic in the aprotic solvent than in H_2O. The Yukawa–Tsuno plot for the aminolysis of **1a–f** is linear, indicating that the electronic nature of the substituent X in the nonleaving group does not affect the rate-determining step (RDS) or reaction mechanism. The Hammett correlation with σ^- constants also exhibits good linearity with a large slope ($\rho_Y = 3.54$) for the reactions of **2a–h** with piperidine, implying that the leaving-group departure occurs at the rate-determining step. Aminolysis of 2,4-dinitrophenyl benzoate (**1c**) results in a linear Brønsted-type plot with a β_{nuc} value of 0.40, suggesting that bond formation between the attacking amine and the carbonyl carbon atom of **1c** is little advanced in the transition state (TS). A concerted mechanism is proposed for the aminolysis of **1a–f** in MeCN. The medium change from H_2O to MeCN appears to force the reaction to proceed concertedly by decreasing the stability of the zwitterionic tetrahedral intermediate ($T^{\pm}$) in aprotic solvent.

Keywords: aminolysis · Brønsted · Hammett · kinetics · solvent effects

Introduction

The mechanism of ester aminolysis has been intensively investigated as a result of its importance in biological processes and synthetic methodology.[1–12] Linear free-energy relationships, such as Brønsted-type and Hammett equations, have been most commonly used to determine reaction mechanisms. Curved Brønsted-type plots, often found for the aminolysis of esters with a good leaving group, have been interpreted in terms of a change in the rate-determining step (RDS) for stepwise reactions.[1–6] The center of the curve in curved Brønsted-type plots has been defined as pK_a^0, for which the rate of breakdown of the zwitterionic tetrahedral intermediate ($T^{\pm}$) is the same as the rate of its formation.[1–2] The rate-determining step has been suggested to change at pK_a^0 from breakdown of $T^{\pm}$ to its formation as the attacking amine becomes more basic than the leaving group by 4 to 5 pK_a units, indicating that the pK_a^0 value is governed by the basicity of the attacking amine and the leaving group.[1–6] However, aminolysis of esters with a poor leaving group or of thiono esters has been suggested to proceed through one or two intermediates ($T^{\pm}$ and its deprotonated counterpart T^-), depending on the basicity and nature of the amines.[7–9]

In contrast to the effects of amine basicity and leaving-group substituents, the effect of nonleaving-group substituents on the reaction mechanism is not yet completely understood. For the pyridinolysis of 2,4-dinitophenyl X-substituted benzoates (X = H, 4-Cl, and 4-NO_2) in 44% aqueous ethanol, Castro et al. demonstrated that the Brønsted-type plot is downwardly curved for the reactions of unsubstituted benzoate, but linear for the corresponding reactions of 4-chloro and 4-nitro derivatives.[10] More recently, the pK_a^0 value has been reported to increase from 9.7 to 9.9 and >10 as the

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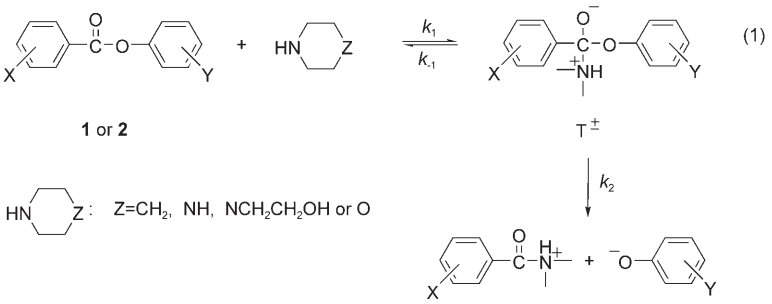
Supporting information for this article is available on the WWW under http://www.chemeurj.org/ or from the author. Please see: Figure S1 for Hammett plots for the reactions of **2a–h** with piperidine in MeCN; Figure S2 for a plot illustrating the dependence of $\Delta\log k_N$(=$\log k_N$ in MeCN − $\log k_N$ in H_2O) on ΔpK_a(=pK_a in MeCN − pK_a in H_2O) for the aminolysis of 2,4-dinitrophenyl benzoate (**1c**) in MeCN and H_2O (contains 20 mol% DMSO) at 25.0 ± 0.1 °C; and Tables S1–S23 for the kinetic data for the aminolysis of **1a–f** and **2a–h** in MeCN.

substituent X changes from H to 4-Cl and 4-NO_2, respectively, for the pyridinolysis of (*S*)-4-nitrophenyl X-substituted thiobenzoates in 44% aqueous ethanol.[11] Thus, Castro et al. concluded that the pK_a^0 value increases as the substituent X in the nonleaving group is substituted for a stronger electron-withdrawing group.[11] This argument is consistent with the conclusion drawn by Gresser and Jencks from reactions of diaryl carbonates with quinuclidines.[12] Gresser and Jencks concluded that the electron-withdrawing substituent in the nonleaving group increased the pK_a^0 value by decreasing the k_2/k_{-1} ratio, that is, an electron-withdrawing substituent in the nonleaving group favors amine expulsion, but retards the departure of the leaving group from $T^{\pm}$ (e.g., k_{-1} and k_2, respectively, in Eq. (1)).[12]

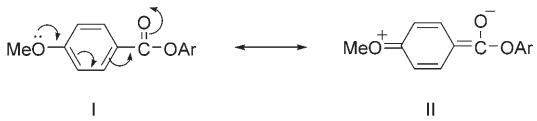


1: Y=2,4-$(NO_2)_2$; X=4-NO_2 **1a**, 4-Cl **1b**, H **1c**, 4-Me **1d**, 4-MeO **1e**, 4-Me_2N **1f**

2: X=H; Y=3-COMe **2a**, 3-CHO **2b**, 4-COOEt **2c**, 4-COMe **2d**, 4-CN **2e**, 4-CHO **2f**, 4-NO_2 **2g**, 3,4-$(NO_2)_2$ **2h**

In contrast, we have shown that the k_2/k_{-1} ratio is independent of the electronic nature of the substituent X in the nonleaving group for aminolyses and alkaline hydrolyses of various esters.[5,6,13,14] Recently we have found that the Hammett plots are nonlinear for the aminolyses of 2,4-dinitrophenyl X-substituted benzoates (**1a**–**e**)[5c] and benzenesulfonates,[6] and for alkaline hydrolyses of **1a**–**e**[13] and their thiono analogues[14] in H_2O (contains 20 mol% DMSO). For all cases, π-electron-donating substituents (e.g., 4-MeO and 4-Me) exhibit negative deviations from the Hammett plot, and the degree of the negative deviation becomes more significant with increasing electron-donating ability. Traditionally, such a curved Hammett plot has been interpreted as a change in the rate-determining step.[15] However, we have attributed the negative deviation exhibited by the electron-donating substituents to the stabilization of the ground-state of the substrate through resonance interactions between the electron-donating substituent X and the electrophilic center (I↔II) in view of the fact that the corresponding Yukawa–Tsuno plots are linear.[5c,6,13,14]

We have extended our study to the reactions of **1a**–**f** and Y-substituted phenyl benzoates **2a**–**h** with a series of alicyclic secondary amines in MeCN [Eq. (1)]. Although scattered information on the aminolyses of esters in aprotic solvent is available,[4a–c] the reaction mechanisms are not yet clearly understood due to a lack of systematic studies. Until recently, mechanistic studies in MeCN have been limited to the reactions of esters with substituents at the acyl position and/or on the leaving group. Structurally similar amines with a wide pK_a range have not been used due to an absence of pK_a data for these compounds in aprotic solvent. In the present study, we have employed not only the substituents X and Y on the nonleaving benzoyl moiety and the leaving phenoxide group, but also alternative substituents at the Z-position in the attacking alicyclic amines, for which pK_a values in MeCN have recently been reported.[18] Such a systematic variation of X, Y, and Z has allowed us to investigate the reaction mechanism systematically. Herein, we report a detailed mechanism for the reaction in aprotic solvent as well as a study into the effect of the reaction medium on the reaction rate and mechanism by comparing the data obtained in this study with those reported for the corresponding reactions performed in aqueous media.



Results and Discussion

All the reactions in this study obeyed pseudo-first-order kinetics with excess amine up to over 90% of the total reaction. Pseudo-first-order rate constants (k_{obsd}) were determined from the equation $\ln(A_\infty - A_t) = -k_{obsd}t + C$. Correlation coefficients were usually higher than 0.9995. It is estimated from replicate runs that the uncertainty in rate constants is less than ±3%. All the plots of k_{obsd} versus amine concentration were linear, passing through the origin, indicating that general base catalysis by a second amine molecule is absent in this study. Thus, the apparent second-order rate constants (k_N) were determined from the slope of the linear plots of k_{obsd} versus amine concentration. Generally five different amine concentrations were used to determine the k_N values. The k_N values determined in this way are summarized in Tables 1–3. The kinetic conditions and results are summarized in Tables S1–S23 in the Supporting Information.

Effect of nonleaving-group substituents X on the reaction rate and mechanism: The second-order rate constant (k_N) increases as the substituent X in the nonleaving group of **1a–f** changes from a strong electron-donating group to a strong electron-withdrawing group (Table 1), that is, the k_N value for the reactions with piperidine increases from 8.98 to 287 and 3120 $M^{-1}s^{-1}$ as the substituent X changes from 4-Me_2N to H and then 4-NO_2, respectively. A similar result is obtained for the corresponding reactions with morpholine. The effect of the electronic nature of the substituent X on the reaction rate is illustrated in Figure 1. The Hammett plots are not linear, that is, the electron-donating substituents, such as 4-Me_2N and 4-MeO, exhibit negative deviations from the linearity, and the degree of deviation is more significant for the stronger electron-donating substituent. However, the corresponding Yukawa–Tsuno plots shown in the inset of Figure 1 exhibit good linearity with ρ_X values of 1.30 and 0.98, and r values of 0.59 and 0.82 for the reactions with piperidine and morpholine, respectively [Eq. (2)].

Table 1. Summary of second-order rate constants (k_N) for the reactions of 2,4-dinitrophenyl X-substituted benzoates (**1a–f**) with piperidine and morpholine at 25 ± 0.1 °C in MeCN and H_2O.[a]

	k_N $M^{-1}s^{-1}$	
X	Piperidine	Morpholine
1a, 4-NO_2	3120 ± 70 (2880 ± 20)	133 ± 1 (138 ± 3)
1b, 4-Cl	518 ± 2 (371 ± 4)	35.7 ± 0.1 (32.7 ± 0.2)
1c, H	287 ± 1 (174 ± 2)	21.7 ± 0.2 (19.6 ± 0.3)
1d, 4-Me	157 ± 2 (100 ± 2)	12.7 ± 0.1 (11.2 ± 0.1)
1e, 4-MeO	68.8 ± 0.7 (56.2 ± 0.9)	5.66 ± 0.16 (5.77 ± 0.06)
1f, 4-Me_2N	8.98 ± 0.06	0.832 ± 0.011

[a] Data in the parenthesis are rate constants for the corresponding reactions performed in H_2O containing 20 mol% DMSO. Data taken from reference [5a].

$$\log(k^X/k^H) = \rho[\sigma^0 + r(\sigma^+ - \sigma^0)] \quad (2)$$

The r value in the Yukawa–Tsuno equation represents the resonance demand of the reaction center or the extent of resonance contribution, while the term $(\sigma^+ - \sigma^0)$ is the resonance substituent constant, which is a measure of the capacity for π-delocalization in the π-electron-donating substituent.[16,17] Equation (2) becomes the Hammett equation when $r = 0$ or the Brown–Okamoto equation when $r = 1$. As the r value in the present system is neither 0 nor 1, the Yukawa–Tsuno plots exhibit better linearity than the Hammett or Brown–Okamoto plots. Thus, the nonlinear Hammett plots shown in Figure 1 are not due to a change in the rate-determining step upon changing the substituent X in the nonleaving group, but due to the ground-state stabilization induced by the resonance interaction between the electron-donating substituent X and the carbonyl group of the substrate (as illustrated by the resonance structures I and II). This argument is consistent with our recent proposal that the electronic nature of the substituent X in the nonleaving group does not affect the reaction mechanism in the aminolysis and hydrolysis of **1a–e** and their related esters.[5,6,13,14]

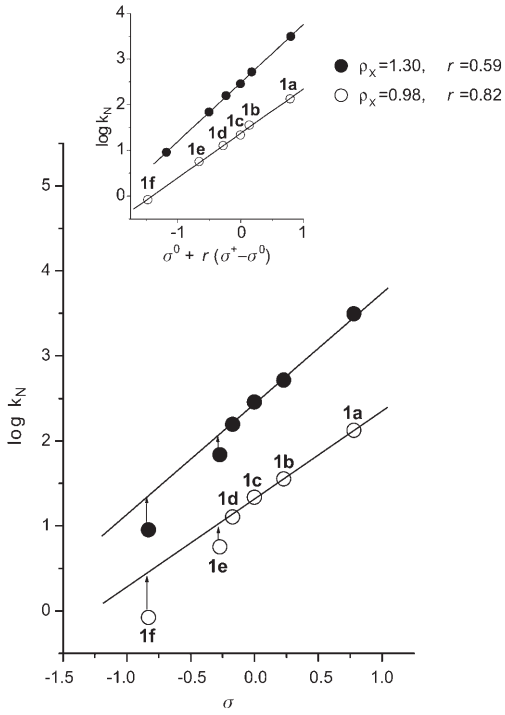


Figure 1. Hammett and Yukawa–Tsuno plots (inset) for the reactions of **1a–f** with piperidine (●) and morpholine (○) in MeCN at 25.0 ± 0.1 °C. The identities of the points are given in Table 1.

An electron-withdrawing substituent X on the nonleaving group of **1a–f** would accelerate the rate of nucleophilic attack, but would retard the rate of leaving-group departure. In contrast, an electron-donating substituent X would inhibit nucleophilic attack, but would increase the rate at which the leaving group departs. Thus, one might expect a large ρ_X value for reactions in which the nucleophilic attack is the rate-determining step, but a small one for reactions in which leaving-group departure is involved in the rate-determining step; this is due to the opposite substituent effect. In fact, a remarkable decrease in the ρ_X value has been reported for the reactions of semicarbazide with X-substituted benzaldehydes in weakly acidic medium (e.g., pH 3.9). The ρ_X has been shown to decrease from 0.91 to nearly zero as the substituent X changes from electron-donating to electron-withdrawing groups.[15a] Jencks has suggested that the reactions proceed through an addition–elimination pathway and attributed the remarkable decrease in the ρ_X value to a change in the rate-determining step.[15a]

The ρ_X values obtained in this study are 1.30 and 0.98 for the reactions of **1a–f** with piperidine and morpholine, respectively. The magnitude of the ρ_X values is slightly smaller for the reactions with weakly basic morpholine than for those with strongly basic piperidine. However, one cannot attribute such a small decrease in the ρ_X value to a change in the rate-determining step. To obtain more information on

the reaction mechanism, the effect of the substituent Y in the leaving group on reactions rates has been investigated.

Effect of the leaving-group substituent Y on the reaction rate and mechanism: The reactivity of **2a–h** increases as the substituent Y on the leaving group becomes a stronger electron-withdrawing group (Table 2), that is, the k_N value for the reactions of **2a–h** with piperidine in MeCN increases from 7.91×10^{-5} to 3.66×10^{-2} and $69.2\,M^{-1}\,s^{-1}$ as the substituent Y changes from 3-COMe to 4-CN and then to 3,4-$(NO_2)_2$, respectively. The effect of substituent Y on the reactivity is illustrated in Figure 2. The Hammett plot is linear with a ρ_Y value of 3.54. This is much larger than the ρ_X value of 1.30 obtained for the reactions of **1a–f** with piperidine, indicating that the rate of the reaction is significantly more dependent on the electronic nature of the substituent in the leaving group than in the nonleaving group.

Table 2. Summary of second-order rate constants (k_N) for the reactions of Y-substituted phenyl benzoates (**2a–h**) with piperidine in MeCN at 25 ± 0.1 °C.

Y	$10^2\,k_N\,M^{-1}\,s^{-1}$	Y	$10^2\,k_N\,M^{-1}\,s^{-1}$
2a, 3-COMe	0.00791 ± 0.00014	**2e**, 4-CN	3.66 ± 0.11
2b, 3-CHO	0.0220 ± 0.0015	**2f**, 4-CHO	2.46 ± 0.03
2c, 4-COOEt	0.224 ± 0.004	**2g**, 4-NO_2	53.9 ± 1.1
2d, 4-COMe	0.334 ± 0.003	**2h**, 3,4-$(NO_2)_2$	6920 ± 70

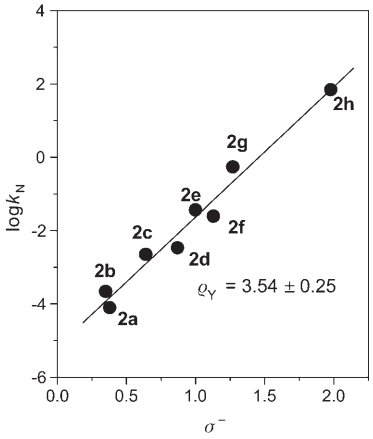
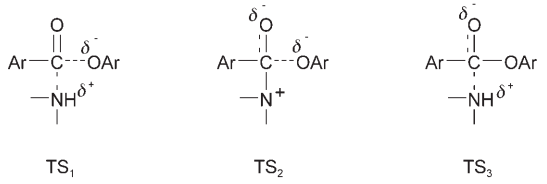


Figure 2. Hammett plot for the reactions of **2a–h** with piperidine in MeCN at 25.0 ± 0.1 °C. The identities of the points are given in Table 2.

More importantly, Figure 2 shows that σ^- constants result in better Hammett correlation than σ or σ^0 constants (for comparison see Figure S1 in the Supporting Information, which illustrates the corresponding Hammett plots with σ or σ^0 constants). If the leaving-group departure were not involved in the rate-determining step, the oxygen atom of the leaving aryloxide should not bear any negative charge in the transition state. In this case, the use of σ^o constants should give the best correlation. In fact, we have recently shown that σ^o constants result in much better Hammett correlation than σ or σ^- constants for the alkaline hydrolyses of **2a–h** and their thiono analogues,[13,14] in which the leaving-group departure has been suggested to be little advanced (if at all) in the transition state of the rate-determining step. However, in the present system, σ^0 (or σ) constants exhibit much poorer correlation than σ^- constants. The fact that σ^- constants give a much better correlation than σ^0 (or σ) constants implies that the oxygen atom in the leaving aryloxide bears a partial negative charge, which can be delocalized on substituent Y through resonance interactions in the transition state. Thus, one can suggest that the leaving-group departure occurs at the rate-determining step for the reactions of **2a–h** with piperidine in MeCN.



Three transition states can be proposed to account for the present result: 1) TS_1 represents the transition-state structure for the reaction in which the nucleophilic attack and the departure of the leaving group occur simultaneously (a concerted mechanism). 2) TS_2 represents the transition-state structure for the stepwise mechanism in which leaving-group departure occurs at the rate-determining step. 3) TS_3 applies to the transition-state structure for the stepwise mechanism in which the leaving-group departure occurs after the rate-determining step. Accordingly, one can exclude TS_3 in the present system on the basis of the fact that σ^- constants result in a much better Hammett correlation than σ^0 or σ constants.

Menger et al. obtained ρ_X and ρ_Y values of 1.02 and 6.24 for the reactions of pyrrolidine with 4-nitrophenyl X-substituted benzoates and Y-substituted phenyl acetates in MeCN, respectively.[4a] Although this result implies that in the RDS the leaving group departs in either a concerted or a stepwise mechanism, Menger et al. chose to favor a stepwise mechanism, as addition intermediates are common in acyl-group transfer reactions in H_2O.[4a]

However, our results could not differentiate a stepwise mechanism (TS_2) from a concerted mechanism (TS_1) as additional data was required. Thus, the kinetic study was extended to the reactions of **1c** with a series of alicyclic secondary amines whose pK_a values in MeCN have recently been reported.[18]

Effect of amine basicity on reaction rate and mechanism: The reactivity of amines toward **1c** increases with the increasing the basicity of amines (Table 3). The effect of amine basicity on reactivity is illustrated in Figure 3. The

Table 3. Summary of second-order rate constants (k_N) for the reactions of 2,4-dinitrophenyl benzoate (**1c**) with alicyclic secondary amines at 25±0.1 °C in MeCN and H_2O.[a]

Entry	Amines	MeCN		H_2O	
		pK_a	k_N M^{-1} s^{-1}	pK_a	k_N M^{-1} s^{-1}
1	piperidine	18.8[b]	287±1	11.02[c]	174±2[c]
2	piperazine	18.2[b]	287±2	9.85[c]	82.1±0.8[c]
3	1-(2-hydroxyethyl)piperazine	17.6[b]	64.7±0.7	9.38[d]	27.4±0.2
4	morpholine	16.0[b]	21.7±0.2	8.65[c]	19.6±0.3[c]

[a] Contains 20 mol% DMSO. [b] The pK_a data in MeCN taken from reference [18]. [c] Data taken from reference [5a]. [d] Data taken from reference [9b].

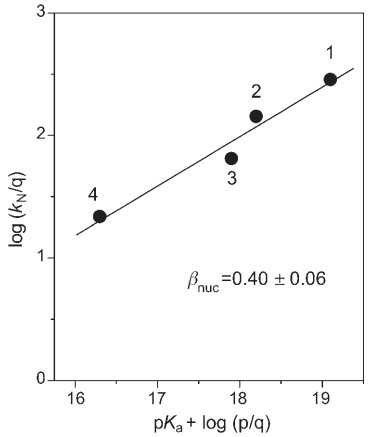


Figure 3. Brønsted-type plot for the reactions of **1c** with alicyclic secondary amines in MeCN at 25.0±0.1 °C. The identities of the points are given in Table 3.

Brønsted-type plot is linear with a β_{nuc} value of 0.40±0.06. The linear Brønsted-type plot suggests that the reactions of **1c** with these amines proceeds through a common mechanism without changing the rate-determining step or the reaction mechanism upon changing the basicity of the amines.

The magnitude of the β_{nuc} values represents the position of the transition state along the reaction coordinate or the relative degree of bond formation between nucleophile and electrophile at the rate-determining transition state.[19] A large β_{nuc} value (0.9±0.2) has often been observed for reactions in which the breakdown of the intermediate to the products is the rate-determining step (TS_2).[1–6] In contrast, a small β_{nuc} value (0.3±0.1) has been reported for reactions which proceed in a stepwise manner through a transition-state structure similar to TS_3.[1–6] In fact, we have recently reported biphasic Brønsted-type plots for the reactions of **1c** with a series of primary and secondary amines in H_2O, that is, β_{nuc} decreases from 0.76±0.02 to 0.35±0.01 as the attacking amine becomes more basic than the leaving group by approximately 5 pK_a units.[5a,b] The biphasic Brønsted-type plots have been attributed to a change in the rate-determining step from the breakdown of a zwitterionic intermediate (e.g., $T^{\pm}$ in Equation (1)) to its formation.

If the aminolysis of **1c** in the present system proceeded through TS_2, a β_{nuc} value of approximately 0.9±0.2 should have been obtained. Thus, the β_{nuc} value of 0.40 obtained in the present study is considered to be too small for reactions which proceed through TS_2. Such a small β_{nuc} value is typical for reactions in which bond formation is not much advanced, indicating that the reaction proceeds through TS_1 or TS_3, in which the degree of bond formation is not significant. However, TS_3 has already been excluded, as mentioned in the preceding section, on the basis of the fact that σ^- constants exhibit much better Hammett correlation than σ or σ^0 constants. Thus, one can propose that the aminolysis of **1a–f** in MeCN proceeds through a concerted mechanism with a transition state similar to TS_1, and the change in the medium from H_2O to MeCN is responsible for the mechanism change from a stepwise to a concerted process. Lee et al. suggested a similar proposal, that is, the solvent change from H_2O to MeCN causes a mechanistic change from stepwise to concerted for the reactions of aryl chlorothionoformates with anilines.[20]

Effect of medium on reaction rate and mechanism: Amines are more reactive in MeCN than in H_2O (Tables 1 and 3). However, the rate enhancement observed upon the medium change from H_2O to MeCN is considered to be insignificant, as these amines are approximately 8 pK_a units more basic in the aprotic solvent than in H_2O.[18] This argument can be further supported by analyzing the effect of the reaction medium on reactivity ($\Delta\log k_N = \log k_N$ in MeCN$-\log k_N$ in H_2O) and on the amine basicity ($\Delta pK_a = pK_a$ in MeCN$-pK_a$ in H_2O). The plot of $\Delta\log k_N$ versus ΔpK_a is linear with a slope of 0.46 (see Figure S2 in the Supporting Information). Such a linear plot implies that the increased basicity of amines is responsible for their enhanced reactivity in MeCN.[21]

The effect of the reaction medium on reactivity has been suggested to be highly dependent on the nature of reactants.[22] Nucleophilic substitution reactions involving anionic nucleophiles exhibit significant rate acceleration, whereas reactions between neutral molecules passing through a partially charged transition state or a zwitterionic intermediate result in rate retardation upon the medium change from H_2O to dipolar aprotic solvents.[22] This is consistent with the fact that the reactivity of the amines in this study increases only slightly, although their basicity increases about 8 pK_a units upon the medium change from H_2O to MeCN.

As MeCN cannot solvate ionic species as strongly as H_2O, partially charged transition states and zwitterionic intermediate $T^{\pm}$ would be destabilized upon the medium change from H_2O to MeCN. One can expect that the zwitterionic intermediate $T^{\pm}$ would be more destabilized than partially charged transition states in MeCN. Thus, one can suggest that the medium change from H_2O to MeCN forces the aminolysis of **1a–f** to proceed concertedly without the involve-

ment of the intermediate $T^{\pm}$ due to its instability in the aprotic solvent.

Conclusion

Kinetic studies on the aminolyses of 2,4-dinitrophenyl X-substituted benzoates (**1a–f**) and Y-substituted phenyl benzoates (**2a–h**) have allowed us to conclude the following:

1) The Yukawa–Tsuno plots for the reactions of **1a–f** exhibit good linearity, indicating that the electronic nature of the substituent X does not affect the reaction mechanism.
2) The fact that σ^- constants result in good Hammett correlation with a ρ_Y value of 3.54 for the reactions of **2a–h**, suggests that the leaving-group departure occurs at the rate-determining step.
3) A β_{nuc} value of 0.40 for the aminolysis of **1c** suggests that bond formation between the carbonyl carbon of **1c** and the attacking amine is little advanced in the transition state.
4) Amines are slightly more reactive in MeCN than in H_2O, although they are approximately 8 pK_a units more basic in the aprotic solvent than in H_2O.
5) The aminolysis of **1a–f** proceeds concertedly through TS_1 in MeCN. The medium change from H_2O to MeCN appears to force the reaction to proceed concertedly by decreasing the stability of the zwitterionic tetrahedral intermediate ($T^{\pm}$) in aprotic solvent.

Experimental Section

Materials: Compounds **1a–f** and **2a–h** were readily prepared from the reaction of X-substituted benzoyl chloride with Y-substituted phenol in the presence of triethylamine in anhydrous ether as previously reported.[4a,5] The purity of these compounds was checked by means of melting point and spectral data, such as ^{1}H NMR and IR spectra. MeCN was distilled over phosphorus pentaoxide under nitrogen. Amines and other chemicals were of the highest quality available.

Kinetics: The kinetic study was performed by using a Scinco S-3150 PDA UV-vis spectrophotometer for slow reactions ($t_{1/2} \geq 10$ s) or an Applied Photophysics SX-17 MV stopped-flow spectrophotometer for fast reactions ($t_{1/2} < 10$ s); both spectrophotometers were equipped with a Neslab RTE-110 constant temperature circulating bath to keep the reaction temperature at 25.0±0.1 °C. All the reactions were carried out under pseudo-first-order conditions in which the amine concentration was at least 20 times greater than the substrate concentration. Solutions were transferred by using Hamilton gas-tight syringes under nitrogen. The reactions were followed by monitoring the aryloxide produced in the reaction at a fixed wavelength, corresponding to the maximum absorption of Y-$C_6H_4O^-$ (λ_{max}). Other detailed kinetic methods have been previously reported.[5a–c]

Product Analysis: Y-substituted phenoxide (Y-$C_6H_4O^-$) was liberated quantitatively and identified as one of the reaction products by comparison of the UV-vis spectra after completion of the reactions with those of authentic samples under the same kinetic conditions.

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