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Aminolysis of Y-Substituted Phenyl Diphenylphosphinates and Benzoates: Effect of Modification of Electrophilic Center from C═O to P═O

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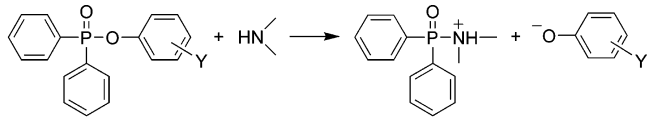
Received June 25, 2006



The effect of modification of the electrophilic center from C═O to P═O on reactivity and reaction mechanism has been investigated for aminolysis of Y-substituted phenyl diphenylphosphinates (**1a**−**j**) and benzoates (**2a**−**i**). The phosphinates **1a**−**j** are less reactive than the benzoates **2a**−**i**. The reactions of 2,4-dinitrophenyl diphenylphosphinate (**1a**) with alicyclic secondary amines resulted in a linear Brønsted-type plot with a β_{nuc} value of 0.38, while the corresponding reactions of 2,4-dinitrophenyl benzoate (**2a**) yielded a curved Brønsted-type plot. Similarly, a linear Brønsted-type plot with a β_{lg} value of −0.66 was obtained for the reactions of **1a**−**j** with piperidine, while the corresponding reactions of **2a**−**i** gave a curved Brønsted-type plot. The linear Brønsted-type plots for the reactions of **1a**−**j** have been taken as evidence for a concerted mechanism, while the curved Brønsted-type plots for the reactions of **2a**−**i** have been suggested to indicate a change in the rate-determining step of a stepwise mechanism. The Hammett plot for the reactions of **1b**−**j** exhibited a poor correlation with σ^- constants ($R^2 = 0.962$) but slightly better correlation with σ^o ($R^2 = 0.986$). However, the Yukawa−Tsuno plot for the same reactions resulted in an excellent correlation ($R^2 = 0.9993$) with an r value of 0.30. The aminolysis of **1a**−**j** has been suggested to proceed through a concerted mechanism with an early transition state on the basis of the small β_{nuc} and small r values.

Introduction

There has been continuous interest in phosphoryl transfer and related reactions due to environmental significance as well as biological importance.[1−10] The need to develop efficient means to destroy stockpiles of toxic organophosphorus compounds has led a number of groups to investigate different approaches toward enhancing decomposition of these compounds. Accordingly, a number of methods have been developed. These include the use of highly reactive α-effect nucleophiles in the presence of cationic surfactants[2−4] and various metal ions.[5−7] The α-effect nucleophiles such as HOO^-, *o*-iodosobenzoate, and oximate anions have shown abnormally enhanced nucleophilic reactivities than would be predicted from their basicity in dephosphoryl reactions.[2−4] Furthermore, the enhanced reactivity of these anionic nucleophiles toward phosphorus compounds has been reported to be more remarkable in the presence of a cationic surfactant such as hexadecyltrimethylammonium ion.[2−4] Alkali metal ions[5] and divalent metal ions (e.g., Mg^{2+}, Ca^{2+}, Zn^{2+}, Cu^{2+}, Co^{2+}, Mn^{2+}, Pt^{2+})[6] have also exhibited significant

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10.1021/jo061308x CCC: $33.50
Published on Web 09/02/2006

catalytic effects in nucleophilic substitution reactions of aryl diphenylphosphinate and its analogues. Besides, La^{3+} ion has been recently shown to be extremely effective on alkaline methanolysis of phosphate di- and triesters.[7]

Kinetic studies have also been performed intensively to investigate the mechanism of biological processes.[5,8−10] However, most studies have been focused on hydrolysis in alkaline conditions. Williams et al. have performed reactions of 4-nitrophenyl diphenylphosphinate with aryloxides in aqueous medium and concluded that the reactions proceed through a concerted mechanism.[8a] The evidence suggested for a concerted mechanism is a linear Brønsted-type plot for the reactions with a series of aryloxides whose pK_a values are greater than and less than that of the leaving 4-nitrophenoxide.[8a] On the other hand, alkaline hydrolysis of aryl diphenylphosphinates has been suggested to proceed through a pentacoordinate intermediate with its formation being the rate-determining step (RDS) on the basis of good Hammett correlations with σ^o constants.[8b,c] A similar conclusion has been drawn for imidazole catalyzed hydrolysis of aryl diphenylphosphinates[8d] and alkaline ethanolysis of aryl dimethylphosphinates.[5a]

Only few reports are available on aminolysis of phosphoryl and related esters.[9,10] Accordingly, their mechanism has not been completely understood. Cook et al. have concluded that aminolysis of 4-nitrophenyl diphenylphosphinate in MeCN proceed through a stepwise mechanism in which breakdown of a zwitterionic pentacoordinate intermediate is the RDS.[9] In the reaction with *n*-butylamine, the breakdown of the zwitterionic intermediate has been shown to be general base catalyzed since the reaction follows a two-term rate law, i.e., one first order in amine and the other second order in amine.[9] On the contrary, Lee et al. have suggested that reactions of phenyl-substituted phenyl chlorophosphates with pyridines proceed through a concerted mechanism in MeCN, since the Brønsted-type plots obtained are linear with small β_{nuc} values (0.16−0.18).[10a]

TABLE 1. Summary of Second-Order Rate Constants (k_N, M^{-1} s^{-1}) for the Reactions of 2,4-Dinitrophenyl Diphenylphosphinate (1a) and 2,4-Dinitrophenyl Benzoate (2a) with Alicyclic Secondary Amines in 80 mol % H_2O/20 mol % DMSO at 25.0 ± 0.1 °C

			k_N/M^{-1} s^{-1}	
entry	amine	pK_a[a]	**1a**	**2a**[b]
1	piperidine	11.02	4.19	174
2	3-methylpiperidine	10.8	4.29	167
3	piperazine	9.85	2.34	82.1
4	1-(2-hydroxyethyl)piperazine	9.38	0.939	
5	morpholine	8.65	0.573	19.6
6	1-formylpiperazine	7.98	0.332	5.43
7	piperazinium ion	5.95	0.0709	0.467

[a] The pK_a data in 20 mol % DMSO. Data were taken from ref 11. [b] The data for the reactions of **2a** were taken from ref 11.

We have performed two series of kinetic studies to investigate the reaction mechanism, i.e., reactions of **1a** with seven different alicyclic secondary amines and reactions of piperidine with nine different Y-substituted phenyl diphenylphosphinates (**1a**−**j**) in water containing 20 mol % dimethyl sulfoxide (DMSO) at 25.0 ± 0.1 °C. The kinetic data obtained in this study have been compared with those reported for the corresponding reactions of Y-substituted phenyl benzoates (**2a**−**i**) since the reaction mechanism for aminolysis of these benzoates has been fairly well understood. We report the effect of modification of the electrophilic center from C═O to P═O on the reactivity and reaction mechanism. We also show that deduction of reaction mechanism based just on Hammett correlations with σ^- or σ^o constants alone can be misleading.

Results and Discussion

All reactions in this study obeyed pseudo-first-order kinetics in the presence of a large excess of amine. From product studies, it is clear that the one molecule of amine involved is the attacking nucleophile, and it is not acting as a general base toward solvent attack. Pseudo-first-order rate constants (k_{obsd}) were determined from the equation $\ln(A_\infty - A_t) = -k_{obsd}t + c$. The correlation coefficient for the linear regression was usually higher than 0.999. The plots of k_{obsd} vs amine concentration were linear passing through the origin, indicating that general base catalysis by the second amine molecule is absent and the contribution of H_2O and/or OH^- ion from amine equilibration with water present to k_{obsd} is negligible. The second-order rate constants (k_N) were determined from the slope of the linear plots of k_{obsd} vs amine concentration. The uncertainty in the k_N values is estimated to be less than 3% from replicate runs. The k_N values determined are summarized in Tables 1 and 2.

Effect of Amine Basicity on Reactivity and Mechanism. As shown in Table 1, the k_N value for the reactions of **1a** decreases as the amine basicity decreases, i.e., it decreases from 4.19 M^{-1} s^{-1} to 0.939 and 0.0709 M^{-1} s^{-1} as the pK_a of the conjugate acid of the amine decreases from 11.02 to 9.38 and 5.95, respectively. A similar result can be seen for the corresponding reactions of **2a.** However, the phosphinate **1a** is much less reactive than the benzoate **2a** regardless of the amine basicity.

The effect of amine basicity on reactivity is illustrated in Figure 1. The Brønsted-type plot for the reactions of **1a** is linear

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TABLE 2. Summary of Apparent Second-Order Rate Constants (k_N, M^{-1} s^{-1}) for the Reactions of Y-Substituted Phenyl Diphenylphosphinates (1a−j) and Y-Substituted Phenyl Benzoates (2a−i) with Piperidine in 80 mol % H_2O/20 mol % DMSO at 25.0 ± 0.1 °C

			k_N/M^{-1} s^{-1}	
entry	Y	pK_a (Y-PhOH)	**1**	**2**[b]
a	2,4-$(NO_2)_2$	4.11	4.19	174
b	3,4-$(NO_2)_2$	5.42	0.664	191
c	2-NO_2,4-Cl	6.46		6.18
d	4-NO_2	7.14	0.0306 (0.000332)[a]	5.94
e	4-CHO	7.66	0.00720	0.852
f	4-CN	7.95	0.0157	
g	4-COMe	8.05	0.00587	0.236
h	3-Cl	9.02	0.00245	0.0159
i	3-COMe	9.19	0.00211	0.00650
j	4-Cl	9.38	0.00149	

[a] The k_N value determined in MeCN. Reference 9. [b] The data for the reactions of **2a**−**i** were taken from ref 15 except the k_N value of **2c**. The k_N value for the reactions of **2c** was determined in this study.

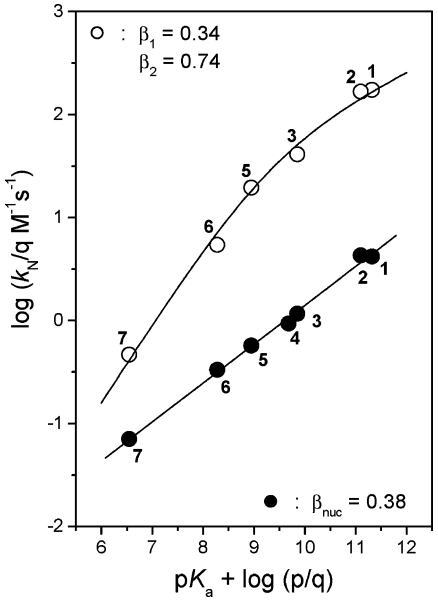
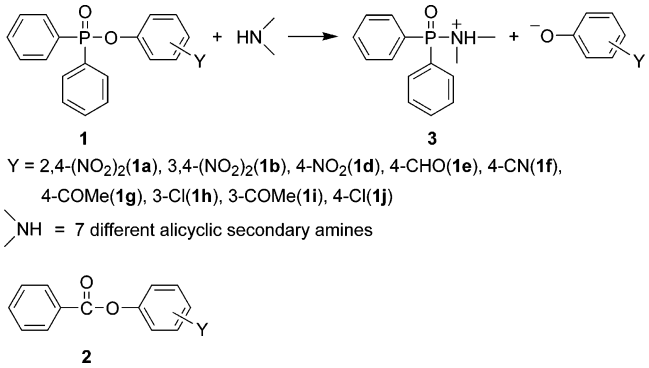


FIGURE 1. Brønsted-type plots for the reactions of 2,4-dinitrophenyl diphenylphosphinate (**1a**, ●) and 2,4-dinitrophenyl benzoate (**2a**, ○) with alicyclic secondary amines in 80 mol % H_2O/20 mol % DMSO at 25.0 ± 0.1 °C. The identity of the points is given in Table 1.

with a β_{nuc} value of 0.38, while the one for the corresponding reactions of **2a** is curved with decreasing the β_{nuc} value from 0.74 to 0.34 as the amine basicity increases.

The linear Brønsted-type plot found for the reaction of **1a** indicates that the basicity of amines does not affect the reaction mechanism in the current reactions over 5 pK_a units. The β_{nuc} of 0.38 determined for the reactions of **1a** is slightly smaller than the lower limit of β_{nuc} reported for the reactions of carboxylic esters which proceed through a concerted mechanism (β_{nuc} = 0.4−0.7).[12,13] However, one can suggest that the aminolysis of **1a** proceeds through a concerted mechanism as shown in Scheme 1, since reactions of phosphinate esters have been reported to result in smaller β_{nuc} values than the corresponding reactions of carbonyl or sulfonyl esters.[14]

SCHEME 1



On the other hand, the β_{nuc} value of the Brønsted-type plot shown in Figure 1 for the reactions of **2a** decreases from 0.74 to 0.34 as the amine basicity increases. On the basis of such a nonlinear Brønsted-type plot, we reported that the aminolysis of **2a** proceeds through a stepwise mechanism with a change in the RDS.[11] However, Castro et al. have recently suggested that the curved Brønsted-type plot for the aminolysis of **2a** is not due to a change in the RDS.[13] It is because the slopes of the nonlinear Brønsted-type plot are not in accordance with those reported for the reactions which have been suggested to proceed through a stepwise mechanism, i.e., $\beta_2 = 0.74$ at the low pK_a region is not large enough (e.g., $\beta_2 = 0.8-1.1$) while $\beta_1 = 0.34$ at the high pK_a region is not small enough for a stepwise mechanism (e.g., $\beta_2 = 0.1-0.3$).[13] Accordingly, the aminolysis of **2a** has been suggested to proceed very likely through a concerted mechanism.[13] The same conclusion has been drawn for the reactions of *S*-2,4-dinitrophenyl X-substituted thiobenzoates with a series of alicyclic secondary amines.[13a] Although Castro et al. have obtained curved Brønsted-type plots (i.e., $\beta_1 = 0.1-0.4$ and $\beta_2 = 0.7$ at high and low pK_a region, respectively), the reactions have been concluded to proceed through a concerted mechanism.[13a]

Thus, the curved Brønsted-type plot shown in Figure 1 for the aminolysis of **2a** appears to be insufficient to conclude whether the reaction proceeds through a concerted mechanism or through a stepwise pathway. To get more conclusive information about the reaction mechanism, the effect of the leaving group basicity on reactivity and mechanism has been investigated in the following section.

Effect of Leaving Group on Reactivity and Mechanism. Table 2 shows that the k_N value for the reactions of the phosphinates **1a**−**j** with piperidine decreases as the basicity of the leaving group increases, i.e., it decreases from 4.19 M^{-1} s^{-1} to 3.06×10^{-2} and 1.49×10^{-3} M^{-1} s^{-1} as the pK_a of the conjugate acid of the leaving aryloxide increases from 4.11 to 7.14 and 9.38, respectively. A similar result is obtained for the corresponding reactions of the benzoates **2a**−**i**.

The effect of the leaving group basicity on reactivity is illustrated in Figure 2. It is shown that the benzoates **2a**−**i** are more reactive than the phosphinates **1a**−**j**. Besides, the Brønsted-type plot for the reactions of **1a**−**j** with piperidine is linear with

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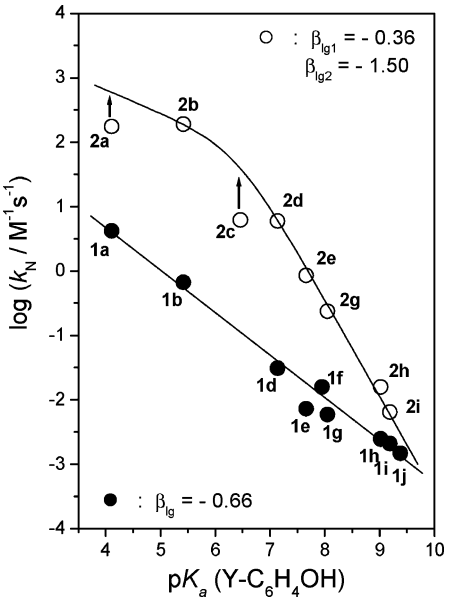


FIGURE 2. Brønsted-type plots for the reactions of Y-substituted phenyl diphenylphosphinates (**1a**−**j**, ●) and Y-substituted phenyl benzoates (**2a**−**i**, ○) with piperidine in 80 mol % H_2O/20 mol % DMSO at 25.0 ± 0.1 °C. The identity of the points is given in Table 2.

$\beta_{lg} = -0.66$, while that for the corresponding reactions of **2a**−**i** is curved with decreasing β_{lg} from −1.50 (β_{lg2}) to −0.36 (β_{lg1}).

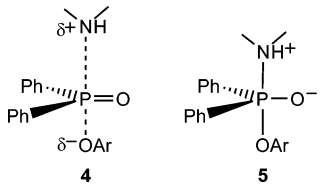
The linear Brønsted-type plot for the reactions of **1a**−**j** with piperidine indicates that the mechanism (or the RDS) is not varied on changing the leaving group basicity over 5 pK_a units. The β_{lg} value of −0.66 is too small for a stepwise mechanism in which collapse of the addition intermediate is the RDS or too large for reactions which proceed through rate determining formation of the intermediate. Accordingly, one can suggest that the aminolysis of **1a**−**j** in the current study proceeds through a concerted mechanism. This is consistent with the preceding argument that the aminolysis of **1a** proceeds through a concerted mechanism on the basis of the linear Brønsted-type plot with $\beta_{nuc} = 0.38$.

However, Cook et al. have concluded that reactions of 4-nitrophenyl diphenylphosphinate (**1d**) with various types of amines (including piperidine and morpholine) in MeCN proceed through a zwitterionic pentacoordinate intermediate in which collapse of the intermediate is the RDS.[9] One can suggest that the medium change from MeCN to aqueous DMSO is responsible for the opposing reaction mechanism since the reactions in the current study were performed in H_2O containing 20 mol % DMSO. This argument can be supported from the fact that the effect of medium on the reactivity and amine basicity is significant, e.g., as shown in Table 2, piperidine is ca. 2 orders of power less reactive toward **1d** in MeCN ($k_N = 3.32 \times 10^{-4}$ M^{-1} s^{-1}) than in the aqueous DMSO ($k_N = 3.06 \times 10^{-2}$ M^{-1} s^{-1}) although it has been reported to be ca. 7 pK_a units more basic in the former medium than in the latter.[16] Furthermore, we have recently shown that the medium change from aqueous DMSO to MeCN causes a change in reaction mechanism for aminolysis of aryl benzoates.[17]

As shown in Figure 2, the Brønsted-type plot for the reactions of **2a**−**i** is curved downwardly except **2a** and **2c**. The slope of the curved Brønsted-type plot for the reactions of **2b** and **2d**−**i** with piperidine decreases from −1.50 to −0.36 as the pK_a of the conjugate acid of the leaving aryloxide decreases. Since such a curved Brønsted-type plot is typical for reactions which proceed through a stepwise mechanism with a change in the RDS, the reactions of **2b** and **2d**−**i** with piperidine have been suggested to proceed through a stepwise mechanism.[15]

It is noted that **2a** and **2c** exhibit negative deviations from the curved Brønsted-type plot. Furthermore, **2a** is less reactive than **2b** although the former has a less basic leaving group than the latter. Thus, one might insist that the reaction of **2a** proceeds through a different mechanism, e.g., through a concerted mechanism. However, we propose that the negative deviation shown by **2a** and **2c** is not due to the nature of the reaction mechanism. Instead, steric hindrance is considered to be responsible for the low reactivity shown by **2a** and **2c**. This is because both **2a** and **2c** have a nitro group at the 2-position of the leaving aryloxide, and the presence of the 2-NO_2 group would exert large steric hindrance. A similar conclusion has been drawn for reactions of aryl phenyl carbonates with quinuclidine. Gresser and Jencks have found that phenyl 2,4-dinitrophenyl carbonate is less reactive than phenyl 3,4-dinitrophenyl carbonate and concluded that steric hindrance exerted by the 2-NO_2 group is responsible for the lower reactivity of the former carbonate.[18]

The steric hindrance appears to be insignificant for the phosphinate system since **1a** lies on the linear Brønsted-type plot. Several factors can be suggested to account for the absence of steric hindrance in the reactions of the phosphinate esters. (1) Steric hindrance would be significant for reactions in which bond formation between the electrophilic center and nucleophile is advanced greatly in the TS. Since β_{nuc} represents a relative degree of bond formation in the TS, the small β_{nuc} value determined in the aminolysis of **1a** (i.e., $\beta_{nuc} = 0.38$) suggests that the bond formation is not much advanced. This argument explains why the steric hindrance is unimportant for the reactions of **1a**. (2) The size of the electrophilic center is much larger in the phosphinate ester than in the benzoate ester. Besides, the electrophilic center of **1a** is tetrahedral at the ground state but becomes trigonal bipyramidal at the TS or the intermediate.[9,10] The attacking and leaving groups have been suggested to occupy the apical positions of the trigonal bipyramidal TS **4** or intermediate **5**.[9,10] Thus, the 2-NO_2 group in the leaving group of **1a** is too far away from the nucleophile to exert steric hindrance.



Reaction Mechanism Determined from Hammett and Yukawa−Tsuno Plots. To get further information on the mechanism for the reactions of **1a**−**j** with piperidine, Hammett plots have been constructed with use of σ^o and σ^- constants in Figure 3. Correlations of rate constants with σ^o and σ^- constants

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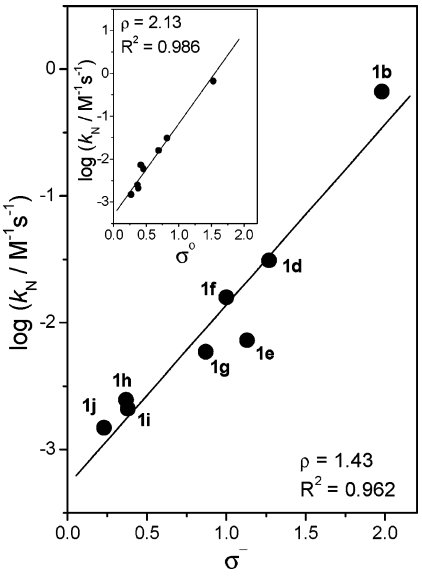

FIGURE 3. Plots of log k_N vs σ^- (or σ^o, inset) for the reactions of Y-substituted phenyl diphenylphosphinates (**1b**−**j**) with piperidine in 80 mol % H_2O/20 mol % DMSO at 25.0 ± 0.1 °C. The identity of the points is given in Table 2.

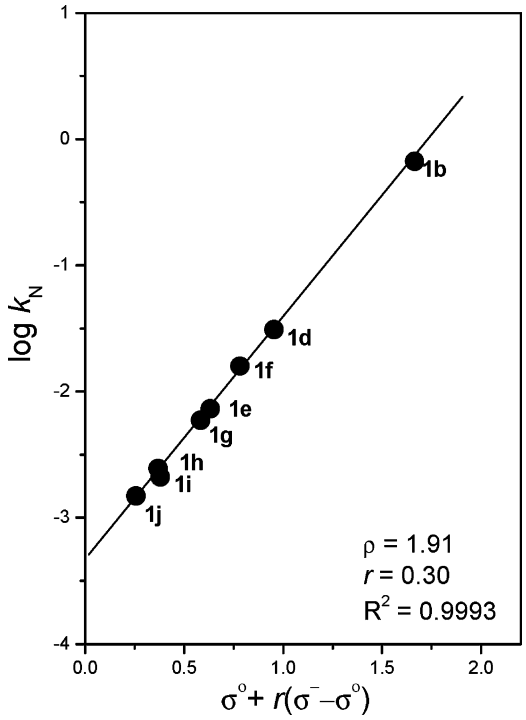

FIGURE 4. Yukawa−Tsuno plot for the reactions of Y-substituted phenyl diphenylphosphinates (**1b**−**j**) with piperidine in 80 mol % H_2O/20 mol % DMSO at 25.0 ± 0.1 °C. The identity of the points is given in Table 2.

have often been attempted to investigate whether the leaving group departure occurs at the RDS or not.[5a,8b,c,19] If the leaving group departure occurs at the RDS either in a concerted or stepwise mechanism, a partial negative charge would develop at the oxygen atom of the leaving aryloxide. Since such a negative charge can be delocalized on the substituent in the leaving group, σ^- constants should give a better linear correlation than σ^o. On the contrary, σ^o constants should result in a better linearity than σ^- when the leaving group departure occurs after the RDS. In fact, σ^o constants have been reported to exhibit much better Hammett correlations than σ^- constants for alkaline hydrolysis of aryl diphenylphosphinates[8c] and diphenylphosphinothioates,[8b] imidazole catalyzed hydrolysis of aryl diphenylphosphinates,[8d] and alkaline ethanolysis of aryl dimethylphosphinates.[5a] Thus, these reactions have been concluded to proceed through a stepwise mechanism in which the leaving group departure occurs after the RDS.[5a,8b−d]

As shown in Figure 3, σ^- constants exhibit a poor Hammett correlation ($R^2 = 0.962$). A slightly better correlation with σ^o is shown ($R^2 = 0.986$) in the inset of Figure 3, indicating that the leaving group departure is not advanced at the RDS. Thus, one might suggest that the aminolysis of **1b**−**j** proceeds through a stepwise mechanism in which the departure of the leaving group occurs after the RDS. Clearly, this is inconsistent with the preceding argument that the reactions of **1a**−**j** proceed through a concerted mechanism on the basis of the linear Brønsted-type plots with $\beta_{nuc} = 0.38$ (Figure 1) and $\beta_{lg} = -0.66$ (Figure 2).

We have recently shown that determination of reaction mechanism based just on a linear or nonlinear Hammett plot can be misleading for nucleophilic substitution reactions of aryl benzoates and related systems.[11,20−22] For example, the Hammett plot for aminolysis of 2,4-dinitrophenyl X-substituted benzoates has been found to be nonlinear, i.e., the slope of the Hammett plot decreases as the substituent X in the benzoyl moiety changes from electron donating groups to electron withdrawing ones.[11] Traditionally, such a nonlinear Hammett plot has been interpreted as a change in the RDS. However, we have shown that the nonlinear Hammett plot is not due to a change in the RDS on the basis of the fact that the Yukawa−Tsuno plot for the same reaction exhibits excellent linearity.[11]

$$\log(k^X/k^H) = \rho[\sigma^o + r(\sigma^- - \sigma^o)] \quad (1)$$

The Yukawa−Tsuno equation (eq 1)[23,24] has been employed in this study. The magnitude of the r value in the Yukawa−Tsuno equation represents the resonance demand of the reaction center or the extent of resonance contribution.[23,24] As shown in Figure 4, the Yukawa−Tsuno plot for the reactions of **1b**−**j** with piperidine results in an excellent linear correlation ($R^2 = 0.9993$) with $r = 0.30$. The best correlation would be obtained with σ^- constants when $r = 1$ or with σ^o constants when $r = 0$. Since the r value determined in this study is neither 0 nor 1, the Yukawa−Tsuno plot exhibits the best linear correlation.

The fact that $r \neq 0$ for the aminolysis of **1b**−**j** indicates that the leaving group cleavage occurs at the RDS. This is consistent

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with the preceding argument that the current aminolysis of **1a**−**j** proceeds through a concerted mechanism. However, one can suggest that only a small amount of negative charge would develop on the oxygen atom of the leaving aryloxide on the basis of the small r value. Thus, one can conclude that the aminolysis of **1a**−**j** proceeds through a concerted mechanism in which nucleophilic attack and leaving group departure are advanced only to a small extent at the TS on the basis of the small β_{nuc} (=0.38) and small r (=0.30) values, respectively.

Conclusions

The present study has allowed us to conclude the following: (1) The phophinates **1a**−**j** are less reactive than the benzoates **2a**−**i**. (2) The aminolysis of **1a**−**j** proceeds through a concerted mechanism, while the corresponding reaction of **2a**−**i** proceeds through a stepwise mechanism with a change in the RDS. (3) The reactions of **1b**−**j** result in a poor Hammett correlation with σ^- constants but slightly better correlation with σ^o. However, this result does not indicate that the departure of the leaving group occurs after the RDS, since the corresponding Yukawa−Tsuno plot exhibits an excellent linear correlation with $r = 0.30$. (4) The aminolysis of **1a**−**j** proceeds through an early TS, i.e., bond formation of nucleophiles and bond cleavage of the leaving group are advanced only to a small extent at the TS.

Experimental Section

Materials. Aryl diphenylphosphinates **1a**−**j** were prepared by modification of literature procedures.[5,8a,9] Diphenylphosphinyl chloride (1.9 mL, 10 mmol) was dissolved in dry ether (20 mL). Y-substituted phenol (10 mmol) and triethylamine (1.4 mL, 10 mmol) were dissolved in dry ether (20 mL) and added to the acid chloride solution slowly. The reaction mixture was stirred under nitrogen at room temperature. The progress of the reaction was monitored by TLC. When the reaction was complete, the reaction mixture was worked up as follows: $Et_3NH^+Cl^-$ was filtered off, and then the ether solution was concentrated under reduced pressure. The crude product was purified by column chromatography (silica gel, methylene chloride/ethyl acetate 50/50). Their purity was checked by their melting points for the known compounds and the identity of unknown compounds **1h**, **1i**, and **1j** was checked by elemental analysis and ^{1}H NMR spectra (Supporting Information).

3-Chlorophenyl diphenylphosphinate (1h): mp 108−110 °C; ^{1}H NMR (250 MHz, $CDCl_3$) δ 7.01−7.14 (m, 4H), 7.47−7.54 (m, 6H), 7.84−7.92 (m, 4H). Anal. Calcd for $C_{18}H_{14}ClO_2P$: C, 65.77; H, 4.29. Found: C, 65.77; H, 4.30.

3-Acetylphenyl diphenylphosphinate (1i): mp 99−101 °C; ^{1}H NMR (250 MHz, $CDCl_3$) δ 2.52 (s, 3H), 7.15−7.25 (m, 1H), 7.34−7.48 (m, 7H), 7.50−7.54 (m, 2H), 7.86−7.94 (m, 4H). Anal. Calcd for $C_{20}H_{17}O_3P$: C, 71.42; H, 5.09. Found: C, 71.23; H, 5.11.

4-Chlorophenyl diphenylphosphinate (1j): mp 119−121 °C; ^{1}H NMR (250 MHz, $CDCl_3$) δ 7.16−7.19 (m, 4H), 7.46−7.53 (m, 6H), 7.83−7.91 (m, 4H). Anal. Calcd for $C_{18}H_{14}ClO_2P$: C, 65.77; H, 4.29. Found: C, 65.62; H, 4.26.

Amines and other chemicals were of the highest quality available. Doubly glass distilled water was further boiled and cooled under nitrogen just before use. Due to low solubility of **1a**−**j** in pure water, aqueous DMSO (80 mol % H_2O/20 mol % DMSO) was used as the reaction medium.

Kinetics. The kinetic study was performed with a UV−vis spectrophotometer equipped with a constant temperature circulating bath to keep the reaction mixture at 25.0 ± 0.1 °C. The reactions were followed by monitoring the appearance of the leaving aryloxide. All the reactions were carried out under pseudo-first-order conditions in which amine concentrations were at least 20 times greater than the substrate concentration. The amine stock solution of ca. 0.2 M was prepared by dissolving 2 equiv of free amine and 1 equiv of standardized HCl solution to make a self-buffered solution in a 25.0 mL volumetric flask.

Typically, the reaction was initiated by adding 5 μL of a 0.02 M solution of 2,4-dinitrophenyl diphenylphosphinate (**1a**) in acetonitrile to a 10 mm quartz UV cell containing 2.50 mL of the thermostated reaction mixture made up of solvent and aliquot of the amine stock solution. All the solutions were transferred by gastight syringes. Generally, the amine concentration was varied over the range (5−100) × 10^{-3} M, while the substrate concentration was 4 × 10^{-5} M. Pseudo-first-order rate constants (k_{obsd}) were calculated from the equation $\ln(A_\infty - A_t) = -k_{obsd}t + C$. The plots of $\ln(A_\infty - A_t)$ vs time were linear over ca. 90% of the total reaction. Usually, five different amine concentrations were employed and replicate values of k_{obsd} were determined to obtain the second-order rate constants (k_N) from the slope of linear plots of k_{obsd} vs amine concentrations.

Products Analysis. Y-substituted phenoxide was liberated quantitatively and identified as one of the products in the reaction of **1a**−**j** with piperidine by comparison of the UV−vis spectra after completion of the reactions with those of authentic samples under the same reaction conditions. The other product, diphenylpiperidinophosphine oxide, was analyzed quantitatively by HPLC (R_f = 3.60 min, eluent = CH_3CN, flow rate = 1.0 mL/min, detection at 225 nm).

Acknowledgment. This work was supported by the Korea Research Foundation (2005-015-C00256).

Supporting Information Available: ^{1}H NMR spectra for compounds **1h**, **1i**, and **1j**; Tables S1−S7 for the kinetic conditions and data for reactions of **1a** with seven different alicyclic secondary amines and Tables S8−S16 for the kinetic data for reactions of **1b**−**j** and **2c** with piperidine. This material is available free of charge via the Internet at http://pubs.acs.org.

JO061308X