Received: 1 April 2008,

Accepted: 30 April 2008,

(www.interscience.wiley.com) DOI 10.1002/poc.1399

Revised: 30 April 2008,

Kinetics and mechanism of the pyridinolysis of diaryl carbonates

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The reactions of 4-methylphenyl and 4-chlorophenyl 4-nitrophenyl carbonates (1 and 2, respectively), phenyl, 4-methylphenyl, 4-chlorophenyl, and 4-nitrophenyl 2,4-dinitrophenyl carbonates (3, 4, 5, and 6, respectively), and bis(2,4-dinitrophenyl) carbonate (7) with a series of pyridines are studied kinetically at 25.0 °C in 44 wt% ethanol-water and an ionic strength of 0.2 M (KCl). The reactions are followed spectrophotometrically and under excess amine pseudo-first-order rate coefficients (k_{obs}) are found. For all these reactions, plots of k_{obs} versus free amine concentration at constant pH are linear, the slope (k_N) being independent of pH. The Brønsted-type plots (log k_N vs. p K_a of the conjugate acids of the pyridines) are all biphasic (linear portions at high and low p K_a and a curvature in between). These plots are in accordance with a stepwise mechanism, through a zwitterionic tetrahedral intermediate (T^{\pm}), and a change in the rate-determining step from formation of T^{\pm} to its breakdown to products, as the pyridine basicity decreases. Also studied are the effects of the leaving, non-leaving, and electrophilic groups of the substrate, and of the amine nature, on the pK_a^0 value (value at the center of curvature of the Brønsted-type plots). Copyright © 2008 John Wiley & Sons, Ltd.

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Keywords: kinetics; mechanism; pyridinolysis; diaryl carbonates; Brønsted plots

INTRODUCTION

The kinetics and mechanisms of the aminolysis of alkyl aryl carbonates are well documented.^[1–9] The pyridinolysis reactions of 4-nitrophenyl methyl and phenyl methyl carbonates in aqueous solution show linear Brønsted-type plots with slopes *ca.* 1, which were explained by stepwise mechanisms, through a zwitterionic tetrahedral intermediate (T[±]), where its breakdown to products is the rate-determining step.^[1,2] The same aminolysis of 2,4-dinitrophenyl methyl and 2,4,6-trinitrophenyl methyl carbonates in aqueous solution exhibit biphasic (two linear portions and a curvature in between) Brønsted-type plots, with slopes $\beta_1 = 0.2$ (high pK_a) and $\beta_2 = 0.8-0.9$ (low pK_a).^[3,4] These plots were attributed to stepwise mechanisms and a change in the rate-limiting step, from T[±] breakdown to its formation as the pyridine becomes more basic.^[3,4]

The reactions of benzylamines with ethyl X-phenyl carbonates (X = MeO, Cl, CN, NO₂) in acetonitrile show linear Brønsted-type plots, with slopes $\beta = 1.7$ –2.3.^[6] From these slope values and other considerations it was deduced that these reactions obey a stepwise mechanism, with T[±] breakdown to products as rate determining.^[6] It is noteworthy that these slopes are larger than those found in aqueous solution ($\beta = 0.8$ –1.1) when breakdown of T[±] is the rate-determining step, which could be attributed to the fact that the pK_a values plotted were those in water and not those in acetonitrile.

In contrast, the reactions of secondary alicyclic (SA) amines with 2,4-dinitrophenyl methyl and 2,4,6-trinitrophenyl methyl carbonates in aqueous solution are concerted (single step with no T[±] intermediate), as shown by the linear Brønsted-type plots obtained, with slopes 0.48 and 0.36, respectively.^[8,9]

The aminolysis reactions of diaryl carbonates have also been subjected to kinetic studies,^[10–19] although not as extensively as those of alkyl aryl carbonates. The reactions of quinuclidines with 3- and 4-nitrophenyl phenyl carbonates and 3,4- and 2,4-dinitrophenyl phenyl carbonates were found to be stepwise, as judged by the biphasic Brønsted-type plots obtained.^[10,11] The reactions of SA amines,^[12,13] anilines,^[14] and quinuclidines^[13] with 4-methylphenyl and 4-chlorophenyl 4-nitrophenyl carbonates (1 and 2, respectively) were also found to be stepwise on the basis of Brønsted-type plots, either biphasic or linear with large slopes.

In contrast, the reactions of SA amines^[9] and quinuclidines^[15] with phenyl 2,4-dinitrophenyl carbonate (**3**), as well as those of SA amines,^[12,16] quinuclidines,^[15] and anilines,^[16] with 4-methylphenyl and 4-chlorophenyl 2,4-dinitrophenyl carbonates (**4** and **5**, respectively) were claimed to be concerted. Similarly, the reactions of SA amines with 4-nitrophenyl 2,4-dinitrophenyl (**6**) and bis(2,4-dinitrophenyl) (**7**) carbonates were also found to be concerted.^[17] For all these concerted reactions, linear Brønsted-type plots with slopes $\beta = 0.4-0.7$ were obtained.

On the other hand, the reactions of primary alkyl amines with 4-nitrophenyl phenyl carbonate show a biphasic Brønsted-type plot with slopes $\beta_1 = 0.27$ (high p K_a) and $\beta_2 = 0.99$ (low p K_a),

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which was attributed to a stepwise mechanism and a change in the rate-limiting step. $^{[18,19]}$

As seen above, there are still some uncertainties regarding the reason why some reactions are stepwise and others concerted. Furthermore, the effects of the leaving, non-leaving, and electrophilic (CO vs. CS) groups of the substrate and the amine nature on the type of mechanism are not clearly understood. In order to further extend our investigations on the kinetics and mechanisms of the aminolysis of diaryl carbonates in this work we report our kinetic results for the reactions of seven diaryl carbonates (1-7) with a series of seven pyridines (as shown in structures below). Our main goal is to assess the effect of the leaving, non-leaving, and electrophilic groups of the substrate, and of the amine nature, on the kinetics and mechanism. This will be achieved by comparison of the title reactions between them and with the aminolysis of similar carbonates. It is of particular interest to evaluate the influence of the above groups on the pK_a value for the center of the Brønsted curvature (pK_a^0). The pK_a^0 value is important because it is a measure of the leaving abilities from the tetrahedral intermediate of both the amine and the leaving group of the substrate (as shown below).



RESULTS AND DISCUSSION

The reactions were studied in 44 wt% ethanol-water, at 25.0 °C and an ionic strength of 0.2 (KCl). Under excess of amine over the substrate, pseudo-first-order rate coefficients (k_{obs}) were obtained for all reactions. The experimental conditions of the reactions and the values of k_{obs} are shown in Tables 1–7 in Supplementary Materials.

The kinetic law obtained under the reaction conditions is described by Eqn (1), where P is 4-nitrophenoxide or 2,4-dinitrophenoxide anion and S is the substrate:

$$\frac{\mathrm{d}[P]}{\mathrm{d}t} = k_{\mathrm{obs}}[S] \tag{1}$$

Plots of k_{obs} against concentration of free pyridine at constant pH were linear, in accordance with Eqn (2), where k_0 and k_N are the rate coefficients for solvolysis and pyridinolysis of the substrates, respectively. The values of k_0 and k_N were obtained as the intercept and slope, respectively, of plots of Eqn (2), and were pH-independent:

$$k_{\rm obs} = k_0 + k_{\rm N}$$
 [free pyridine] (2)

Table 1 shows the values of pK_a of the pyridinium ions and those of k_N for the reactions under study. With these values the Brønsted-type plots of Figs 1–3 were obtained.

					$k_{\rm N}/{\rm s}^{-1}{\rm M}^{-1}$			
Pyridine substituent	рК _а	1	2	3	4	5	9	7
4-Oxy	11.5	$\textbf{2960}\pm\textbf{40}$	8800 ± 100	8900 ± 100	5900 ± 300	17500 ± 600	80000 ± 2000	214000 ± 8000
3,4-Diamino	9.45	129 ± 5	380 ± 10				60000 ± 2000	83000 ± 2000
4-Dimethylamino	9.14	121 ± 3	300 ± 10	1831 ± 43	1430 ± 33	$\textbf{4184}\pm\textbf{89}$	17400 ± 400	62700 ± 1000
4-Amino	8.98	90 ± 3	251 ± 9	1767 ± 42	1045 ± 19	2673 ± 74	9000 ± 200	34200 ± 2000
4-Amino-3-bromo	6.9	0.56 ± 0.02	1.17 ± 0.06	139 ± 3	78 ± 3	223 ± 6	1560 ± 30	10300 ± 300
3,4-Dimethyl	5.68	0.015 ± 0.001	0.035 ± 0.001					
None	4.63	0.0018 ± 0.0002	0.0038 ± 0.0005	1.68 ± 0.07	1.25 ± 0.03	$\textbf{2.29}\pm\textbf{0.09}$	11.4 ± 0.3	68 ± 2
3-Carbamoyl	2.67			0.029 ± 0.001	0.024 ± 0.001	0.049 ± 0.001	0.20 ± 0.02	0.9 ± 0.1
3-Chloro	2.17						0.066 ± 0.008	0.47 ± 0.07



Figure 1. Brønsted-type plots obtained for the reactions of pyridines with 4-methylphenyl 4-nitrophenyl carbonate (1, \bigcirc) and 4-chlorophenyl 4-nitrophenyl carbonate (2, \bigcirc), in 44 wt% ethanol–water, at 25.0 °C and an ionic strength of 0.2 M



Figure 3. Brønsted-type plots obtained for the reactions of pyridines with 4-nitrophenyl 2,4-dinitrophenyl carbonate (6, \bullet) and bis(2,4-dinitrophenyl) carbonate (7, \bigcirc), in 44 wt% ethanol-water, at 25.0 °C and an ionic strength of 0.2 M



Figure 2. Brønsted-type plots obtained for the reactions of pyridines with phenyl 2,4-dinitrophenyl carbonate (**3**, **●**), 4-methylphenyl 2,4-dinitrophenyl carbonate (**4**, \bigcirc), and 4-chlorophenyl 2,4-dinitrophenyl carbonate (**5**, **■**), in 44 wt% ethanol–water, at 25.0 °C and an ionic strength of 0.2 M

The biphasic Brønsted plots found for the pyridinolysis of carbonates **1–7** can be explained by the existence of a zwitterionic tetrahedral intermediate (T^{\pm}) on the reaction pathway and a change in the rate-determining step, from breakdown to products of T^{\pm} (step k_2 in Scheme 1) to formation of T^{\pm} (step k_1 in Scheme 1), as the amine becomes more basic.^[3,10,11]

The lines in the Brønsted plots of Figs 1–3 were calculated by means of a semiempirical equation, Eqn (3), based on the existence of the intermediate T^{\pm} on the reaction pathway.^[3,10,11] This equation contains four parameters: β_1 and β_2 , which are the





Brønsted slopes at high and low pK_a , respectively, and k_N^0 and pK_a^0 , which are the corresponding values at the center of the curvature. The Brønsted curves were calculated by means of Eqn (3), using the parameters (obtained by nonlinear least-squares fitting) summarized in Table 2:

$$\log (k_{\rm N}/k_{\rm N}^0) = \beta_2 (pK_{\rm a} - pK_{\rm a}^0) - \log(1 + a/2)$$

$$\log a = (\beta_2 - \beta_1) (pK_{\rm a} - pK_{\rm a}^0)$$
(3)

The relatively large errors of β_1 and pK_a^0 for the pyridinolysis of carbonates **1** and **2** can be attributed to the fact that for these reactions there is only one amine (4-oxypyridine) that clearly belongs to the region where the formation of the intermediate T^{\pm} (k_1 step in Scheme 1) is rate limiting. Namely, for these reactions there is only one amine whose pK_a is much greater than pK_a^0 .

Table 2. Parameters in Eqn (3) obtained for the pyridinolysis of diaryl carbonates 1–7									
Substrate	$\log k_{\rm N}^0$	pK_a^0	eta_1	β_2	R^2				
1	$\textbf{2.43} \pm \textbf{1.17}$	9.6±1.4	0.42 ± 0.30	1.1 ± 0.1	0.9976				
2	$\textbf{2.7}\pm\textbf{1.1}$	9.5 ± 1.2	$\textbf{0.45} \pm \textbf{0.25}$	1.15 ± 0.09	0.9980				
3	2.8 ± 0.2	8.0 ± 0.3	0.24 ± 0.04	0.83 ± 0.03	0.9996				
4	2.7 ± 0.1	8.3 ± 0.2	$\textbf{0.23}\pm\textbf{0.03}$	$\textbf{0.80} \pm \textbf{0.02}$	0.9998				
5	3.2 ± 0.1	8.3 ± 0.6	0.23 ± 0.08	0.82 ± 0.05	0.9998				
6	3.6 ± 0.4	$\textbf{7.6} \pm \textbf{0.8}$	0.27 ± 0.11	0.93 ± 0.07	0.996				
7	4.1 ± 0.4	7.2 ± 0.6	$\textbf{0.22}\pm\textbf{0.09}$	$\textbf{0.97} \pm \textbf{0.07}$	0.997				

Taking into account the shape of the Brønsted plots obtained and the values of slopes, the most likely mechanism for the reactions under scrutiny is the stepwise process shown in Scheme 1. In this Scheme X, Y, and Z were defined above and Py represents a pyridine.

Similar shapes and slopes to those of the Brønsted plots in Figs 1–3 were found in the pyridinolysis of 2,4-dinitrophenyl acetate,^[2] 2,4-dinitrophenyl, and 2,4,6-trinitrophenyl methyl carbonates,^[3,4] and in the SA aminolysis of 4-nitrophenyl methyl carbonate,^[9] and carbonates **1** and **2**.^[12,13] The Brønsted plots obtained in the present work are also in accordance with those found in the quinuclidinolysis of diaryl carbonates^[10,11] and in the reactions of primary amines with 4-nitrophenyl phenyl carbonate.^[18,19] All these reactions were found to be governed by stepwise mechanisms, through a zwitterionic tetrahedral intermediate.

Effect of the leaving group

The aim of this section is to assess how the leaving group (nucleofuge) of the substrate affects the rate constants involved in the mechanism (Scheme 1) and how this affects the pK_a^0 value. For the reactions of 4-oxypiridine with all the carbonates studied in this work the rate-determining step is the formation of the zwitterionic tetrahedral intermediate (T^{\pm}) and, therefore, $k_{\rm N} = k_1$ in Scheme 1. From a comparison of the k_1 values between carbonates 1 and 4 and between 2 and 5 (Table 1), where there is a change in the leaving group from 4-nitrophenoxy to 2,4-dinitrophenoxy for the same non-leaving group, it can be observed that the k_1 values for the dinitro derivatives (4 and 5) are approximately two-fold larger than those for the corresponding mononitro derivatives (1 and 2). This result is obviously due to the presence of a second nitro group in the substrate, which increases the electron-withdrawing ability from the leaving group, leading to a more positive carbonyl carbon atom and favoring, therefore, the 4-oxypyridine attack.

On the other hand, when the second step is rate determining, $k_N = k_1 k_2 / k_{-1}$. Taking as an example the reactions of the unsubstituted pyridine, Table 1 shows that the k_N values for the reactions of this amine with the dinitro derivatives (**4** and **5**) are approximately 600–700-fold greater than those for the corresponding mononitro derivatives (**1** and **2**). Taking into account that the k_1 values are only twice as large for the former carbonates, it can be deduced that the ratio k_2 / k_{-1} is approximately 300-fold greater for the dinitro derivatives. This should be mainly due to a larger k_2 for the latter carbonates since these leaving groups should hardly affect k_{-1} (they are both

weakly basic).^[10,11] The change of 4-nitrophenoxy by 2,4-dinitrophenoxy in the tetrahedral intermediate increases k_2 due to the much lower basicity of 2,4-dinitrphenoxide compared with 4-nitrophenoxide (the pK_a for the corresponding phenols in water at 25°C are 4.1 and 7.1, respectively),^[20] which makes the former a much better nucleofuge.

Also in accordance with the above discussion, and another proof that the pyridinolysis of carbonates **1–7** are stepwise, is the fact that the pK_a^0 values found (Table 2) for the dinitro derivatives (about 8.3) are lower than those of the corresponding mononitro carbonates (about 9.5). This is because, according to the tetrahedral intermediate hypothesis, an equation can be derived, Eqn (4),^[9] which shows that a larger k_2/k_{-1} ratio means a lower pK_a^0 value:

$$\log k_{-1}/k_2 = (\beta_2 - \beta_1) (pK_a^0 - pK_a)$$
(4)

According to the k_1 and k_N values for the reactions of 4-oxypyridine and pyridine, respectively, with carbonates **1**, **2**, **4**, and **5** and the pK_a values of 4-nitrophenol and 2,4-dinitrophenol (as shown above), the Brønsted slopes for the leaving group (β_{lg}) can be estimated. The resulting values are $\beta_{lg} = -0.1$ for k_1 (T[±] formation as rate limiting) and -0.94 for k_N (T[±] breakdown as rate determining). These values are also in agreement with those usually found for the stepwise aminolysis of carbonates and esters.^[10,11,21-26]

Effect of the amine nature

Our aim here is to evaluate the effect of the nature of the amine (i.e., pyridines vs. SA amines) on the pK_a^0 value and, therefore, on the k_{-1}/k_2 ratio. The reactions of SA amines with carbonates **1** and **2** exhibit biphasic Brønsted plots, with the curvature center at $pK_a = pK_a^0 = 10.5$.^[12,13] As seen in Table 2 the pK_a^0 for the pyridinolysis of **1** and **2** are *ca*. 9.5. The larger pK_a^0 value for the reactions of SA amines can be attributed to the faster nucleofugality from the intermediate T[±] (larger k_{-1} in Scheme 1) of an SA amine compared with an isobasic pyridine.^[27,28] Since the k_2 value should not be affected by the amine basicity or nature,^[10,11] the larger k_{-1} values for the SA amines (compared with isobasic pyridines) mean a larger pK_a^0 , according to Eqn (4). The larger k_{-1} for SA amines indicates that the intermediate T[±] formed with these amines is destabilized relative to that arising from isobasic pyridines.

The destabilization of T^{\pm} with SA amines can also be confirmed by comparison of the mechanisms found for the SA aminolysis and pyridinolysis of carbonates **3–7**. The mechanism for the former aminolysis is concerted,^[9,12,16,17] whereas that for the latter aminolysis is stepwise (this work). This shows that the tetrahedral intermediate formed with pyridines is destabilized by the change of this amine by an isobasic SA amine.

Influence of the non-leaving group

There is some controversy regarding the influence of the non-leaving group of the substrate on the kinetics and mechanism of the aminolysis of esters and carbonates. In some cases there is a pK_{a}^{0} shift by the change of non-leaving group, whereas in other instances there is no shift. The shift of pK_a^0 with the change in non-leaving group is important because this is related to the shift in the k_{-1}/k_2 ratio, as shown by Eqn (4). Table 2 shows that the pK_{a}^{0} values for a given leaving group do not vary significantly with the variation of the non-leaving group. Thus, the pK_a^0 values are 9.6 and 9.5 for the two mononitro derivatives (carbonates 1 and 2) and ca. 7-8 for the substrates with dinitro leaving groups (carbonates 3-7). These results are in line with those found in the SA aminolysis of carbonates 1 and 2, for which the pK_a^0 values are 10.5 and 10.6, respectively.^[12,13] In other reactions there is a small influence of the non-leaving group on the pK_a^0 value. This is the case of the pyridinolysis of methyl 2,4-dinitrophenyl carbonate^[3] and carbonate **3** (this work), where the change of methoxy by phenoxy as non-leaving group changes the pK_{a}^{0} value from 7.8 to 8.0. Similarly, for the pyridinolysis of ethyl and phenyl 2,4-dinitrophenyl thionocarbonates the pK_{2}^{0} value changes from 6.8 to 7.0 by the change of ethoxy to phenoxy.^[29,30] A more significant influence of the non-leaving group on the pK_a^0 value can be observed by comparing the pyridinolysis of S-methyl and O-methyl 2,4-dinitrophenyl carbonates: the pK_a^0 value changes from 7.3 to 7.8.^[3,31] Similarly, in the reactions of SA amines with ethyl and phenyl 2,4-dinitrophenyl thionocarbonates, the pK_a^0 value increases from 7.0 to 7.7 by the change of ethoxy to phenoxy as the non-leaving group.^[30]

In order to evaluate the influence of the non-leaving group of the substrate on the kinetics of the title reactions, a multiparametric study was undertaken. With the experimental $k_{\rm N}$ values obtained for the reactions of carbonates **3–7** with pyridines with $pK_{\rm a}$ greater than $pK_{\rm a}^0$, where $k_{\rm N} = k_1$, Eqn (5) was obtained (n = 15, $R^2 = 0.964$). In this equation $pK_{\rm N}$ and $pK_{\rm nlg}$ are the $pK_{\rm a}$ of the conjugate acids of the nucleophiles and non-leaving groups, respectively:

$$\log k_1 = 2.8 + 0.29 \, \mathrm{pK_N} - 0.20 \, \mathrm{pK_{nlg}} \tag{5}$$

On the other hand, using the experimental k_N values for the reactions of carbonates **3–7** with pyridines with pK_a lower than pK_a^0 , where the k_2 step in Scheme 1 is rate determining and $k_N = k_1k_2/k_{-1}$, Eqn (6) was obtained (n = 14, $R^2 = 0.996$):

$$\log k_{\rm N} = -1.3 + 0.89 \, {\rm pK_N} - 0.23 \, {\rm pK_{nlg}} \tag{6}$$

The coefficients of pK_N (β_N) in both equations are in accordance with those found in the aminolysis of carbonates, esters, and their thio derivatives when formation and breakdown of the intermediate T^{\pm} , respectively, are the rate-limiting steps.^[27,28] On the other hand, the coefficients of pK_{nlg} (β_{nlg}) for k_1 and k_N , Eqns (5) and (6), are closely similar, indicating that the charge development (from reactant to transition state) on the oxygen of the non-leaving group is similar for rate determining formation and breakdown of T^{\pm} .

Subtracting Eqn (6) from Eqn (5), Eqn (7) is obtained. This equation shows the dependence of pK_{nlg} on the k_{-1}/k_2 ratio for the pyridinolysis of carbonates **3–7**:

$$\log(k_{-1}/k_2) = 4.1 - 0.6 \, \text{pK}_{\text{N}} + 0.03 \, \text{pK}_{\text{nlg}} \tag{7}$$

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Equation (7) shows that there is only a marginal effect of the non-leaving group basicity on the k_2/k_{-1} ratio. As this ratio is mainly responsible for the pK_a^0 value (as shown in Eqn (4)), we conclude that, in the case of the title reactions, the non-leaving group effect on the pK_a^0 value is negligible.

In contrast to the above results, a significant influence of the non-leaving group on the pK_a^0 value has been found in the pyridinolysis and SA aminolysis of *S*-4-nitrophenyl 4-substituted thiobenzoates^[32–34] and in the pyridinolysis of *S*-2,4-nitrophenyl 4-substituted thiobenzoates.^[35] For the SA aminolysis, there is a pK_a^0 shift from 9.7 to >10.8 for a change in the non-leaving group from 4-methylphenyl to 4-nitrophenyl.^[32,34] For the reactions with pyridines, the pK_a^0 value increases from 9.4 to 10.7 (for the mononitro derivatives)^[33,34] and from 8.5 to 9.9 (for the dinitro compounds)^[35] for the same change of non-leaving group.

The smaller variation of the pK_a^0 value with the non-leaving group found for carbonates compared with benzoates could be due to the fact that for carbonates there is a longer distance between the substituent in the non-leaving group and the central carbonyl carbon. Therefore, a smaller influence of the non-leaving group on the values of k_{-1} and k_2 (and therefore, a smaller effect on the pK_a^0 value) should be expected for carbonates, relative to benzoates. Nevertheless, Um and co-workers^[36–38] have found that for the aminolysis of aryl X-substituted benzoates in 80 mol% water/ 20 mol% DMSO there is no variation of the pK_a^0 value with the X substituent.

Influence of the electrophilic group

In order to assess the influence of the electrophilic group (CO vs. CS) on the kinetics and pK_a^0 value we can compare the pyridinolysis reactions of phenyl 2,4-dinitrophenyl thionocarbonate and its carbonate derivative. For the thionocarbonate a biphasic Brønsted-type plot with $pK_a^0 = 7.0$ was obtained.^[30] For the pyridinolysis of the corresponding carbonate derivative (carbonate **3**) the pK_a^0 value found is 8.0 (this work). This means that for a given pyridine the k_{-1}/k_2 ratio is larger for the carbonate compared with the thionocarbonate, see Eqn (4).

The above results are in agreement with those obtained in similar reactions. For those of primary amines with 4-nitrophenyl thionobenzoate a biphasic Brønsted plot with $pK_a^0 = 9.2$ was found.^[39] For the same aminolysis of the corresponding benzoate a linear Brønsted plot with slope 0.9 was obtained, which indicates that the decomposition of the intermediate T^{\pm} to products is rate limiting for the whole amine series (pK_a ranging from 5.7 to 10.9).^[39] This means that for the reactions of 4-nitrophenyl benzoate, $pK_a^0 > 10.9$. The same results were found for the reactions of primary alkyl amines with 4-nitrophenyl phenyl carbonate and its analogous thionocarbonate.^[19] The pK_{2}^{0} values for these reactions are 9.5 and 8.5, respectively.^[19] Namely, there is an increase of one pK_a unit by the replacement of CS by CO. An increase in the pK_a^0 value was also found in the pyridinolysis of 4-nitrophenyl benzoate ($pK_a^0 ca. 12$) and its thiono analog $(pK_a^0 = 9.3)$.^[37] Similarly, for the reactions of SA amines with 4-nitrophenyl thiolacetate the values of k_{-1} and k_2 , and also the values of the k_{-1}/k_2 ratio, are larger than those for the same aminolysis of 4-nitrophenyl dithioacetate.^[40] According to Eqn (4) The influence of the electrophilic group on the reactivity toward pyridines can also be evaluated. For pyridines of $pK_a > pK_a^0$, for which $k_N = k_1$, the k_1 values are greater for carbonates than thionocarbonates (for example for a hypothetical pyridine with $pK_a = 10$ carbonate **3** is 36 times more reactive than the corresponding thionocarbonate).^[30] This shows that CO is a better electrophile toward pyridines than CS. The same was found in the pyridinolysis of alkyl aryl thionocarbonates and their corresponding carbonates: the k_1 values are larger for the latter compounds compared with the former.^[29]

In the region of $pK_a < pK_a^0$ (where T^{\pm} breakdown to products is rate determining), carbonate **3** is slightly more reactive than the corresponding thionocarbonate.^[30] As in this region $k_N = k_1k_2/k_{-1}$ and k_1 is much greater for carbonates (as shown above), it follows that k_2/k_{-1} should be greater for the thionocarbonate. This is in accordance with the larger k_{-1}/k_2 values found in the pyridinolysis of alkyl aryl carbonates relative to those in the same aminolysis of the corresponding thionocarbonates.^[29] These results are also in agreement with the larger pK_a^0 value (larger k_{-1}/k_2 ratio) found for the pyridinolysis of carbonate **3** (this work) compared with that obtained for the same aminolysis of phenyl 2,4-dinitrophenyl thionocarbonate.^[30]

EXPERIMENTAL

Materials

The series of pyridines were purified as reported.^[42,43] Carbonates 1,^[12] 2,^[13] 3,^[9] 4,^[12] 5,^[16] and 7^[44] were prepared as described. Carbonate 6 was prepared as follows: to 2.0 g (10.8 mmol) of 4-nitrophenyl chloroformate in 40 ml of anhydrous acetonitrile, a mixture of 1 ml of pyridine and 1.685 g (10.8 mmol) of 2,4-dinitrophenol in acetonitrile was added at room temperature and left 3 h with stirring. The mixture was washed three times with cold water, dried with magnesium sulfate and the solvent evaporated off. The solid obtained was recrystallized from a dichloromethane-hexane mixture yielding a solid that melted at 134-135 °C, and was identified as follows: NMR-¹H (400 MHz, CDCl₃) δ (ppm): 7.52 (d, 2H, J = 9.2 Hz); 7.70 (d, 1H, J = 8.8 Hz); 8.35 (d, 2H, J = 9.2 Hz); 8.63 (dd, 1H, J = 2.8 Hz, J = 9.2 Hz); 9.09 (d, 1H, J = 2.8 Hz). NMR⁻¹³C (400 MHz, CDCl₃) δ (ppm): 121.71 (C₂',C₆'); 122.30 (C₃); 125.60 (C₃',C₅'); 126.19 (C₆); 129.75 (C₅); 141.10 (C₂); 145.89 (C₁); 146.25 (C₄'); 147.85 (C₄); 149.39 (C=O); 154.71 (C₁'). Anal. Calcd. for C13H7N3O9: C, 44.71; H, 2.02; N, 12.03. Found: C, 44.71; H, 1.84; N, 11.98.

Kinetics measurements

These were carried out by means of a HP-8453 diode array spectrophotometer in 44 wt% ethanol–water, at 25.0 \pm 0.1 $^\circ$ C and an ionic strength of 0.2 M (KCI). The reactions were studied by monitoring the appearance of 4-nitrophenoxide anion at 400 nm or 2,4-dinitrophenoxide anion at 360 nm.

All the reactions were examined under excess of amine over the substrate. The initial substrate concentration was 5×10^{-5} M,

and the pH was maintained either by partial protonation of the pyridines or by means of an external buffer.

Pseudo-first-order rate coefficients (k_{obs}) were found throughout and determined by means of the spectrophotometer kinetic software for first-order reactions. The experimental conditions of the reactions and the values of k_{obs} are shown in Tables 1–7 in Supplementary Materials.

Product studies

In the reactions of carbonates **1** and **2**, 4-nitrophenoxide ion was found as one of the products of the reactions; in those of carbonates **3–7**, 2,4-dinitrophenoxide anion was obtained as one of the products. This was achieved by a comparison of the UV–Vis spectra after completion of the reactions with those of authentic samples under the same experimental conditions.

CONCLUSIONS

From the title reactions the following conclusions can be drawn: (i) The biphasic Brønsted-type plots (log k_N vs. pK_a of pyridinium ions) obtained, the magnitude of the slopes, and the pK_a values found for the center of the break (pK_a^0) are in accordance with those for a stepwise mechanism. (ii) An important influence of the leaving group on the pK_a^0 value and only a marginal effect of the non-leaving group were found. (iii) SA amines shift the pK_a^0 to higher values, relative to pyridines, due to the faster nucleofugality of an SA amine from the intermediate T^{\pm} compared with that of an isobasic pyridine. (iv) The change of CS by CO as the electrophilic group also enlarges the pK_a^0 value.

Acknowledgements

We thank MECESUP of Chile (Projects PUC-0004 and RED QUI-MICA UCH-01), FONDECYT of Chile (Projects 1020538 and 1060593) for financial assistance.

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