Kinetic study of the reactions of methyl 2,4,6-trinitrophenyl carbonate with anilines

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Dedicated to Professor Rita H. de Rossi

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Abstract

The title reactions in water are subjected to a kinetic investigation. Under excess amine, pseudo-first-order rate coefficients (k_{obsd}) are obtained. Plots of k_{obsd} against aniline concentration are linear, with k_{N} as the slope. The Brønsted-type plot (log k_{N} *vs* anilinium pK_{a}) is linear with slope 0.7, consistent with a concerted mechanism. By comparison of these reactions with others, it is concluded that anilines destabilize the tetrahedral intermediate relative to isobasic pyridines. The change of 2,4-dinitrophenoxide by 2,4,6-trinitrophenoxide as the leaving group of the carbonate destabilizes the tetrahedral intermediate and makes possible a change in mechanism.

Keywords: Alkyl aryl carbonate, aminolysis, anilines, Brønsted plots, kinetics

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Introduction

The kinetics and mechanism of the aminolysis of alkyl aryl carbonates[1-3] and diaryl carbonates[3b,4,5] is well documented. Regarding the former reactions, there have been reports on the pyridinolysis of methyl aryl carbonates (aryl = phenyl, 4-nitrophenyl, 2,4-dinitrophenyl, and 2,4,6-trinitrophenyl, **1**, **2**, **3**, and **4**, respectively),[1] the reactions of **3** with anilines,[3a] the reactions of **2**, **3** and **4** with secondary alicyclic (SA) amines,[3b,c] and the reactions of **2** and **3** with quinuclidines.[3b] Among the aminolysis of diaryl carbonates studied are the reactions of quinuclidines with 4-nitrophenyl and 2,4-dinitrophenyl phenyl carbonates (**5** and **6**, respectively),[4] and those of SA amines with **6**, 4-methylphenyl and 4-chlorophenyl 2,4-dinitrophenyl carbonates (**7** and **8**, respectively)[3b,5a,c] and 4-methylphenyl and 4-chlorophenyl 4-nitrophenyl carbonates (**9** and **10**, respectively).[5a,b] The reactions of anilines with **7** and **8**[5c] and those of quinuclidines with **9** and **10**[5b] have also been subjected to kinetic investigations.

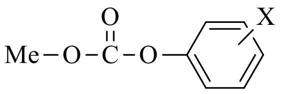
Some of the above reactions have been described as stepwise, through a zwitterionic tetrahedral intermediate ($T^{\pm}$), due to the curved Brønsted-type plots obtained. Examples of this behavior are the reactions of pyridines with **3** and **4**,[1b,d] and those of SA amines with **2**,[3b] **9**,[5a] and **10**.[5b] These curved Brønsted plots are usually biphasic, *i.e.*, they show two linear portions, one at low amine basicity (with slopes β = 0.8 - 1) and the other at high amine basicity (β = 0.2 - 0.3), which have been assigned to rate-determining breakdown and formation of $T^{\pm}$, respectively.[1,4] In other reactions, linear Brønsted plots with slopes in the range β 0.7 - 1.1 have been found, which have been explained by a stepwise process where breakdown of $T^{\pm}$ to products is rate limiting. This is the case of the reactions of **1**[1c] and **2**[1a] with pyridines, that of **3** with anilines[3a], and those of **2**,[3b] **5**,[4] **9**,[5b] and **10**[5b] with quinuclidines.

The change in the rate-determining step has been discussed also as a function of the leaving group ability and the electron withdrawal or donation of the nonleaving group.

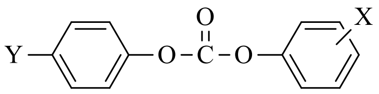
Other aminolysis of carbonates have been found to be concerted, *i.e.*, these reactions take place in a single step, with no intermediate. This is the case of the reactions of SA amines with **3**,[3b] **4**,[3c] **6**,[3b] **7**,[5a] and **8**,[5c] the reactions of quinuclidines with **3**[3b] and those of anilines with **7** and **8**.[5c] Most of these reactions exhibit linear Brønsted-type plots with slopes β = 0.4 – 0.7 and one of them shows a slightly curved Brønsted plot.[5a]

The mechanistic change from stepwise to concert depends mainly on the leaving ability of the nucleofuge and the nature of the amine. In general, it has been shown that the better the leaving abilities of the substrate nucleofuge and the amine from the $T^{\pm}$ intermediate, the more favorable is the concerted mechanism.

To shed more light on the influence of the groups attached to the $T^{\pm}$ intermediate on the reaction mechanism, in this work we investigate the reactions of a series of anilines with methyl 2,4,6-trinitrophenyl carbonate **4**. The aim is to compare this mechanism with those of the same substrate with other amine series and those of methyl 2,4-dinitrophenyl carbonate **3** and other compounds with anilines and in this way assess the influence of the leaving group of the substrate and amine nature on the reaction mechanism.



1 X = H
2 X = 4-NO_2
3 X = 2,4-$(NO_2)_2$
4 X = 2,4,6-$(NO_2)_3$



5 Y= H ; X = 4-NO_2
6 Y = H ; X = 2,4-$(NO_2)_2$
7 Y = Me ; X = 2,4-$(NO_2)_2$
8 Y = Cl ; X = 2,4-$(NO_2)_2$
9 Y = Me ; X = 4-NO_2
10 Y = Cl ; X = 4-NO_2

Results and Discussion

The kinetic law obtained under the reaction conditions is that described by equation 1, where P is 2,4,6-trinitrophenoxide anion, S is the substrate, and k_{obsd} is the pseudo-first-order rate coefficient (excess of amine over the substrate was used throughout).

$$\frac{d[P]}{dt} = k_{obsd}[S] \qquad (\mathbf{1})$$

Plots of k_{obsd} against [free amine] at constant pH were linear, in accordance with equation 2, where k_0 and k_N are the rate coefficients for solvolysis and aminolysis of the substrate, respectively. The values of k_0 and k_N were obtained as the intercept and slope, respectively, of plots of k_{obsd} against [free amine]. These values were pH independent, within the pH range employed for the reactions. For the 7.0 – 7.5 pH range the values of k_0 were *ca.* 10^{-4} s^{-1}, and were significant only for the reactions with the less basic anilines. The values of the range of k_{obsd} and the experimental conditions of the reactions are shown in Table 1.

$$k_{obsd} = k_0 + k_N\,[\text{free amine}] \qquad (\mathbf{2})$$

Table 1. Experimental conditions and k_{obsd} values for the reactions of anilines with methyl 2,4,6-trinitrophenyl carbonate **4**[a]

Amine	pH[b]	10^3 $[N]_{tot}$ / M[c]	10^3 k_{obsd} / s^{-1}	No. of runs
4-methoxyaniline	7.0	0.194-1.65	4.10-34.9	6
	7.2	0.194-1.65	10.9-32.0	6
	7.5	0.194-1.65	9.90-28.9	6
4-methylaniline	7.0	0.515-5.15	6.50-43.4	7
	7.2	0.515-5.15	4.40-43.0	7
	7.5	0.515-5.15	4.70-41.2	7
aniline	7.0	10.0-100	32.5-258	7
	7.2	10.0-100	29.5-291	7
	7.5	10.0-100	41.1-315	7
3-methoxyaniline	7.0	0.30-3.0	0.80-6.98	7
	7.2	0.30-3.0	0.86-6.72	7
	7.5	0.30-3.0	0.87-7.70	7
3-aminoacetophenone	7.0	0.075-0.75	0.152-0.790	7
	7.2	0.075-0.75	0.210-0.835	7
	7.5	0.075-0.75	0.241-0.962	7
3-aminobenzonitrile	7.0	0.282-2.82	0.134-0.525	7
	7.2	0.282-2.82	0.133-0.538	7
	7.5	0.564-2.82	0.180-0.546	6
4-aminoacetophenone	7.0	0.348-3.48	0.124-0.313	7

	7.2	0.348-3.48	0.146-0.370	6
	7.5	0.348-3.48	0.161-0.355	7

[a]In water, at 25.0 ºC and an ionic strength of 0.2 (KCl). [b]pH maintained with 0.01M phosphate buffer. [c]Concentration of total amine (free base plus protonated forms).

The values of k_N are shown in Table 2, together with those of the pK_a of the conjugate acids of the anilines. With these k_N values and those of the statistically corrected pK_a of the conjugate acids of the anilines (with q = 1 and p = 3),[6] the Brønsted-type plot of Figure 1 was obtained. The plot is linear with slope $\beta = 0.7$.

Table 2. Values of pK_a for the conjugate acids of anilines and k_N values for the reactions of these amines with methyl 2,4,6-trinitrophenyl carbonate **4**[a]

Amine	pK_a	k_N/s^{-1}M^{-1} [b]
4-methoxyaniline	5.65	17.1±1.5
4-methylaniline	5.08	8.2±0.2
Aniline	4.73	2.8±0.1
3-methoxyaniline	4.36	2.3±0.1
3-aminoacetophenone	3.64	1.00±0.05
3-aminobenzonitrile	2.90	0.16±0.01
4-aminoacetophenone	2.42	0.063±0.005

[a]Both the pK_a and k_N values were determined in water, at 25.0 °C and an ionic strength of 0.2 (KCl).

[b]Errors shown are standard deviations.

For the reaction studied in this work the magnitude of the Brønsted slope, β 0.7, is near the lower limit of the Brønsted slopes found in the stepwise aminolysis of similar substrates when breakdown to products of the zwitterionic tetrahedral intermediate ($T^{\pm}$) is the rate-determining step.[1-4,7] For instance, Brønsted slopes of 0.7 – 0.8 have been found in the stepwise reactions of SA amines with phenyl and 4-chlorophenyl ethyl thiolcarbonates in water.[7] Similarly, Brønsted slope values of 0.8 or slightly lower have been reported for the stepwise aminolysis of 2,4-dinitrophenyl acetate and 1-acetoxy-4-methoxypyridinium ion.[8]

On the other hand, the β value found in this work is near the upper limit found for the aminolysis proceeding by concerted-type reactions. In fact, linear Brønsted plots with slope values of *ca.* 0.6 have been found for the *concerted* reactions of pyridines with *N*-methoxycarbonylisoquinolinium ion[9] and SA amines with ethyl 2,4-dinitrophenyl thiolcarbonate.[10] Furthermore, linear Brønsted plots with slopes greater than 0.6 have been obtained in the concerted anilinolysis of bis(4-nitrophenyl) carbonate ($\beta = 0.65$),[11] and carbonates **7** ($\beta = 0.68$) and **8** ($\beta = 0.66$).[5c] The concerted phenolysis of several esters also exhibit Brønsted slopes greater than 0.6. Among these esters are 4-chloro-2-nitrophenyl acetate ($\beta = 0.64$),[12] 3-nitrophenyl formate ($\beta = 0.64$),[13] and 3-nitrophenyl acetate ($\beta = 0.66$).[13]

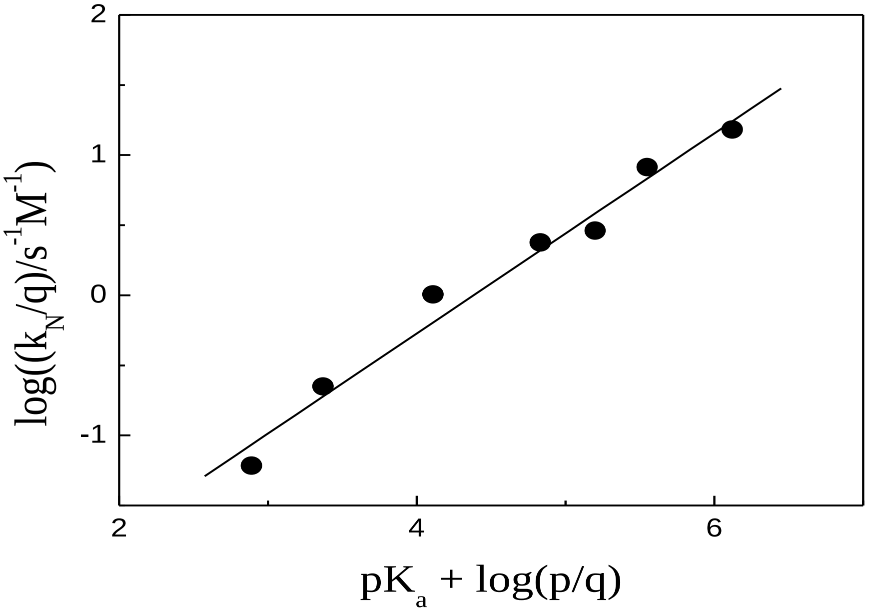
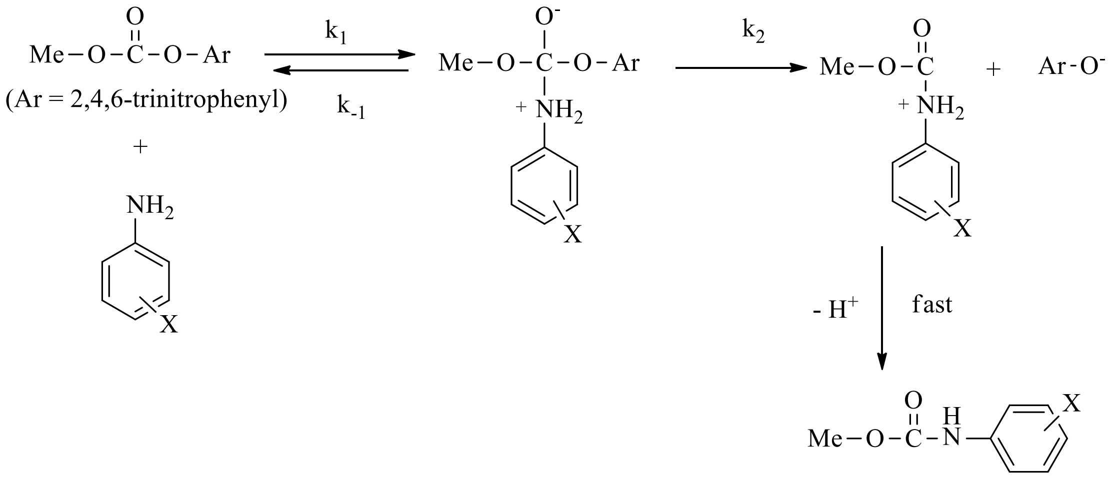
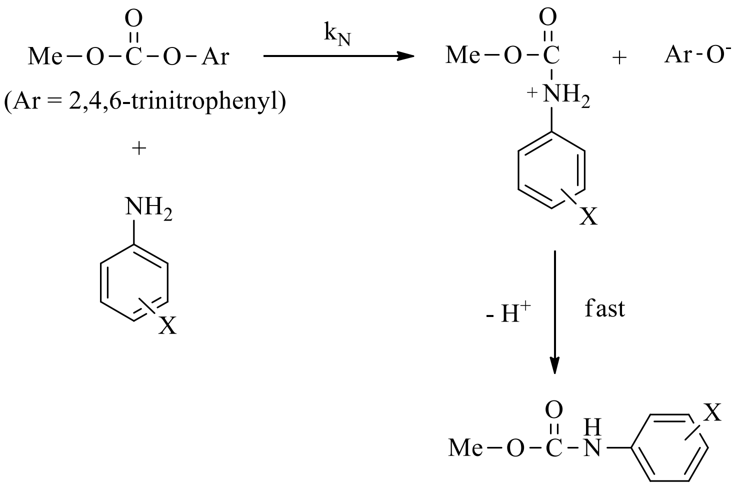


Figure 1. Brønsted plot (statistically corrected) for the reactions of anilines with methyl 2,4,6-trinitrophenyl carbonate **4** in water, at 25.0 °C and an ionic strength of 0.2 (KCl).

Therefore, judging only by the magnitude of the Brønsted slope (β 0.7) found for the reactions under scrutiny it is difficult to decide which mechanism (stepwise or concerted) governs these reactions. These mechanisms are depicted in Scheme 1 (stepwise) and Scheme 2 (concerted).



Scheme 1. Stepwise mechanism.



Scheme 2. Concerted mechanism.

On the other hand, the reaction of ethyl 2,4,6-trinitrophenyl thiolcarbonate with anilines in water is concerted.[14] It is known that phenoxide groups are better nucleofuges than *isobasic* benzenethiolates.[15] On the other hand, the pK_a of 2,4,6-trinitrophenol is 0.3,[16] whereas that of 2,4,6-trinitrobenzenethiol is 1.4.[17] From this point of view, and assuming that the substitution of methyl by ethyl does not affect the mechanism,[18] the reactions of this work should be governed by a concerted mechanism (Scheme 2).

On the other hand, the reactions of carbonate **4** with pyridines in water[1d] are stepwise, whereas those of the same substrate with SA amines in the same solvent are concerted.[3c] The change of mechanism was attributed to the greater nucleofugality from the hypothetical tetrahedral intermediate of SA amines compared with isobasic pyridines.[3c] It is known that the nucleofugality of anilines is intermediate between those of isobasic pyridines and SA amines.[14] Therefore, the probable concerted mechanism for the reactions under the present investigation could be justified by the larger leaving ability of anilines, relative to pyridines, from the zwitterionic tetrahedral intermediate. This should kinetically destabilize the intermediate and make possible the change in mechanism, from stepwise (for pyridines) to concerted (for anilines). Although anilines should stabilize the tetrahedral intermediate relative to SA amines, probably this stabilization is not sufficient to change the mechanism to stepwise.

On the other hand, the anilinolysis of carbonate **3** in water has been described as stepwise on the basis of the linear Brønsted plot obtained with a slope (β) of 0.9.[3a] This means that the change of the leaving group of the substrate, from 2,4-dinitrophenoxide to 2,4,6-trinitrophenoxide, destabilizes the zwitterionic tetrahedral intermediate (due to the greater nucleofugality of the latter) and changes the mechanism from stepwise to concerted.

Although we are more inclined towards a concerted mechanism for the title reactions, nevertheless, in view of the borderline value of the Brønsted slope found for the reactions of this work, the possibility that both mechanisms (stepwise and concerted) occur simultaneously cannot rigorously be ruled out.

Experimental Section

General. 2,4,6-Trinitrophenyl methyl carbonate **4** was prepared as described.[1d] The anilines were purified either by distillation or recrystallization.[19] Methyl *N*-phenyl carbamate (CH_3O-CO-NH-Ph), which is one of the products of the reaction of carbonate **4** with aniline, was prepared as published for the synthesis of ethyl phenyl carbamate,[14] using methyl chloroformate, instead of ethyl chloroformate, and aniline in acetonitrile. The crystallized (ethanol) methyl *N*-phenyl carbamate melted at 46.0 - 46.5ºC. This product was identified by ^1H NMR (200 MHz, $CDCl_3$) and IR analyses.

Kinetic measurements. These were carried out in water solution, at 25.0 ± 0.1 ºC, ionic strength 0.2 M (KCl). The reactions were followed at 360 nm (formation of 2,4,6-trinitrophenoxide anion) by means of a diode array spectrophotometer.

The reactions were studied under excess amine over the substrate. The initial substrate concentration was 5×10^{-5} M. Phosphate buffer (0.01M) was used in all reactions.

Pseudo-first-order rate coefficients (k_{obsd}) were found throughout; these were determined by means of the spectrophotometer kinetic software for first order reactions. The experimental conditions of the reactions and the k_{obsd} values are shown in Table 1.

Product studies. For the present reactions one of the products was identified as 2,4,6-trinitrophenoxide anion; this was achieved by comparison of the UV-vis spectra after completion of the reactions with an authentic sample of 5×10^{-5} M 2,4,6-trinitrophenol, under the same conditions. In the reaction with aniline, the other product was identified as methyl *N*-phenyl carbamate. This was carried out by HPLC, by comparison of a sample at the end of the reaction with an authentic sample of the corresponding product. HPLC conditions: column, Supelcosil LC-18 (250 x 4.6 mm, 5μm); eluant, acetonitrile / water = 50 / 50; isocratic mode 0.4 mL / min.

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