

## Kinetics and Mechanism of Anilinolysis of Phenyl *N*-Phenyl Phosphoramidochloridate in Acetonitrile

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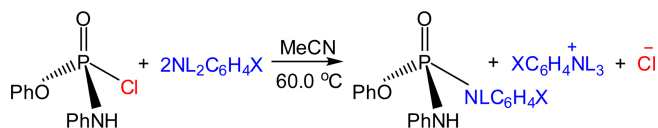
Received March 9, 2012, Accepted July 11, 2012

The kinetic studies on the reactions of phenyl *N*-phenyl phosphoramidochloridate (**8**) with substituted anilines (XC<sub>6</sub>H<sub>4</sub>NH<sub>2</sub>) and deuterated anilines (XC<sub>6</sub>H<sub>4</sub>ND<sub>2</sub>) have been carried out in acetonitrile at 60.0 °C. The obtained deuterium kinetic isotope effects (DKIEs;  $k_H/k_D$ ) are huge secondary inverse ( $k_H/k_D = 0.52$ – $0.69$ ). A concerted mechanism is proposed with a backside attack transition state (TS) on the basis of the secondary inverse DKIEs and the variation trends of the  $k_H/k_D$  values with X. The degree of bond formation in the TS is really extensive taking into account the very small values of the DKIEs. The steric effects of the two ligands on the rates are extensively discussed for the aminolyses of the chlorophosphate-type substrates on the basis of the Taft equation.

**Key Words** : Phosphoryl transfer reaction, Anilinolysis, Phenyl *N*-phenyl phosphoramidochloridate, Deuterium kinetic isotope effect, Steric effect

### Introduction

To extend the phosphoryl and thiophosphoryl transfer reactions of anilinolyses, the kinetic studies on the reactions of phenyl *N*-phenyl phosphoramidochloridate (**8**), involving anilino (C<sub>6</sub>H<sub>5</sub>NH) ligand, with substituted anilines (XC<sub>6</sub>H<sub>4</sub>NH<sub>2</sub>) and deuterated anilines (XC<sub>6</sub>H<sub>4</sub>ND<sub>2</sub>) have been carried out in acetonitrile (MeCN) at 60.0 ± 0.1 °C (Scheme 1). The kinetic data of the present work are compared with those of the anilinolyses of (R<sub>1</sub>O)(R<sub>2</sub>O)P(=O)Cl-type chlorophosphates: dimethyl [**1**: (MeO)<sub>2</sub>P(=O)Cl],<sup>1a</sup> diethyl [**2**: (EtO)<sub>2</sub>P(=O)Cl],<sup>1a</sup> dipropyl [**3**: (PrO)<sub>2</sub>P(=O)Cl],<sup>1b</sup> dibutyl [**4**: (BuO)<sub>2</sub>P(=O)Cl],<sup>1c</sup> diisopropyl [**5**: (*i*-PrO)<sub>2</sub>P(=O)Cl],<sup>1d</sup> Y-aryl ethyl [**6**: (EtO)(YC<sub>6</sub>H<sub>4</sub>O)P(=O)Cl],<sup>1e</sup> and Y-aryl phenyl [**7**: (PhO)(YC<sub>6</sub>H<sub>4</sub>O)P(=O)Cl]<sup>1f</sup> chlorophosphates in MeCN. The steric effects of the two ligands on the anilinolysis rates of the eight substrates (**1**–**8**) are discussed by means of the Taft eq.<sup>2</sup> The numbering of the substrates of **1**–**8** follows the sequence of the summation of the Taft steric constants of the two ligands, R<sub>1</sub> and R<sub>2</sub>.<sup>2</sup>



L = H or D  
X = 4-MeO, 4-Me, 3-Me, H, 4-F, 4-Cl, 3-Cl

**Scheme 1.** The anilinolysis of phenyl *N*-phenyl phosphoramidochloridate (**8**) in MeCN at 60.0 °C.

### Results and Discussion

The observed pseudo-first-order rate constants ( $k_{\text{obsd}}$ ) were found to follow Eq. (1) for all the reactions under pseudo-

first-order conditions with a large excess of aniline nucleophile. The  $k_0$  values were negligible ( $k_0 \approx 0$ ) in MeCN. The second-order rate constants ( $k_{\text{H(D)}}$ ) were determined with at least five concentrations of anilines. The linear plots of Eq. (1) suggest that there is no base-catalysis or noticeable side reaction and that the overall reaction is described by Scheme 1.

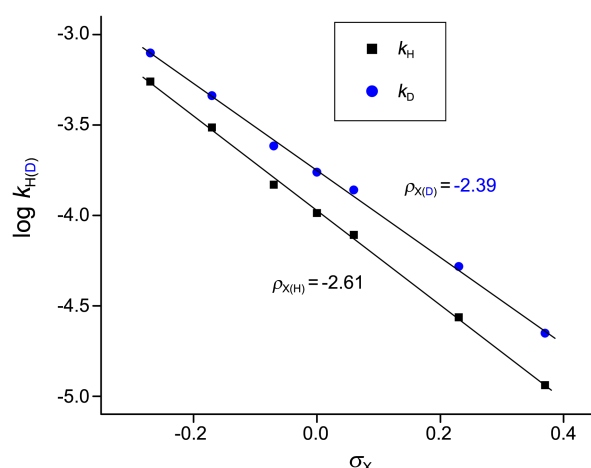
$$k_{\text{obsd}} = k_0 + k_{\text{H(D)}} [\text{XC}_6\text{H}_4\text{NH}_2(\text{D}_2)] \quad (1)$$

The second-order rate constants ( $k_H$  and  $k_D$ ) are summarized in Table 1, together with the deuterium kinetic isotope effects (DKIEs;  $k_H/k_D$ ) and Hammett  $\rho_X$  and Brönsted  $\beta_X$  selectivity parameters. The  $\text{p}K_a(\text{X})$  values of the X-anilines in water were used to obtain the Brönsted  $\beta_X$  values in MeCN, and this procedure was justified experimentally and theoretically.<sup>3</sup> The values of  $\text{p}K_a(\text{X})$  and  $\sigma_X$  of the deuterated

**Table 1.** The Second-Order Rate Constants ( $k_{\text{H(D)}} \times 10^4/\text{M}^{-1} \text{s}^{-1}$ ), Selectivity Parameters ( $\rho_X$  and  $\beta_X$ ),<sup>a</sup> and DKIEs ( $k_H/k_D$ ) of the Reactions of Phenyl *N*-Phenyl Phosphoramidochloridate (**8**) with XC<sub>6</sub>H<sub>4</sub>NH<sub>2</sub>(D<sub>2</sub>) in MeCN at 60.0 °C

X	$k_H \times 10^4$	$k_D \times 10^4$	$k_H/k_D$
4-MeO	5.50 ± 0.03 <sup>b</sup>	7.92 ± 0.02	0.694 ± 0.004 <sup>g</sup>
4-Me	3.06 ± 0.01	4.60 ± 0.04	0.665 ± 0.006
3-Me	1.48 ± 0.01	2.42 ± 0.01	0.612 ± 0.005
H	1.03 ± 0.01	1.73 ± 0.01	0.595 ± 0.007
4-F	0.780 ± 0.004	1.38 ± 0.01	0.565 ± 0.005
4-Cl	0.273 ± 0.003	0.521 ± 0.004	0.524 ± 0.007
3-Cl	0.115 ± 0.001	0.223 ± 0.001	0.516 ± 0.005
$-\rho_X(\text{H and D})$	2.61 ± 0.02 <sup>c</sup>	2.39 ± 0.02 <sup>e</sup>	
$\beta_X(\text{H and D})$	0.93 ± 0.03 <sup>d</sup>	0.85 ± 0.02 <sup>f</sup>	

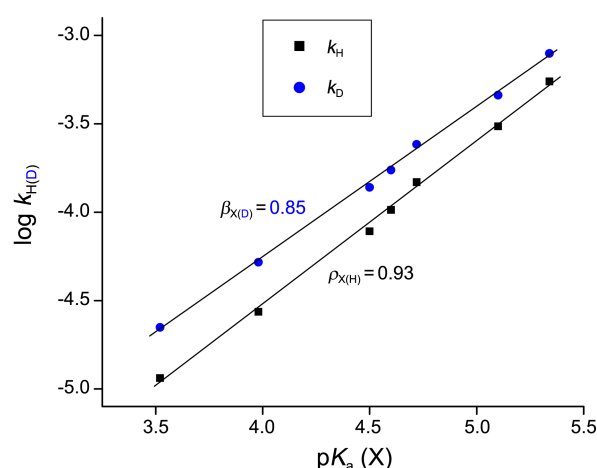
<sup>a</sup>The  $\sigma$  values were taken from ref. 6. The  $\text{p}K_a$  values of X-anilines in water were taken from ref. 7. <sup>b</sup>Standard deviation. <sup>c</sup>Correlation coefficient,  $r = 0.999$ . <sup>d</sup> $r = 0.999$ . <sup>e</sup> $r = 0.999$ . <sup>f</sup> $r = 0.999$ . <sup>g</sup>Standard error  $\{= 1/k_D[(\Delta k_H)^2 + (k_H/k_D)^2 \times (\Delta k_D)^2]^{1/2}\}$  from ref. 8.



**Figure 1.** The Hammett plots ( $\log k_{H(D)}$  vs  $\sigma_X$ ) of the reactions of phenyl *N*-phenyl phosphoramidochloridate (**8**) with  $\text{XC}_6\text{H}_4\text{NH}_2$  ( $\text{D}_2$ ) in MeCN at 60.0 °C.

X-anilines are assumed to be identical to those of the X-anilines. Perrin and coworkers reported that the basicities of  $\beta$ -deuterated analogs of benzylamine, *N,N*-dimethylaniline and methylamine increase roughly by 0.02  $\text{p}K_a$  units per deuterium, and that these effects are additive.<sup>4</sup> Thus, the  $\text{p}K_a(\text{X})$  values of deuterated X-anilines may be slightly greater than those of X-anilines, however, the difference is too small to be taken into account. Figures 2 and 3 show the Hammett ( $\log k_{H(D)}$  vs  $\sigma_X$ ) and Brønsted [ $\log k_{H(D)}$  vs  $\text{p}K_a(\text{X})$ ] plots with X, respectively. The stronger nucleophile leads to the faster rate as observed in a typical nucleophilic substitution reaction with positive charge development at the nucleophilic N atom in the TS. The obtained DKIEs are the largest secondary inverse ( $k_H/k_D = 0.52\text{--}0.69 < 1$ ) for the P=O systems, observed in this lab.<sup>5</sup> The values of DKIEs invariably decrease as the aniline becomes less basic. The magnitudes of  $\rho_X$  and  $\beta_X$  values with anilines are slightly greater than those with deuterated anilines, suggesting more sensitive to substituent X effects of anilines compared to those of deuterated anilines.

The second-order rate constants ( $k_H$ ) with unsubstituted aniline ( $\text{C}_6\text{H}_5\text{NH}_2$ ) at 55.0 °C, NBO charges at the reaction center P atom [B3LYP/6-311+G(d,p) level of theory] in the



**Figure 2.** The Brønsted plots [ $\log k_{H(D)}$  vs  $\text{p}K_a(\text{X})$ ] of the reactions of phenyl *N*-phenyl phosphoramidochloridate (**8**) with  $\text{XC}_6\text{H}_4\text{NH}_2$  ( $\text{D}_2$ ) in MeCN at 60.0 °C.

gas phase,<sup>10</sup> summations of the Taft steric constants of  $\text{R}_1$  and  $\text{R}_2$  [ $\Sigma E_s = E_s(\text{R}_1) + E_s(\text{R}_2)$ ],<sup>2</sup> Brønsted coefficients ( $\beta_{X(H)}$  and  $\beta_{X(D)}$ ), DKIEs ( $k_H/k_D$ ), and cross-interaction constants (CICs;  $\rho_{XY}$ )<sup>11</sup> of the reactions of **1-8** with  $\text{XC}_6\text{H}_4\text{NH}_2(\text{D}_2)$  in MeCN are summarized in Table 2. The Brønsted coefficients ( $\beta_{X(H)}$ ) are in the range of 1.0–1.2, when excluding **7**. There is no correlation between the second-order rate constant ( $k_H$  with  $\text{C}_6\text{H}_5\text{NH}_2$ ) and positive (NBO) charge at the reaction center P atom in MeCN at 55.0 °C as seen in Figure 3, implying that the inductive effects of the two ligands do not play any role to decide the reactivity of anilinolyses of **1-8**.

The Taft Eq. (2) can be used to rationalize the steric effects of the two ligands on the reaction rate where  $k_H$  is the second-order rate constant with  $\text{C}_6\text{H}_5\text{NH}_2$ ,  $E_s$  is the Taft steric constant [ $E_s(\text{R}) = 0(\text{Me}); -0.07(\text{Et}); -0.36(\text{Pr}); -0.39(\text{Bu}); -0.47(i\text{-Pr}); -2.48(\text{Ph})$ ],  $\Sigma E_s$  is the summation of the steric constants of the two ligands, and  $\delta$  is the sensitivity coefficient.<sup>2</sup>

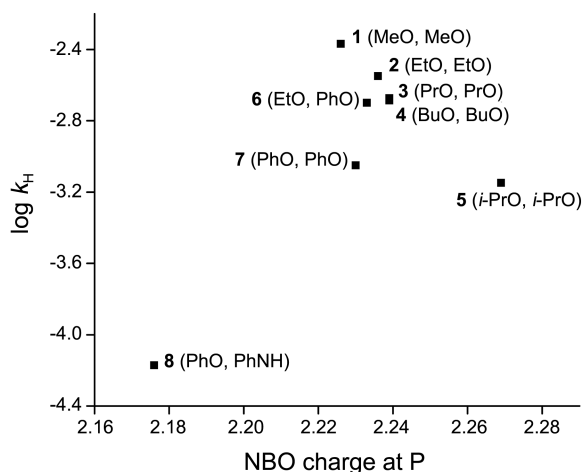
$$\log k_H = \delta \Sigma E_s + C \quad (2)$$

Figure 4 shows the Taft plot of  $\log k_H$  with unsubstituted aniline ( $\text{C}_6\text{H}_5\text{NH}_2$ ) against the summation of the Taft steric constants of the two ligands for the anilinolyses of eight (**1-**

**Table 2.** Summary of the Second-Order Rate Constants ( $k_H \times 10^3/\text{M}^{-1} \text{ s}^{-1}$ ) with  $\text{C}_6\text{H}_5\text{NH}_2$  at 55.0 °C, NBO Charges at the Reaction Center P Atom, Summations of the Taft Steric Constants of  $\text{R}_1$  and  $\text{R}_2$  [ $\Sigma E_s = E_s(\text{R}_1) + E_s(\text{R}_2)$ ], Brønsted Coefficients ( $\beta_{X(H)}$ ), DKIEs ( $k_H/k_D$ ), and CICs ( $\rho_{XY}$ ) for the Reactions of **1-8** with  $\text{XC}_6\text{H}_4\text{NH}_2(\text{D}_2)$  in MeCN

Substrate	$k_H \times 10^3^a$	Charge at P	$-\Sigma E_s^d$	$\beta_{X(H)}$	$k_H/k_D$	$\rho_{XY}$
<b>1:</b> $(\text{MeO})_2\text{P}(=\text{O})\text{Cl}$	4.28	2.226	0.00	0.96	0.80–0.98	–
<b>2:</b> $(\text{EtO})_2\text{P}(=\text{O})\text{Cl}$	2.82	2.236	0.14	1.06	0.71–0.92	–
<b>3:</b> $(\text{PrO})_2\text{P}(=\text{O})\text{Cl}$	2.12	2.239	0.72	1.08	0.74–1.09	–
<b>4:</b> $(\text{BuO})_2\text{P}(=\text{O})\text{Cl}$	2.06	2.239	0.78	1.11	0.86–1.10	–
<b>5:</b> $(i\text{-PrO})_2\text{P}(=\text{O})\text{Cl}$	0.710	2.269	0.94	1.10	0.71–0.95	–
<b>6:</b> $(\text{EtO})(\text{YC}_6\text{H}_4\text{O})\text{P}(=\text{O})\text{Cl}$	2.00 <sup>b</sup>	2.233 <sup>b</sup>	2.55	1.09–1.20	1.07–1.28	–0.60
<b>7:</b> $(\text{PhO})(\text{YC}_6\text{H}_4\text{O})\text{P}(=\text{O})\text{Cl}$	0.891 <sup>b</sup>	2.230 <sup>b</sup>	4.96	1.24–1.68	0.61–0.87	–1.31
<b>8:</b> $(\text{PhO})(\text{PhNH})\text{P}(=\text{O})\text{Cl}$	0.0674 <sup>c</sup>	2.176	4.98 <sup>e</sup>	0.93	0.52–0.69	–

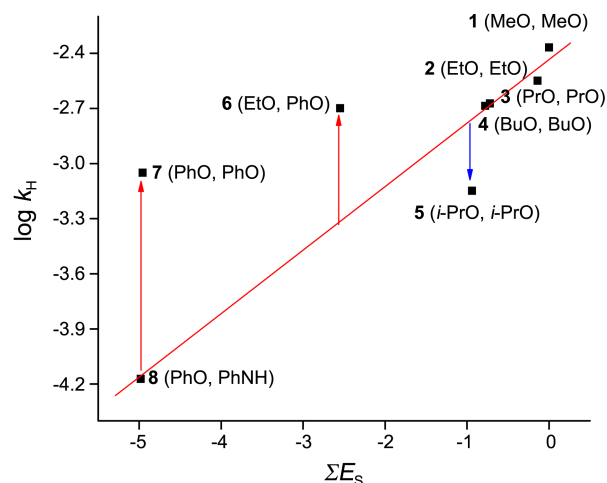
<sup>a</sup>The values with unsubstituted aniline at 55.0 °C. <sup>b</sup>The values with Y = H. <sup>c</sup>Experimental value at 55.0 °C. <sup>d</sup>Note that the value of  $\Sigma E_s$  is not ' $E_s(\text{R}_1\text{O}) + E_s(\text{R}_2\text{O})$ ' but ' $E_s(\text{R}_1) + E_s(\text{R}_2)$ ' since the data of Taft steric constants of  $\text{R}_i\text{O}$  are not available. <sup>e</sup>See ref. 9.



**Figure 3.** The plot of  $\log k_H$  with unsubstituted aniline against NBO charge at the reaction center P atom in the substrate for the anilinolyses of **1-8** in MeCN at 55.0 °C. The number of the substrate and two ligands are displayed next to the corresponding point.

**8**) substrates in MeCN at 55.0 °C, according to Eq. (2). The anilinolysis rates of **1-4** and **6-8** (excluding **5**) are very roughly dependent upon the steric effects of the two ligands and the rate is inversely proportional to the size of the two ligands. The pyridinolysis rates of **1-4** and **8** are also qualitatively dependent upon the steric effects of the two ligands (see Fig. R1).<sup>12,13</sup> The anilinolyses of **6** with ethoxy and phenoxy ligands and **7** with two phenoxy ligands show great positive deviations from the plot. The pyridinolysis of **7** also shows exceptionally great positive deviation from the plot.<sup>12a,13</sup> On the contrary, the anilinolysis of **5** with two *i*-PrO ligands shows great negative deviation from the plot. The substrate of **5** has not only the greatest magnitude of the positive charge at the reaction center P atom among eight substrates but also smaller size of the two ligands compared to **6-8**. These indicate that the anilinolysis rate of **5** is exceptionally slow to be rationalized by the conventional stereoelectronic effects. The pyridinolysis of **5** also shows great negative deviation from the plot.<sup>12c,13</sup> At this point, the authors tentatively suggest that the exceptionally slow rates of the anilinolysis and pyridinolysis of **5** are attributed to an unexpected steric hindrance of the two *i*-PrO ligands which cannot be predicted by the Taft  $\Sigma E_s$ . The sensitivity coefficient for the anilinolyses of five substrates of **1-4** and **8** gives  $\delta = 0.35$  with  $r = 0.998$ , while that for the pyridinolyses of five substrates of **1-4** and **8** gave  $\delta = 0.14$  with  $r = 0.963$ .<sup>13</sup> The steric effects of the two ligands on the anilinolysis rates are much greater than those on the pyridinolysis rates. It should be noted that the value of  $\Sigma E_s$  is not ' $E_s(R_1O) + E_s(R_2O)$ ' but ' $E_s(R_1) + E_s(R_2)$ ' because of the lack of data of the Taft steric constant of  $R_2O$ .

The DKIEs are one of the strong tools to clarify the reaction mechanism. The DKIEs have provided a useful means to determine the TS structures in the nucleophilic substitution reactions, and how the reactants, especially through changes in substituents, alter the TS structures.

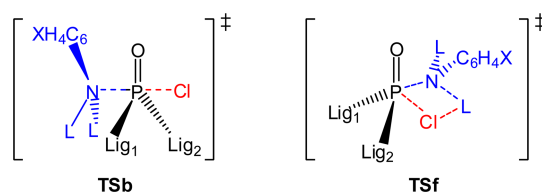


**Figure 4.** The Taft plot of  $\log k_H$  with unsubstituted aniline against  $\Sigma E_s$  for the anilinolyses of **1-8** in MeCN at 55.0 °C. The number of the substrate and two ligands are displayed next to the corresponding point.

Incorporation of deuterium in the nucleophile has an advantage in that the  $\alpha$ -DKIEs reflect only the degree of bond formation. When partial deprotonation of the aniline occurs in a rate-limiting step by hydrogen bonding, the  $k_H/k_D$  values are greater than unity, primary normal ( $k_H/k_D > 1.0$ ).<sup>14</sup> The greater the extent of the hydrogen bond, the value of  $k_H/k_D$  becomes greater. In contrast, the DKIEs can only be secondary inverse ( $k_H/k_D < 1.0$ ) in a normal  $S_N2$  reaction, since the N–H(D) vibrational frequencies invariably increase upon going to the TS because of an increase in steric congestion in the bond-making process.<sup>15</sup> The greater the degree of the steric congestion in the TS, the value of  $k_H/k_D$  becomes smaller.

Thus, the attacking direction of aniline nucleophile can be *semi*-quantitatively divided into three groups on the basis of the magnitudes of the  $k_H/k_D$  values: (i) predominant backside attack TSb (Scheme 2) when  $k_H/k_D < 1$ ; (ii) the fraction of the frontside attack involving a hydrogen-bonded four-center-type TSf (Scheme 2) is greater than that of backside attack TSb when  $1.0 < k_H/k_D < 1.1$ ; (iii) predominant frontside attack involving a hydrogen-bonded four-center-type TSf when  $k_H/k_D > 1.1$ .<sup>16</sup>

The DKIEs of the anilinolyses of **1-8** are as follows: (i) secondary inverse for **1** ( $k_H/k_D = 0.80$ - $0.98$ ),<sup>1a</sup> **2** ( $k_H/k_D = 0.71$ - $0.92$ ),<sup>1a</sup> **5** ( $k_H/k_D = 0.71$ - $0.92$ ),<sup>1d</sup> **7** ( $k_H/k_D = 0.61$ - $0.87$ )<sup>1f</sup> and **8** ( $k_H/k_D = 0.52$ - $0.69$ ); (ii) primary normal ( $k_H/k_D = 1.01$ - $1.09$ ) with the strongly basic anilines while secondary



**Scheme 2.** Backside attack TSb and frontside attack TSf for the anilinolyses of chlorophosphates. The two ligands are denoted as Lig<sub>1</sub> and Lig<sub>2</sub>.

inverse ( $k_H/k_D = 0.74$ – $0.82$ ) with the weakly basic anilines for **3**;<sup>1b</sup> (iii) secondary inverse ( $k_H/k_D = 0.86$ – $0.97$ ) with the strongly basic anilines while primary normal ( $k_H/k_D = 1.04$ – $1.10$ ) with the weakly basic anilines for **4**;<sup>1c</sup> and (iv) primary normal ( $k_H/k_D = 1.07$ – $1.28$ ) for **6**.<sup>1c</sup> The authors accordingly propose the attacking direction of the aniline nucleophile: (i) predominant backside attack TSb for **1**, **2**, **5**, **7**, and **8**; (ii) predominant backside attack TSb with the weakly basic anilines and grater frontside attack involving a hydrogen-bonded four-center-type TSf than that of backside attack TSb with the strongly basic anilines for **3**; (iii) predominant backside attack TSb with the strongly basic anilines and grater fraction of frontside attack TSf than that of backside attack TSb with the weakly basic anilines for **4**; (iv) predominant frontside attack involving a hydrogen-bonded four-center-type TSf for **6**.

The CIC is also one of the strong tools to clarify the reaction mechanism.<sup>9</sup> The sign of the CIC ( $\rho_{XY}$ ) is negative in a normal  $S_N2$  reaction (or in a stepwise reaction with a rate-limiting bond formation), and positive in a stepwise reaction with a rate-limiting leaving group expulsion from the intermediate. The magnitude of the CIC is inversely proportional to the distance between X and Y through the reaction center; the tighter the TS, the greater the magnitude of the CIC. Thus, the authors proposed that the anilinolyses of **6** and **7** proceed through a concerted mechanism on the basis of the negative sign of CIC, and the TS of **7** with  $\rho_{XY} = -1.31$ <sup>1f</sup> is tighter than that of **6** with  $\rho_{XY} = -0.60$ .<sup>1c</sup> The authors proposed that the anilinolyses of **1**, **2**, **3**, and **4** proceed through a concerted mechanism.<sup>1a-c</sup> In the case of **5**, a stepwise mechanism with a rate-limiting bond breaking for the strongly basic anilines and with a rate-limiting bond formation for the weakly basic anilines were proposed on the basis of the variation trends of the values of DKIEs with X.<sup>1d,17</sup> In the present work of **8**, the authors propose a concerted  $S_N2$  mechanism on the basis of the variation trends of the values of DKIEs with X,<sup>17</sup> and the degree of bond formation in the TS is very extensively taking into account the considerably small values, *i.e.*, huge secondary inverse DKIEs, of  $k_H/k_D = 0.52$ – $0.69$ .

Activation parameters, enthalpy and entropy of activation, are determined of the reaction of phenyl *N*-phenyl phosphoramidochloridate with  $C_6H_5NH_2$  in MeCN (Table S1). The activation enthalpy ( $16.0 \text{ kcal mol}^{-1}$ ) is greater than those ( $2$ – $10 \text{ kcal mol}^{-1}$ ) for typical aminolyses of  $P=O$  systems while the magnitude of activation entropy ( $-29 \text{ cal mol}^{-1} \text{ K}^{-1}$ ) is smaller than those ( $-40$  to  $-70 \text{ cal mol}^{-1} \text{ K}^{-1}$ ) for typical aminolyses of  $P=O$  systems. This may be ascribed to the greater degree of bond formation of the present work compared to typical  $P=O$  systems.

## Experimental Section

**Materials.** Phenyl *N*-phenyl phosphoramidochloridate (99%) and HPLC grade acetonitrile (water content is less than 0.005%) were used without further purification. Anilines were redistilled or recrystallized before use as previously

described.<sup>1</sup> Deuterated anilines were synthesized by heating anilines and deuterium oxide (99.9 atom %D) and one drop of HCl as catalyst at  $85^\circ\text{C}$  for 72 hr, and after numerous attempts, anilines were deuterated more than 98%, as confirmed by  $^1\text{H-NMR}$ ,  $^2\text{D-NMR}$ , and GC-MS comparing 4-chloroaniline with deuterated 4-chloroaniline ( $4\text{-Cl-C}_6\text{H}_4\text{ND}_2$ ) (see supporting information).

**Kinetic Procedure.** Rates were measured conductometrically at  $60.0^\circ\text{C}$ . The conductivity bridge used in this work was a self-made computer automated A/D converter conductivity bridge. Pseudo-first-order rate constants,  $k_{\text{obsd}}$  were measured by curve fitting analysis in origin program with a large excess of anilines,  $[\text{substrate}] = 1 \times 10^{-3} \text{ M}$  and  $[\text{X-aniline}] = (0.1\text{--}0.5) \text{ M}$ . Second-order rate constants,  $k_2$ , were obtained from the slope of a plot of  $k_{\text{obsd}}$  vs.  $[\text{X-aniline}]$  with at least five concentrations of anilines. The pseudo-first-order rate constant values ( $k_{\text{obsd}}$ ) were the average of at least three runs that were reproducible within  $\pm 3\%$ .

**Product Analysis.** Phenyl *N*-phenyl phosphoramidochloridate was reacted with excess 4-methoxyaniline, for more than 15 half-lives at  $60.0^\circ\text{C}$  in MeCN. The 4-methoxyaniline hydrochloride salt was separated by filtration. Acetonitrile was evaporated under reduced pressure. The product was isolated with ether by a work-up process and dried over anhydrous  $\text{MgSO}_4$ . After filtration the product was isolated by evaporating the solvent under reduced pressure. The analytical and spectroscopic data of the product gave the following results (see supporting information):

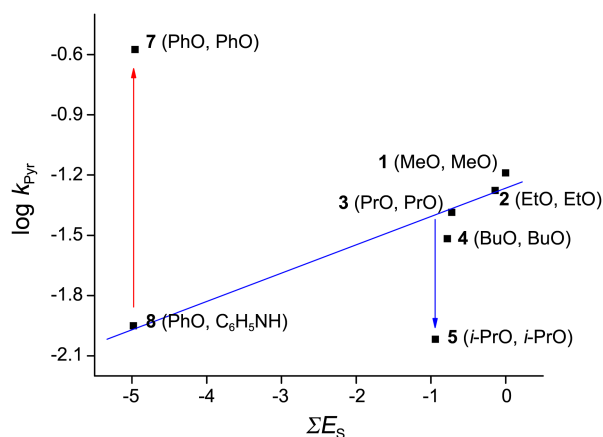
**(PhO)(NHPh)P(=O)NHC<sub>6</sub>H<sub>4</sub>-4-CH<sub>3</sub>O:** Dark brown solid, mp  $160$ – $162^\circ\text{C}$ ;  $^1\text{H NMR}$  ( $400 \text{ MHz}$ ,  $\text{CDCl}_3$ )  $\delta$  3.74 (s, 3H,  $\text{OCH}_3$ ), 5.58 (s, 1H, NH), 5.78 (s, 1H, NH), 6.76–6.79 (d,  $J = 8.4 \text{ Hz}$ , 2H, phenyl), 6.96–7.04 (t,  $J = 8.8 \text{ Hz}$ , 3H, phenyl), 7.07–7.09 (d,  $J = 8.4 \text{ Hz}$ , 2H, phenyl), 7.18–7.31 (m, 7H, phenyl);  $^{13}\text{C NMR}$  ( $100 \text{ MHz}$ ,  $\text{CDCl}_3$ )  $\delta$  55.68 ( $\text{OCH}_3$ ), 114.81, 118.53, 120.76, 120.80, 121.42, 122.58, 125.34, 129.55, 129.93 ( $\text{C}=\text{C}$ , aromatic);  $^{31}\text{P NMR}$  ( $162 \text{ MHz}$ ,  $\text{CDCl}_3$ )  $\delta$  3.81 (s, 1P,  $\text{P}=\text{O}$ ); MS (ESI)  $m/z$  354 ( $\text{M}^+$ ).

**Acknowledgments.** This work was supported by Inha University Research Grant.

## References and Notes

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  13. Fig. R1 shows the Taft plot of  $\log k_{\text{pyr}}$  with unsubstituted pyridine (C<sub>5</sub>H<sub>5</sub>N) against the summation of the Taft steric constants of the two ligands for the pyridinolyses of seven substrates of **1-5**, **7**, and **8** in MeCN at 35.0 °C.



**Figure R1.** The Taft plot of  $\log k_{\text{pyr}}$  vs  $\Sigma E_s$  for the reactions of **1-5**, **7**, and **8** with C<sub>5</sub>H<sub>5</sub>N in MeCN at 35.0 °C.

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16. This lab has cumulated a lot of data of DKIEs for the anilinolyses of various kinds of substrates in MeCN and DMSO.
17. The values of the secondary inverse DKIEs with X of **1**, **2**, **3**, **4**, **7**, and **8** invariably decrease as the aniline becomes weaker. However, the values of the secondary inverse DKIEs with X of **5** invariably increase and then invariably decrease as the aniline becomes weaker. The values of the primary normal DKIEs with X of **3**, **4** and **6** invariably increase as the aniline becomes weaker.