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Experimental and theoretical study on the substitution reactions of aryl 2,4-dinitrophenyl carbonates with quinuclidines

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Abstract—The reactions of quinuclidines with phenyl, 4-methylphenyl, and 4-chlorophenyl 2,4-dinitrophenyl carbonates are kinetically evaluated in aqueous solution. The Brønsted-type plots (log k_N vs pK_a of quinuclidinium ions) are linear. The magnitude of the slopes and validated theoretical scales of electrophilicity and nucleophilicity confirm the concerted nature of these reactions.

1. Introduction

The kinetics and mechanisms of the aminolysis of carbonyl compounds are well documented.[1–9] Some of these reports concern the reactions of pyridines with some aryl methyl carbonates, with aryl=phenyl, 4-nitrophenyl, 2,4-dinitrophenyl, and 2,4,6-trinitrophenyl, (hereafter MPC, MNPC, MDNPC, and MTNPC, respectively),[1] the reactions of MNPC, MDNPC, and MTNPC with secondary alicyclic (SA) amines,[2] the reactions of MNPC and MDNPC with quinuclidines[2c] and the reactions of MDNPC with anilines.[2a] Other reactions involving SA amines with phenyl, 4-methylphenyl, and 4-chlorophenyl 2,4-dinitrophenyl carbonates (PDNPC, MPDNPC and ClPDNPC, respectively)[2c,5a,c] and with 4-methylphenyl and 4-chlorophenyl 4-nitrophenyl carbonates (MPNPC and ClPNPC, respectively)[5a,b] have been the subject of experimental studies. Also investigated have been the reactions of phenyl 4-nitrophenyl carbonate (PNPC), MPNPC, ClPNPC, and PDNPC with quinuclidines[4,5] and those of MPDNPC and ClPDNPC with anilines.[5c]

Some of these processes have been described as stepwise, going through a zwitterionic tetrahedral intermediate ($T^{\pm}$). This conclusion has been drawn based on the biphasic Brønsted-type plots obtained (reactions of SA amines with MNPC,[2c] MPNPC,[5a] and ClPNPC[5b] and those of pyridines with MDNPC[1b] and MTNPC[1d]). These biphasic plots show two linear portions, at low (with slope β ca. 1) and high (β ca. 0.3) pK_a values of the conjugate acid of the amine, which have been assigned to rate-determining breakdown and formation of $T^{\pm}$, respectively. In other reactions linear Brønsted plots with slopes within the β range of 0.7–1.1 have been found. These reactions have been associated with stepwise processes, where the breakdown to products is the rate-determining step. This is the case of the reactions of MPC[1c] and MNPC[1a] with pyridines, those of MDNPC with anilines,[2a] and those of MNPC,[2c] PNPC,[4] MPNPC,[5b] and ClPNPC[5b] with quinuclidines. The change in the rate-determining step has been discussed as a function of the different leaving group abilities. In the case of the diaryl carbonates, this change has been argued in terms of the electron withdrawing or electron releasing abilities of the nonleaving groups.

Other aminolysis of carbonates have been found to be concerted. This is the case of the reactions of SA amines with MDNPC,[2c] MTNPC,[2b] PDNPC,[2c] MPDNPC,[5a] and ClPDNPC[5c] and the reactions of MPDNPC and ClPDNPC toward anilines.[5c] These reactions exhibit linear Brønsted-type plots with slopes $\beta=0.4$–0.7 or slightly curved plots. The Brønsted β value alone is not sufficient for the diagnosis of a concerted mechanism. A definitive proof that the title

Keywords: Aminolysis of diaryl carbonates; Electrophilicity scale; Nucleophilicity scale; Electrophilicity/nucleophilicity difference; Reaction mechanisms.
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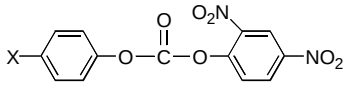
reactions are concerted implies the prediction of the pK_a position at the break of the biphasic Brønsted-type plot (pK_a^0) for a hypothetical stepwise mechanism. It would be further necessary to show that this value falls within the pK_a range of the amines employed.[10] It is also important to obtain a large number of data, which cover a substantial pK_a range above and below the pK_a^0 value.[11]

A pertinent alternative is to complement the experimental study with reliable theoretical and computational models of chemical reactivity in order to establish the global reactivity patterns at the ground state of the substrates. We propose in this work such an analysis based on theoretical scales of global electrophilicity/nucleophilicity for the reference series of diaryl carbonates and alkyl aryl carbonates and related amines,[12] respectively.

In order to further extend our investigations on the kinetics and mechanisms of the aminolysis of diaryl carbonates, in this work we report kinetic results for the quinuclidinolysis of PDNPC, MPDNPC, and ClPDNPC (see structures below) in water. By comparing these reactions with the aminolyses of similar carbonates in aqueous ethanol and in water, the influence of the leaving and nonleaving groups, as well as solvent effects and amine nature on the kinetics and mechanism may be completely examined. Another objective of this work is to confirm the mechanism of the title reactions by theoretical studies.[12]



PDNPC (X = H)
MPDNPC (X = Me)
ClPDNPC (X = Cl)

2. Results and discussion

Under amine excess over the substrate, pseudo-first-order rate coefficients (k_{obsd}) were obtained for all reactions. The experimental conditions of the reactions and the values of k_{obsd} are shown in Tables 1–3.

2.1. Experimental studies of the mechanism based on the analysis of the Brønsted-type plots

The kinetic law obtained under the reaction conditions is that described by Eq. 1, where $DNPO^-$ is 2,4-dinitrophenoxide anion and S is the substrate.

$$\frac{d[DNPO^-]}{dt} = k_{obsd}[S] \quad (1)$$

Plots of k_{obsd} against concentration of free quinuclidine (except for DABCO, see below) at constant pH were linear in accordance with Eq. 2, where k_0 and k_N are the rate coefficients for hydrolysis and aminolysis of the substrates, respectively. The values of k_0 and k_N were obtained as the intercept and slope, respectively, of plots of Eq. 2, and were pH-independent.

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

The reactions with mixtures of DABCO and $DABCOH^+$ ion were studied at the pH range 5.0–7.0, where a mixture of both amines are present. In these cases the k_N values were obtained through Eqs. 3 and 4. In these equations k_{Nobsd} is a global nucleophilic rate constant (corresponding to the mixture of nucleophiles), $[N]_{tot}$ is the total amine (DABCO + $DABCOH^+$) concentration, F_N and F_{NH} are the molar fractions of DABCO and $DABCOH^+$, respectively, and k_N and k_{NH} are their corresponding nucleophilic

Table 1. Experimental conditions and k_{obsd} values for the reactions of quinuclidines with phenyl 2,4-dinitrophenyl carbonate (PDNPC)[a]

Amine	pH	F_N[b]	$10^4[N]_{tot}/M$[c]	$10^2 k_{obsd}/s^{-1}$	No. of runs
Quinuclidine	11.4	0.5	28.8–962	204–7210	6
3-Hydroxyquinuclidine	9.3	0.24	1.00–10.0	0.648–3.16	6
	9.8	0.5	1.00–962	0.881–3140	11
	10.1	0.67	2.00–11.9	1.74–11.1	6
3-Chloroquinuclidine	8.7	0.33	1.00–10.0	0.414–3.70	6
	9.0	0.50	1.00–24.0	0.361–2650	13
	9.3	0.67	1.00–6.00	0.574–4.76	4
DABCO + $DABCOH^+$	5.0	[d]	31.8–271	0.0427–0.155	6
	5.3	[e]	32.1–225	0.0565–0.188	5
	5.6	[f]	81.5–277	0.137–0.321	4
	6.0	[g]	269–1080	1.32–5.50	5
	6.3	[h]	99.1–991	0.640–5.33	7
	6.5	[i]	92.8–834	1.12–6.62	5
	6.8	[j]	107–1070	2.62–15.2	6
3-Quinuclidinone	7.2	0.33	20.0–120	1.18–9.49	6
	7.5	0.50	20.0–3600	1.47–394	12
	7.8	0.67	20.0–120	3.00–15.2	6

[a] In water, at 25 °C, ionic strength 0.2 M (KCl).
[b] Free amine fraction.
[c] Concentration of total amine (free base plus protonated forms).
[d] Free DABCO and $DABCOH^+$ ion fractions are 0.0001498 and 0.98995, respectively.
[e] Free DABCO and $DABCOH^+$ ion fractions are 0.0003004 and 0.994714, respectively.
[f] Free DABCO and $DABCOH^+$ ion fractions are 0.0006007 and 0.996895, respectively.
[g] Free DABCO and $DABCOH^+$ ion fractions are 0.0015098 and 0.997493, respectively.
[h] Free DABCO and $DABCOH^+$ ion fractions are 0.0030093 and 0.996491, respectively.
[i] Free DABCO and $DABCOH^+$ ion fractions are 0.004762 and 0.994923, respectively.
[j] Free DABCO and $DABCOH^+$ ion fractions are 0.009458 and 0.990385, respectively.

Table 2. Experimental conditions and k_{obsd} values for the reactions of quinuclidines with 4-chlorophenyl 2,4-dinitrophenyl carbonate (ClPDNPC)[a]

Amine	pH	F_N[b]	$10^4[N]_{tot}/M$[c]	$10^2 k_{obsd}/s^{-1}$	No. of runs
Quinuclidine	11.4	0.5	38.4–41.0	430–7070	5
3-Hydroxyquinuclidine	9.36	0.24	1.00–10.0	0.393–3.20	6
	9.8	0.5	1.00–1920	0.965–7160	11
	10.1	0.67	2.00–12.0	1.66–18.2	6
3-Chloroquinuclidine	8.7	0.33	2.00–12.0	0.585–4.80	6
	9.0	0.50	1.00–3360	0.517–6410	13
	9.3	0.67	4.00–12.0	2.55–8.32	5
DABCO + $DABCOH^+$	5.0	[d]	31.8–271	0.043–0.146	6
	5.3	[e]	32.1–273	0.062–0.22	6
	5.6	[f]	81.5–326	0.183–0.397	6
	6.0	[g]	269–915	1.43–4.70	5
	6.3	[h]	99.1–991	0.713–5.18	7
	6.5	[i]	92.8–834	1.25–6.53	5
	6.8	[j]	107–1070	2.50–14.5	7
3-Quinuclidinone	7.2	0.33	20.4–121	2.42–12.8	6
	7.5	0.50	20.2–3600	3.03–585	12
	7.8	0.67	20.2–121	3.48–19.8	6

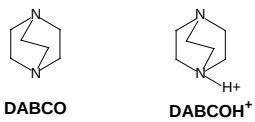
[a] In water, at 25 °C, ionic strength 0.2 M (KCl).
[b] Free amine fraction.
[c] Concentration of total amine (free base plus protonated forms).
[d] Free DABCO and $DABCOH^+$ ion fractions are 0.0001498 and 0.98995, respectively.
[e] Free DABCO and $DABCOH^+$ ion fractions are 0.0003004 and 0.994714, respectively.
[f] Free DABCO and $DABCOH^+$ ion fractions are 0.0006007 and 0.996895, respectively.
[g] Free DABCO and $DABCOH^+$ ion fractions are 0.0015098 and 0.997493, respectively.
[h] Free DABCO and $DABCOH^+$ ion fractions are 0.0030093 and 0.996491, respectively.
[i] Free DABCO and $DABCOH^+$ ion fractions are 0.004762 and 0.994923, respectively.
[j] Free DABCO and $DABCOH^+$ ion fractions are 0.009458 and 0.990385, respectively.

Table 3. Experimental conditions and k_{obsd} values for the reactions of quinuclidines with 4-methylphenyl 2,4-dinitrophenyl carbonate (MPDNPC)[a]

Amine	pH	F_N[b]	$10^4[N]_{tot}/M$[c]	$10^2 k_{obsd}/s^{-1}$	No. of runs
Quinuclidine	11.4	0.5	28.8–962	196–5740	6
3-Hydroxyquinuclidine	9.8	0.5	240–3600	1110–11400	6
3-Chloroquinuclidine	9.0	0.5	120–2400	102–2530	6
DABCO + $DABCOH^+$	5.6	[d]	179–326	0.222–0.378	4
	6.0	[e]	269–1080	0.861–3.80	5
	6.3	[f]	99.1–991	0.463–3.54	7
	6.5	[g]	92.8–834	0.738–4.67	4
	6.8	[h]	268–750	2.94–8.37	4
	7.0	[i]	100–703	2.07–11.7	5
3-Quinuclidinone	7.5	0.5	240–3600	16.7–3240	6

[a] In water, at 25 °C, ionic strength 0.2 M (KCl).
[b] Free amine fraction.
[c] Concentration of total amine (free base plus protonated forms).
[d] Free DABCO and $DABCOH^+$ ion fractions are 0.0006007 and 0.996895, respectively.
[e] Free DABCO and $DABCOH^+$ ion fractions are 0.0015098 and 0.997493, respectively.
[f] Free DABCO and $DABCOH^+$ ion fractions are 0.0030093 and 0.996491, respectively.
[g] Free DABCO and $DABCOH^+$ ion fractions are 0.004762 and 0.994923, respectively.
[h] Free DABCO and $DABCOH^+$ ion fractions are 0.009458 and 0.990385, respectively.
[i] Free DABCO and $DABCOH^+$ ion fractions are 0.014908 and 0.984993, respectively.

rate constants. The values of k_{Nobsd} were obtained as the slopes of linear plots of k_{obsd} versus $[N]_{tot}$ at constant pH. The k_N and k_{NH} values for the reactions with DABCO and $DABCOH^+$, respectively, were determined graphically through Eqs. 3 and 4.



$$k_{obsd} = k_0 + k_{Nobs}[N]_{tot} \quad (3)$$

$$k_{Nobsd} = F_N k_N + F_{NH} k_{NH} \quad (4)$$

The values of k_N for the reactions of DABCO and $DABCOH^+$ ion with the three aryl carbonates, as well as those of the pK_a of the their conjugate acids, were statistically corrected with $q=2$ and $p=2$, respectively. The reactions with the other quinuclidines were not corrected statistically ($q=1$ and $p=1$). The statistical parameter q is the number of equivalent basic sites of the amine and p is the number of equivalent protons of the conjugate acid of the amine.[13]

Table 4 shows the corrected values of pK_a of the quinuclidinium ions and those of the corrected k_N values for the reactions under study. The pK_a values and those of k_N for the quinuclidinolysis of PDNPC, both obtained at ionic strength 0.2 M, agree well with those reported at ionic strength 1.0 M in the same solvent and temperature.[4] With these corrected values the Brønsted-type plots of Figure 1 were obtained. These plots are linear with slopes (β_N) 0.54, 0.57, and 0.57 for the reactions with PDNPC, MPDNPC, and ClPDNPC, respectively.

Table 4. Values of corrected pK_a for the conjugate acids of quinuclidines and corrected k_N values for the reactions of these amines with phenyl 2,4-dinitrophenyl carbonate (PDNPC), 4-methylphenyl 2,4-dinitrophenyl carbonate (MPDNPC), and 4-chlorophenyl 2,4-dinitrophenyl carbonate (ClPDNPC)[a]

Amine	Corrected pK_a	k_N q^{-1}/s^{-1} M^{-1}		
		PDNPC	MPDNPC	ClPDNPC
Quinuclidine	11.4	1510±50	1210±20	2190±80
3-Hydroxyquinuclidine	9.8	670±10	590±40	738±4
3-Chloroquinuclidine	9.0	203±6	210±10	329±4
DABCO	8.6	66±13	56±6	69±11
3-Quinuclidinone	7.5	21.6±0.5	18.4±0.6	27.6±0.4
DABCOH$^+$	3.2[b]	0.09±0.05	0.05±0.04	0.07±0.04

[a] Both the pK_a and k_N values were determined in aqueous solution, at 25.0 °C, ionic strength 0.2 (KCl).
[b] pK_a value from Ref. 14, corrected with $p=2$ (see text).

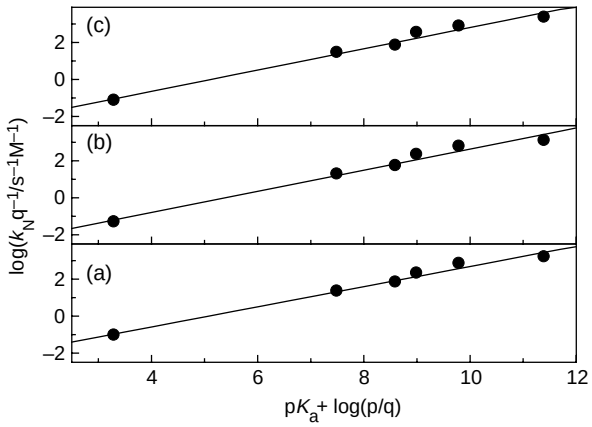


Figure 1. Brønsted-type plots obtained in the reactions of quinuclidines with (a) phenyl 2,4-dinitrophenyl carbonate (PDNPC), (b) 4-methylphenyl 2,4-dinitrophenyl carbonate (MPDNPC) and (c) 4-chlorophenyl 2,4-dinitrophenyl carbonate (ClPDNPC), in water, at 25.0 °C and an ionic strength of 0.2 M.

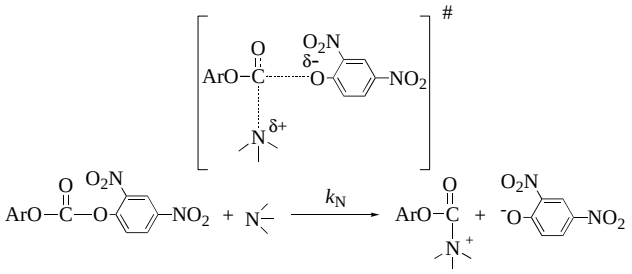
The values of β found for the reactions of quinuclidines with PDNPC, MPDNPC, and ClPDNPC (Fig. 1) are in agreement with those obtained in the following concerted aminolyses in water: SA amines with 2,4,6-trinitrophenyl acetate,[2b] methyl 2,4,6-trinitrophenyl carbonate,[2b] methyl 2,4-dinitrophenyl carbonate,[2c] and phenyl 2,4-dinitrophenyl carbonate[2c] ($\beta=0.41$, 0.36, 0.48, and 0.39, respectively). The slopes are also in agreement with those obtained for the reactions of SA amines with *S*-(2,4-dinitrophenyl) and *S*-(2,4,6-trinitrophenyl) *O*-ethyl thiocarbonates ($\beta=0.56$ and 0.48, respectively),[15] the reactions of quinuclidines with these two substrates ($\beta=0.54$ and 0.47, respectively),[16] and those of anilines with the latter compound ($\beta=0.54$).[17] These β values are also in agreement with those found in the concerted reactions of SA amines and anilines with MPDNPC and ClPDNPC in 44 wt% ethanol–water ($\beta=$ 0.44–0.68),[5a,c] and the concerted methoxycarbonyl group transfer between isoquinoline and pyridines in water ($\beta=$ 0.58).[10a]

The pyridinolysis of methyl 2,4-dinitrophenyl carbonate in water exhibits a biphasic Brønsted-type plot with a pK_a^0 value of 7.8.[1b] It is known that quinuclidines are better nucleofuges from a tetrahedral intermediate than isobasic pyridines,[16,18] which implies a larger pK_a^0 value for the former amines. On the other hand, the change of methoxy or ethoxy to phenoxy as the nonleaving group also enhances the pK_a^0 value.[19] Therefore, the pK_a^0 value for the quinuclidinolysis of PDNPC should be larger than 7.8 if this reaction were stepwise. If the predicted pK_a^0 value were within the pK_a range for the quinuclidines employed in this work, a biphasic Brønsted plot would be expected. As seen in Figure 1 this is not the case. If, on the other hand, the pK_a^0 value were much larger than 7.8 and outside the pK_a range for the quinuclidines, the rate-determining step for the quinuclidinolysis of PDNPC would be the breakdown to products of the tetrahedral intermediate ($T^{\pm}$). Nevertheless, the Brønsted slope obtained for this reaction (Fig. 1) is small compared to the slopes observed when decomposition to products of $T^{\pm}$ is the rate limiting step ($\beta=0.8$–1.1).[1b,2c,4,5a,b,16,20]

Furthermore, there are additional proofs that the title reactions are concerted: (1) the reactions of SA amines with methyl 4-nitrophenyl carbonate (MNPC) in water are stepwise,[2c] in contrast to those of the same amines with methyl 2,4-dinitrophenyl carbonate in the same solvent, which are concerted.[2c] (2) Similarly, the mechanism for the reactions of quinuclidines in water changes from stepwise to concerted by the same change of carbonates.[2c] (3) Other examples are: the stepwise SA aminolysis of MPNPC[5a] and ClPNPC[5b] in aqueous ethanol, in contrast to the concerted reactions of the same amines with MPDNPC[5a] and ClPDNPC[5c] in the same solvent. Namely, in these reactions the addition of a second nitro substituent in the leaving group of the substrate shifts the mechanism from a two-steps to a single-step process.[21] On the other hand, the quinuclidinolysis of phenyl 4-nitrophenyl carbonate in water is stepwise (see above).[4] Therefore, it is likely that the addition of a second nitro substituent to the leaving group of the latter carbonate (to give PDNPC) changes the mechanism from stepwise to concerted. Furthermore, the change of the carbonate from MNPC to PDNPC, MPDNPC or ClPDNPC in their reactions with SA amines changes the mechanism from stepwise to concerted.[2c,5a,c] Since the quinuclidinolysis of MNPC is stepwise, it is reasonable that the quinuclidinolysis of the title substrates would be concerted.

Taking into account the slopes of the Brønsted plots obtained, the arguments given above, the kinetic law and product studies, the most likely mechanism for the reactions under scrutiny is the concerted process. Scheme 1 shows the single-step reaction, with its transition state. In this Scheme,

Ar is 4-X-phenyl (X=H, Me, Cl) and N represents a quinuclidine.



Scheme 1.

In order to evaluate the influence of the nonleaving group of the substrate on the kinetics and mechanism of the aminolysis studied, Brønsted plots (not shown) were obtained. These plots were drawn with the corrected k_N values found in this work (Table 4) and the pK_a values of the conjugate acids of the nonleaving groups (the latter are 10.1, 9.9, and 9.4 for 4-methylphenol, phenol, and 4-chlorophenol, respectively). The β_{nlg} values are negative for all the quinuclidines, ranging from −0.13 to −0.36, with a mean value −0.22. The latter value is acceptable for a concerted mechanism and is in accordance with that found for the concerted phenolysis of diaryl carbonates ($\beta_{nlg}=-0.27$).[22]

The slightly greater reactivity of ClPDNPC with respect to PDNPC and MPDNPC (Table 4) may be traced to the negative value of β_{nlg} and the larger value of the pK_a of 4-methylphenol and phenol as compared to that of 4-chlorophenol. This result is in agreement with theoretical studies.[12,21]

Figure 2 shows a comparison of the Brønsted-type plots obtained for the concerted quinuclidinolysis of PDNPC (this work) and methyl 2,4-dinitrophenyl carbonate (MDNPC),[2c] both in aqueous solution.

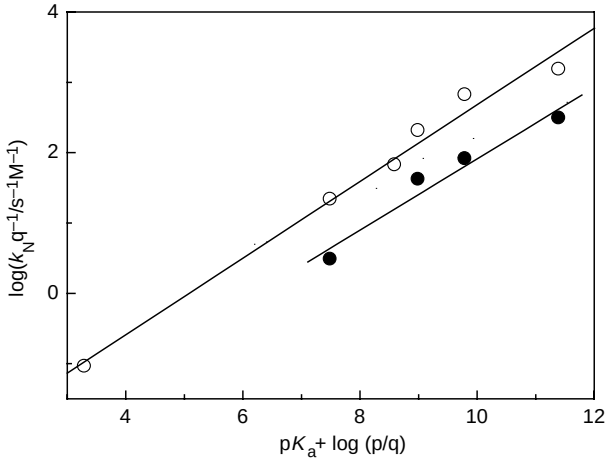


Figure 2. Brønsted-type plots (statistically corrected) for the quinuclidinolysis of phenyl 2,4-dinitrophenyl carbonate (PDNPC) (○, this work) and MDNPC (●, Ref. 2c), in water, at 25.0 °C and an ionic strength of 0.2 M.

The k_N values for the quinuclidinolysis of PDNPC (this work) are larger than those found for the same aminolysis of MDNPC[2c] in the same solvent. This result is in line with the behaviour of the concerted reactions of the same substrates with SA amines[2c] and can be explained by the greater electron withdrawing effect of the PhO as compared to MeO as the nonleaving group in the substrate.

2.2. Nature of the reaction mechanisms based on the theoretical electrophilicity/nucleophilicity indices

As mentioned above, a definitive proof that the title reactions are concerted, implies the prediction of the pK_a position at the break of the biphasic Brønsted-type plot (pK_a^0) for an hypothetical stepwise mechanism, which demands this value to fall within the pK_a range of the amines employed.[10] Another pertinent alternative is to complement the experimental study with reliable theoretical studies of chemical reactivity in order to establish the relative stability of the hypothetical tetrahedral intermediates involved in analogous reactions. We propose here such an analysis based on theoretical scales of global electrophilicity/nucleophilicity for the reference series of diaryl carbonates and alkyl aryl carbonates and related amines,[12] respectively. Validated theoretical scales of electrophilicity/nucleophilicity[21,23–29] have proven to be useful tools to rationalize the observed reaction mechanisms in related systems.[12,21] They may be further used to predict the degree of polar character of the process at the transition state.[30,31] Within this framework, we have previously proposed a useful empirical rule, based on theoretical electrophilicity/nucleophilicity indexes to rationalize the reaction mechanism for a series of carbonates[12] and thiocarbonates[21] derivatives with neutral and charged reagents of varying nucleophilicity.[12] This rule states that the greater the electrophilicity–nucleophilicity difference, the greater concerted character the reaction mechanism will possess. Conversely, a small electrophilicity/nucleophilicity gap will in general be associated with a stepwise reaction mechanism. Other attempts to relate reactivity indexes and reactions mechanisms have been reported.[28,29] Beyond the electrophilicity/nucleophilicity scales, some mechanistic change from stepwise to concerted may be attributed to the different leaving abilities of the nucleofuge.[1b–d,2c,4,5a–c,12,21]

The global electrophilicity index, ω, which measures the stabilization in energy when the system acquires and additional electronic charge (ΔN) from the environment, has been given the following expression:[32]

$$\omega = \frac{\mu^2}{2\eta} \tag{5}$$

Conceptually, the electrophilicity index encompasses two classical concepts involved in the propensity of any atomic or molecular system to bind an extra electronic charge from the environment, namely, the electronegativity $\chi=-\mu$ (where μ is the electronic chemical potential) and the chemical hardness η, measuring the resistance of the system to exchange electronic charge with the environment. Both quantities are easily obtained from a finite difference method together with Koopman's theorem, in terms of the one electron energy levels of the frontier molecular orbitals HOMO and LUMO,[32] as

shown in Eqs. 6 and 7, respectively

$$\mu = \frac{\varepsilon_H + \varepsilon_L}{2} \quad (6)$$

$$\eta \cong \varepsilon_L - \varepsilon_H \quad (7)$$

With μ and η values at hand, the electrophilicity index was evaluated using Eq. 5. The global electrophilicity is not sensitive to solvent effects,[33] and therefore the gas phase value suffices to establish an absolute hierarchy of the electron accepting ability of these systems. Ab inito HF/3-21G calculations were performed using the Gaussian 98 suite of programs[34] in order to evaluate the electronic quantities required to estimate the ground state electrophilicity index for the series of carbonates derivatives considered in the present study.

The experimental and theoretical scales of electrophilicity/nucleophilicity are useful tools to discuss reaction feasibility,[24] inter and intramolecular reactivity[25] and reaction mechanisms.[12,21] The nucleophilicity number ω^- has been represented using the critical points of the molecular electrostatic potential.[12] For the aminolysis of carbonates[12] and thiocarbonates,[21] we reported an empirical rule stating that the larger the electrophilicity/nucleophilicity difference, the greater the concerted character of the reaction mechanism. Conversely, a small electrophilicity/nucleophilecity gap will be associated, in general, with a stepwise reaction mechanism. This model uses the nucleophilicity–electrophilicity difference index, $\Delta_{NE}=|\varpi^- - \omega|$, as a criterion to predict the degree of polar character of the electrophile/nucleophile interaction.[12,21] The parameter ϖ^- is the average nucleophilicity evaluated for a set of secondary alicyclic amines, that are allowed to react with a series of carbonates (electrophiles).[12]

Table 5. Energy of the frontier molecular orbitals HOMO and LUMO (ε_H and ε_L), electronic chemical potential (μ), and chemical hardness (η)

Carbonate	ε_{HOMO} (a.u.)	ε_{LUMO} (a.u.)	μ (eV)	η (eV)
MTNPC	−0.43551	−0.09719	−6.08	11.80
MDNPC	−0.40089	0.00293	−5.41	10.99
ClPDNPC	−0.35179	0.00745	−4.68	9.77
MPDNPC	−0.34269	−0.01218	−4.83	8.99
PDNPC	−0.34412	0.01174	−4.52	9.68
PNPC	−0.34372	0.04075	−4.12	10.46
ClPNPC	−0.35396	0.04445	−4.21	10.84
MPNPC	−0.34020	0.04849	−3.97	10.58
MNPC	−0.37142	0.05283	−4.33	11.54
(*m*)PNPC	−0.35183	0.07957	−3.70	11.74

Table 5 shows the energy values of the frontier molecular orbitals HOMO and LUMO (ε_H and ε_L), electronic chemical potential (μ), and chemical hardness (η) for the series of carbonates and Table 6 shows the electrophilicity index (ω) for the series of carbonates and the corresponding Δ_{NE} values for the substitution reactions that have been kinetically evaluated for reactions with secondary (SA) and tertiary (Q) alicyclic amines, via either concerted or stepwise mechanisms.[2b,c,4,5a–c] As can be seen, those electrophiles that react via a stepwise pathway display Δ_{NE} values smaller than or approximately equal to 1.1 eV. Carbonates that have been evaluated to react via a concerted pathway, on the other hand, consistently show Δ_{NE} values greater than 1.1 eV. However, the dividing line around $\Delta_{NE}=1.1$ eV is certainly arbitrary. A more reliable criterion may be obtained by taking an interval between the maximum and minimum values around the border line. Based on these results, the empirical rule can be applicable for the nucleophilic substitution reactions examined here. These results can be used either to predict the mechanism of the aminolysis of compounds not kinetically evaluated to date or to validate the kinetically proposed mechanism.

Table 6. Nucleophilicity–electrophilicity differences (Δ_{NE})[a] and predicted and experimenthal mechanisms for the reactions of secondary alicyclic (SA) amines and quinuclidines (Q) with diaryl carbonates and alkyl aryl carbonates

HF/3-21G				Mechanism	
Carbonate	ω (eV)	Amine series	Δ_{NE} (eV)[a]	Exptl	Pred.
MTNPC	1.57	SA	1.80	Conc[2b]	Conc
		Q	1.68		Conc
MDNPC	1.33	SA	1.56	Conc[2c]	Conc
		Q	1.44	Conc[2c]	Conc
ClPDNPC	1.30	SA	1.53	Conc[5c]	Conc
		Q	1.41	Conc[b]	Conc
MPDNPC	1.16	SA	1.39	Conc[5a]	Conc
		Q	1.27	Conc[b]	Conc
PDNPC	1.10	SA	1.33	Conc[2c]	Conc
		Q	1.21	Conc[b]	Conc
PNPC	0.86	SA	1.09		Stepwise
		Q	0.97	Stepwise[4]	Stepwise
ClPNPC	0.84	SA	1.07	Stepwise[5b]	Stepwise
		Q	0.95	Stepwise[5b]	Stepwise
MPNPC	0.84	SA	1.07	Stepwise[5a]	Stepwise
		Q	0.95	Stepwise[5b]	Stepwise
MNPC	0.81	SA	1.04	Stepwise[2c]	Stepwise
		Q	0.92	Stepwise[2c]	Stepwise
(*m*)PNPC	0.58	Q	0.81	Stepwise[4]	Stepwise

[a] $(\Delta_{NE})=|\omega^- - \omega|$; $\varpi^- = -0.228$ and -0.1075 eV for SA and Q, respectively.
[b] This work.

3. Experimental

3.1. Materials

The series of quinuclidines were purified as reported.[4] The carbonates, PDNPC,[4] MPDNPC,[5a] and ClPDNPC,[5c] were prepared as described.

3.2. Kinetic measurements

These were carried out by means of either a HP-8453 diode array spectrophotometer or a Applied Photophysics DX17MV stopped flow spectrophotometer in aqueous solution, at 25.0±0.1 °C, ionic strength 0.2 M (KCl). The reactions were studied by monitoring the appearance of 2,4-dinitrophenoxide anion at 360 nm.

The reactions in the stopped flow spectrophotometer were carried out with unequal mixing. The carbonate dissolved in dry acetonitrile was placed in the smaller syringe (0.1 mL) and the larger syringe (2.5 mL) was filled with the amine aqueous solution. The total acetonitrile concentration was 3.85% (v/v).

All the reactions were examined under excess amine over the substrate. The initial substrate concentration was 5×10^{-5} M, and the pH was maintained by partial protonation of the quinuclidines.

Pseudo-first-order rate coefficients (k_{obsd}) were found throughout and determined by means of the spectrophotometer kinetic software for first order reactions.

3.3. Determination of pK_a values

The pK_a value of the conjugated acid of DABCO was determined by a potentiometric method, in water, at 25.0±0.1 °C, and an ionic strength of 0.2 M (maintained with KCl). The value obtained was 8.9±0.1.

3.4. Product studies

One of the products of the reactions under scrutiny was identified as 2,4-dinitrophenoxide anion, as shown by a comparison of the UV–vis spectra after completion of the reactions with an authentic sample under the same experimental conditions.

4. Concluding remarks

In this work, we have experimentally and theoretically examined the reactivity of diaryl carbonates (PDNPC, MPDNPC and ClPDNPC) toward alicyclic amines. For the reactions of quinuclidines with these substrates the Brønsted-type plots (log k_N vs pK_a of quinuclidinium ions) are linear. The magnitude of the slopes and other arguments suggest that these mechanisms are concerted. The electrophilicity of the diaryl carbonates may be conveniently described in terms of the electronic reactivity index proposed by Parr et al.[32] The global electrophilicity index assesses well the substituent effects of the strong electron withdrawing –NO_2 group, which is known to have its greatest effectiveness at the *para* position[21] of the phenyl ring. The increasing substitutions by one and two –NO_2 groups increases the electrophilicity number and makes an almost additive contribution by group.[21] These analyses are consistent with the available experimental data[35] and also with the recently proposed Hammett substituent constants.[21] On the other hand, the electrophilicity/nucleophilicity scales may also be used to rationalize reaction mechanisms in these systems: while highly electrophilic diaryl carbonates will in general undergo aminolysis via a concerted route, those marginally electrophilic will react with quinuclidines via a stepwise route. This thereby confirms that the quinuclidinolysis of aryl dinitrophenyl carbonates is a concerted process.

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