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Kinetics and mechanism of the reactions of polyallylamine with aryl acetates and aryl methyl carbonates

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ABSTRACT: The reactions of polyallylamine (PAA) with 4-nitrophenyl acetate (NPA), 2,4-dinitrophenyl acetate (DNPA), 2,4,6-trinitrophenyl acetate (TNPA), 4-nitrophenyl methyl carbonate (NPC), 2,4-dinitrophenyl methyl carbonate (DNPC) and 2,4,6-trinitrophenyl methyl carbonate (TNPC) at pH 7.0–11.5 were subjected to a kinetic investigation in aqueous solution at 25.0 °C and an ionic strength of 0.1 M (KCl). Potentiometric titration curves were obtained at different polymer concentrations under the same conditions as for the kinetic measurements. The degree of dissociation (α) and pK_{app} values for PAA at each pH were found from the titration curves. The shape of these curves shows a conformational change of the polymer at $\alpha > 0.7$. Similar behavior was observed through the dependence of logk_N on either pH or α, where k_N is the second-order rate constant for the title reactions. The k_N value is influenced by the electrostatic interactions in the polymer chain and the conformational changes that PAA undergoes in solution. The Brønsted-type plots (logk_N vs pK_{app}) are linear with slopes (β values) of 0.5, 0.4, 0.5, 0.7, 0.6 and 0.7 for the reactions of PAA with NPA, DNPA, TNPA, NPC, DNPC and TNPC, respectively. These data are consistent with concerted mechanisms. The k_N values increase in the sequence TNPA > DNPA > NPA and TNPC > DNPC > NPC. These results are in accordance with those found for the reactions with monomeric amines, which are due to the increasing nucleofugality of the leaving groups, and also the increasing electrophilic character of the carbonyl carbon, as more nitro groups are added to the substrate. Acetates are more reactive than the corresponding methyl carbonates, which can be explained by the larger electron-releasing effect exerted by MeO relative to Me. PAA destabilizes the putative tetrahedral intermediate relative to the monomeric amines and the stability of tetrahedral intermediates would decrease in the sequence pyridines > anilines > secondary alicyclic amines > quinuclidines > PAA. Copyright © 2006 John Wiley & Sons, Ltd.

KEYWORDS: polyallylamine; aryl acetates; aryl methyl carbonates; kinetics; mechanism

INTRODUCTION

The study of the reactions involving synthetic macromolecules can serve as a model for more complex enzymatic processes. In general, a synthetic polymer can concentrate and/or repel a reactive molecule in its vicinity or, when the synthetic polymer is functionalized with some catalytically active functions, some effects on the kinetics and mechanism of the reactions are observed.[1]

The mechanisms of the aminolysis of aryl acetates,[2] alkyl aryl carbonates[3–5] and diaryl carbonates[4b,6,7] with monomeric amines have been well established. Some of these reactions are known to proceed through a zwitterionic tetrahedral intermediate ($T^{\pm}$) and others by a concerted pathway (a single step). Structure–reactivity correlations, such as the Brønsted-type relationship, have helped to clarify the mechanisms.[2–7]

The apparent acid strength of a polyamine-conjugated acid depends not only on the concentration and type of added salt but also on the degree of dissociation. The variation of these allows a range of basicities of the polyamine without a change in its structure. This has been used advantageously in mechanistic studies where Brønsted plots are represented.[8] The dissociation behavior of polyamines and polyamino acids has been studied using potentiometric titration curves.[8,9]

A systematic study of the kinetics and mechanism of the aminolysis of aryl acetates by poly(ethylenimine) (PEI) was carried out by Arcelli and Concilio.[8] In the absence of a simple salt, a mechanism has been reported that involves substrate–polyelectrolyte interactions similar to the action of an enzyme.[8a] On the other hand, in the presence of salt a stepwise mechanism, through a zwitterionic tetrahedral intermediate ($T^{\pm}$), was obtained.[8b]

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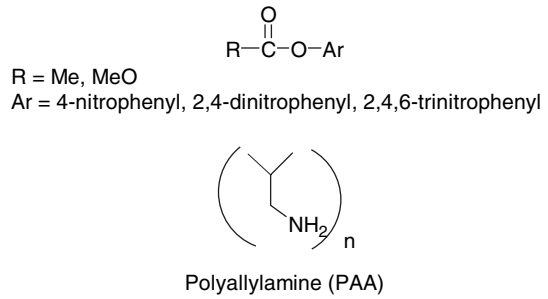


Scheme 1

Some kinetic studies on the hydrolysis of esters with polyelectrolytes containing amine,[10] imidazole,[11] pyridine,[12] and other groups have described increased activity of these polyamines with respect to their monomeric counterparts. On the other hand, modified polyelectrolytes, such as PEI[13] and polyallylamine (PAA)[10] with various hydrophobic groups (alkyl or benzyl), were investigated in order to determine the effect of the environment on the mechanism. In general, these modified polyamines accelerate the hydrolysis reactions relative to unmodified polymers; changes in the mechanism have also been observed.[10a]

The formation of the Schiff bases of pyridoxal-5-phosphate[14a] and pyridoxal[14b] with PAA as bearers of —NH_2— groups is controlled by the same mechanism, although the rate-determining step is different.

In this paper, we report a kinetic study of the reactions of PAA with 4-nitrophenyl acetate (NPA), 2,4-dinitrophenyl acetate (DNPA), 2,4,6-trinitrophenyl acetate (TNPA), 4-nitrophenyl methyl carbonate (NPC), 2,4-dinitrophenyl methyl carbonate (DNPC) and 2,4,6-trinitrophenyl methyl carbonate (TNPC) (Scheme 1). This, together with the investigation of the dissociation behavior of PAA, will allow the determination of the mechanism and the assessment of the effect of the amine group bearer and of the leaving and non-leaving groups of the substrate on the mechanism. We also compared the kinetic results of this study with those reported for the reactions of monomeric amines with the same substrates.

EXPERIMENTAL

Materials

Polyallylamine hydrochloride (PAA), from Polyscience, Warrington, PA, USA, MW = 60 000 Da, was used without further purification. 4-Nitrophenyl acetate (NPA), 2,4-dinitrophenyl acetate (DNPA) and 2,4,6-trinitrophenyl acetate (TNPA) were synthesized as described previously.[15] 4-Nitrophenyl methyl carbonate (NPC), 2,4-dinitrophenyl methyl carbonate (DNPC) and 2,4,6-trinitrophenyl methyl carbonate (TNPC) were synthesized by a standard procedure.[16] All other reagents were of analytical grade.

Table 1. Mean values of degree of dissociation (α_m) and pK_{app} values of the protonated PAA at different pH and concentration ranges[a]

pH	$10^2[N]_{tot}$ (M)[b]	α_m[c]	pK_{app}
7.00	4.96–31.4	0.063	8.17
7.50	5.15–31.4	0.112	8.40
8.00	0.113–0.975	0.233	8.52
8.50	0.106–0.887	0.328	8.81
9.00	0.100–0.827	0.444	9.10
9.50	0.104–0.946	0.586	9.35
10.50	0.034–0.882	0.882	9.63
10.50	0.034–0.257	0.939	9.33
11.00	0.034–0.256	1.0	
11.50	0.034–0.342	1.0	

[a] In aqueous solution at 25 °C, ionic strength 0.1 M (KCl).
[b] Concentration of total amino groups (free base plus protonated forms).
[c] α_m is the mean ionization degree of PAA at each pH at the concentration range stated.

Determination of pK_{app}

The potentiometric titration of PAA was carried out at 25.0 ± 0.1 °C, under nitrogen, by means of a Radiometer autotitrator equipped with a PHM-62 pH-meter, an ABU-11 autoburette, a TTT-60 titrator, an REA-160 recorder, a TTA-60 thermostatic support, a G-2040 glass electrode and a K-4040 calomel electrode. In each experiment, 10 ml of the polymer solution at different concentrations (1×10^{-3} to 5.1×10^{-2} M) and an ionic strength of 0.1 M (KCl) were titrated with NaOH (0.01–0.1 M). The polymer concentration range in the potentiometric titration was similar to that in the kinetic measurements. The apparent dissociation constant (pK_{app}) was calculated according to the equation[9d]

$$pK_{app} = pH + \log(1 - \alpha)/\alpha \quad (1)$$

where α is the degree of dissociation, which is the ratio of the free amino groups to the total polyallylamine concentration (expressed in monomeric units); the free amino group concentration was determined from the volume of NaOH added at each pH.[9a,9d,17]

Table 1 shows the pK_{app} and α_m values of PAA at different pH and at various polymer concentration ranges (α_m is the mean degree of ionization of PAA at each pH at the concentration range stated).

Kinetic measurements

PAA solutions were prepared freshly in the corresponding external buffer of 0.01 M at ionic strength 0.1 M (KCl), at the desired pH. The reactions were initiated by addition of 30 µl of a stock solution of the corresponding acetate to 2.5 ml of polymer solutions thermostated at 25 ± 0.1 °C. The initial concentration of the substrates was 5×10^{-5} M. The kinetic measurements were carried out by following spectrophotometrically the production

Table 2. Experimental conditions and kinetic results for the reactions of PAA with TNPA, DNPA and NPA[a]

pH	$10^2[N]_{tot}$ (M)[b]	$10^2 k_{obs}$ (s^{-1})	No. of runs	k_{Nobs} (M^{-1} s^{-1})	k_N (M^{-1} s^{-1})
TNPA					
7.00[c]	5.41–31.4	4.20–53.0	6	1.84 ± 0.08	29 ± 1
7.50[c]	5.41–31.4	9.75–131	6	4.39 ± 0.4	39 ± 4
8.00[c]	0.113–0.938	2.09–9.15	6	8.9 ± 0.5	38 ± 2
8.50[d]	0.106–0.887	2.38–16.0	5	18 ± 3	53 ± 9
9.00[d]	0.100–0.831	4.30–33.0	10	38 ± 2	85 ± 4
9.50[d]	0.104–0.863	6.85–59.0	6	68 ± 7	116 ± 12
10.05[e]	0.034–0.882	11.8–110	11	114 ± 5	129 ± 6
110.0[e]	0.034–0.256	21.7–75.0	5	257 ± 16	257 ± 16
DNPA					
7.00[c]	4.96–12.8	1.04–4.16	5	0.42 ± 0.03	6.7 ± 0.5
7.50[c]	5.15–16.9	1.54–13.3	6	0.94 ± 0.05	8.4 ± 0.4
8.00[c]	0.113–0.938	0.240– 2.20	6	2.4 ± 0.1	10.2 ± 0.4
8.50[d]	0.106–0.887	0.400–3.60	6	3.7 ± 0.8	11 ± 2
9.00[d]	0.100–0.927	0.620–6.00	11	6.3 ± 0.5	14 ± 1
9.50[d]	0.104–0.946	1.36–12.9	11	13.4 ± 0.6	23 ± 1
10.50[e]	0.034–0.882	2.71–15.5	11	14.9 ± 0.4	16.9 ± 0.5
11.00[e]	0.0341–0.341	5.91–14.9	6	29 ± 2	29 ± 2
11.50[e]	0.0342–0.257	9.59–16.3	6	33 ± 3	33 ± 3
NPA					
7.00[c]	5.06–16.6	0.056–0.277	6	0.019 ± 0.002	0.300 ± 0.003
7.50[c]	5.15–16.9	0.073–0.588	6	0.041 ± 0.003	0.370 ± 0.002
8.00[c]	0.117–0.975	0.013-0.110	6	0.100 ± 0.002	0.43 ± 0.01
8.50[d]	0.106–0.887	0.025–0.193	6	0.21 ± 0.03	0.64 ± 0.09
9.00[d]	0.111–0.927	0.027–0.257	6	0.28 ± 0.03	0.63 ± 0.07
9.50[d]	0.104–0.863	0.081–0.549	6	0.62 ± 0.05	1.06 ± 0.09
10.50[e]	0.034–0.257	0.371–0.612	6	1.04 ± 0.08	$1.11^b \pm 0.09$
11.00[e]	0.034–0.341	0.935–1.58	7	2.20 ± 0.2	2.2 ± 0.2

[a] In aqueous solution at 25 ° C, ionic strength 0.1 M (KCl).
[b] Concentration of total amino groups (free base plus protonated forms).
[c] 0.01 M phosphate buffer.
[d] 0.01 M borate buffer.
[e] 0.01 M carbonate buffer.

of 4-nitrophenoxide (400 nm), 2,4-dinitrophenoxide (355 nm) and 2,4,6-trinitrophenoxide (355 nm) anions using a Hewlett-Packard Model 8453 diode-array spectrophotometer. Under amine excess, pseudo-first-order rate constants (k_{obs}) were found for all reactions. The plots of k_{obs} vs total amine concentration are linear, with k_{Nobs} as slope. Phosphate, borate and carbonate buffers (0.01 M) were used at appropriate pH ranges.

The experimental conditions and the values of k_{obs} and k_{Nobs} for the reactions of PAA with TNPA, DNPA and NPA are summarized in Table 2 and those for the reactions with TNPC, DNPC and NPC in Table 3.

Transmission electron microscopy

PAA solutions (6.6×10^{-3} M), at the same conditions as those of the kinetic measurements, at pH 8.0 and 11.0, were prepared and submitted to a transmission electron microscopy (TEM) study. The photographs show that the macromolecule adopts a rod-like conformation at pH 8.0 and a random coil conformation at pH 11.0.

Product studies

The presence of 4-nitrophenoxide, 2,4-dinitrophenoxide and 2,4,6-trinitrophenoxide anions as products of the reactions was determined spectrophotometrically by comparison of the UV–visible spectra at the end of the reactions with those of authentic samples under the same conditions.

To determine whether these reactions are nucleophilic or amine-catalyzed hydrolysis, an HPLC study was carried out to check the presence of acetic acid as a product of the reaction of DNPA. Acid acetic analysis by HPLC consisted of an IC pack ion-exclusion column (7.8 mm i.d. × 300 mm), 2.5 mM H_2SO_4–acetonitrile–methanol (95:3:2) as mobile phase at a flow-rate of 1.0 ml min^{-1} and a photodiode-array detector coupled to a computer. The detector was set at 210 nm. Acetic acid was identified by comparing the peak retention time of the reactions with that of a standard. Only traces of acetic acid were found in the reaction of DNPA at pH 7.0, showing that amine-catalyzed hydrolysis and/or spontaneous hydrolysis of DNPA are negligible compared with direct amine attack.

Table 3. Experimental conditions and kinetic results for the reactions of PAA with TNPC, DNPC and NPC[a]

pH	$10^2[N]_{tot}$ (M)[b]	$10^2 k_{obs}$ (s^{-1})	No. of runs	k_{Nobs} (M^{-1} s^{-1})	k_N (M^{-1} s^{-1})
TNPC					
7.00[c]	6.07–15.5	2.15–6.19	5	0.44 ± 0.01	6.9 ± 0.2
7.50[c]	4.99–16.4	2.39–13.3	6	0.99 ± 0.04	8.7 ± 0.3
8.00[d]	0.256–0.768	0.604–1.47	5	1.69 ± 0.03	7.9 ± 0.1
8.50[d]	0.195–0.812	1.49–5.47	6	6.4 ± 0.5	21 ± 2
9.00[d]	0.0723–0.542	1.52–11.1	6	19 ± 1	42 ± 2
9.50[d]	0.0686– 0.515	2.99–15.3	6	26 ± 2	44 ± 3
10.50[e]	0.0319–0.239	3.28–18.8	6	67 ± 6	71 ± 6
11.00[e]	0.0327–0.245	11.0–58.7	6	206 ± 17	209 ± 17
11.50[e]	0.036–0.270	30.7–117	6	382 ± 36	380 ± 36
DNPC					
7.00[c]	4.97–16.5	0.330–1.79	12	0.12 ± 0.01	1.70 ± 0.14
7.50[c]	5.11–16.8	0.556–3.46	6	0.25 ± 0.01	2.09 ± 0.08
8.00[d]	0.107–0.895	0.0628–0.425	6	0.43 ± 0.03	2.1 ± 0.1
8.50[d]	0.106–0.879	0.0718–1.10	5	1.35 ± 0.07	4.1 ± 0.2
9.00[d]	0.0722–0.542	0.170–1.32	6	2.4 ± 0.1	5.4 ± 0.2
9.50[d]	0.114–0.946	0.503–4.22	5	4.5 ± 0.2	7.8 ± 0.3
10.50[e]	0.071–0.882	0.927–4.65	12	4.6 ± 0.2	12.5 ± 0.5
11.00[e]	0.0697–0.697	2.20–7.39	7	7.9 ± 0.4	7.9 ± 0.4
11.50[e]	0.0354–0.265	4.58–7.46	6	13 ± 1	13 ± 1
NPC					
7.00[c]	6.07–16.9	0.0192–0.0648	5	0.0041 ± 0.0002	0.060 ± 0.003
7.50[c]	4.99–16.4	0.059–0.301	6	0.022 ± 0.0007	0.182 ± 0.006
8.00[d]	0.256–1.07	0.0156–0.0389	6	0.0291 ± 0.002	0.15 ± 0.01
8.50[d]	0.208–0.866	0.023–0.067	6	0.066 ± 0.001	0.219 ± 0.003
9.00[d]	0.0648–0.486	0.017–0.064	6	0.110 ± 0.007	0.25 ± 0.02
9.50[d]	0.0686–0.515	0.0628–0.251	6	0.43 ± 0.02	0.74 ± 0.03
10.50[e]	0.0319–0.239	0.106–0.286	6	0.81 ± 0.09	0.9 ± 0.1
11.00[e]	0.0654–0.245	0.331–0.593	5	1.45 ± 0.07	1.45 ± 0.07
11.50[e]	0.0335–0.201	1.27–1.76	5	3.0 ± 0.3	3.0 ± 0.3

[a] In aqueous solution at 25 ° C, ionic strength 0.1 M (KCl).
[b] Concentration of total amino groups (free base plus protonated forms).
[c] 0.01 M phosphate buffer.
[d] 0.01 M borate buffer.
[e] 0.01 M carbonate buffer.

RESULTS AND DISCUSSION

The difference in acidic strength between a monomeric amine and the amino groups of a polyamine is well known.[9d] Moreover, basicity changes with the degree of dissociation (α) of these polyamines and, therefore, they show different pK_a values at different pH.[9a,9d] Figure 1 shows the titration curves of pK_{app} vs α at several PAA concentrations. As can be seen, pK_{app} depends on both α and the concentration of the polymer, owing to a change in the charge density of the polyion.

The curves in Figure 1 show that proton release from PAA decreases with increase in the degree of dissociation for the highest polymer concentration used (5.1×10^{-2} M) and that PAA does not exhibit a cooperative transition (hydrogen bond or hydrophobic interactions) in accordance with the behavior described.[9a]

Figure 1 shows that for the more dilute solutions the pK_{app} values increase up to $\alpha \approx 0.7$ and then decrease for $\alpha > 0.7$. These results can be explained by a transition or conformational change of the PAA from rod-like conformation to a random coil form, as has been reported for

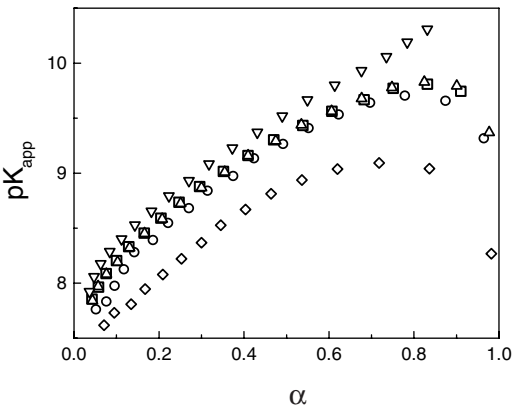


Figure 1. Potentiometric titration of PAA, expressed as pK_{app} versus degree of dissociation (α), in aqueous solution at 25.0 °C and an ionic strength of 0.1 M (KCl). PAA concentrations (M): 1.1×10^{-3} (◇), 3.66×10^{-3} (○), 6.59×10^{-3} (△), 9.16×10^{-3} (□) and 5.1×10^{-2} (▽)

other polyelectrolytes.[9d,17] The conformation change with pH was confirmed by TEM.

A linear dependence of the pseudo-first-order rate constant (k_{obs}) on PAA concentration at each pH was observed, according to the equation

$$k_{obs} = k_0 + k_{Nobs}[N]_{tot} \quad (2)$$

where k_0 and k_{Nobs} are the rate coefficients for spontaneous hydrolysis and aminolysis of the substrates, respectively. These results suggest that there is no substrate-polyelectrolyte association because the presence of this association shows limiting plots, similar to those described for PEI in the absence of KCl.[8a]

No differences in k_{obs} values were observed when reactions were carried out with different fractions of the polymer (water/acetone) and the commercial polymer, thus disregarding the presence of oligomers in the commercial polymer.

In most of the studied reactions, k_0 is negligible in Eqn (2), except those at the higher pH media, where the two terms are important.

The nucleophilic rate constant (k_N) is obtained as the ratio between of k_{Nobs} to the corresponding $\alpha_{m.}$ The values of k_N for the reactions of PAA with NPA, DNPA, TNPA are given in Table 2 and those of NPC, DNPC and TNPC in Table 3.

The nucleophilic rate constants in the reaction of PAA with carbonates are smaller than those for the corresponding acetates at the same pH values. This result can be explained through the larger resonance effect exerted by MeO in the carbonates relative to Me in the acetates, rendering the former carbonyl carbon atom less positively charged and, therefore, inhibiting amine attack. This is in accord with what has been found for the reactions with monomeric amines.[2f,2g,3a]

Figures 2 and 3 show the dependence of $\log k_N$ on pH for the aminolysis of the acetates and carbonates, respectively. As can be seen, below pH 9.5 k_N increases with increase in pH or free amine molar fraction. The presence of protonated amino groups in the polymer leads to a rod-like conformation of the polymer by repulsion of the charges, where each molecule behaves independently. Above pH 10.5, a new increase in k_N with increasing pH is observed. When the amino groups are almost completely deprotonated, interactions between the side chains are permitted and PAA adopts a random coil conformation, which must be more reactive in order to explain the k_N increase when α becomes 1. The change in conformation of PAA is also supported by the TEM study. This behavior is independent of the substrate because the breaks of the above plots take place at approximately the same pH value ($\sim$10.0) for the three substrates. A referee suggested that at pH $>$ 10.5 it is possible that a small but important substrate-polyelectrolyte binding might be present, this complex being responsible for the rate increase when the polyamine is completely deprotonated.

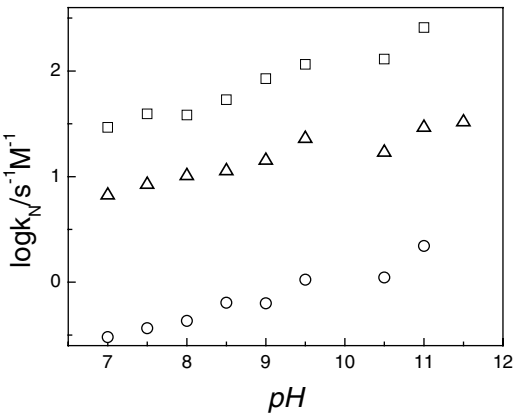


Figure 2. Variation of $\log k_N$ as a function of pH for the reactions of PAA with NPA (○), DNPA (△) and TNPA (□) in aqueous solution at 25.0 °C and an ionic strength of 0.1 M (KCl)

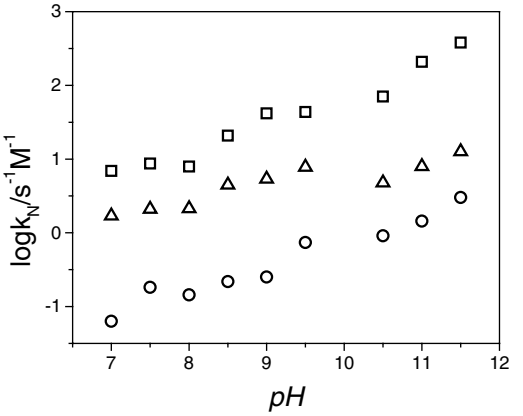


Figure 3. Variation of $\log k_N$ as a function of pH for the reactions of PAA with NPC (○), DNPC (△) and TNPC (□) in aqueous solution at 25.0 °C and an ionic strength of 0.1 M (KCl)

Figures 2 and 3 also show that for the same pH values, the k_N values increase in the sequences TNPA $>$ DNPA $>$ NPA and TNPC $>$ DNPC $>$ NPC. These sequences are the same as those for the reactions with monomeric amines,[2f] due to the increasing nucleofugality of the leaving groups, and also the increasing electrophilic character of the carbonyl carbon, as more nitro groups are added to the substrate.

Figures 4 and 5 show Brønsted-type plots for the reactions of PAA with acetates and methyl carbonates, respectively, studied at the pH range 7.0–9.5, where the polymer adopts a linear conformation. The plots are linear with the following slopes (β): TNPA 0.5, DNPA 0.4, NPA 0.5, TNPC 0.7, DNPC 0.6 and NPC 0.7. These β values are similar to those found for the aminolysis (monomeric amines) of carbonyl compounds when the mechanism is concerted, as in the reactions of secondary alicyclic (SA) amines with TNPA,[2f] TNPC,[2f] DNPC[4b] and phenyl 2,4-dinitrophenyl carbonate[4b] ($\beta = 0.41, 0.36,$

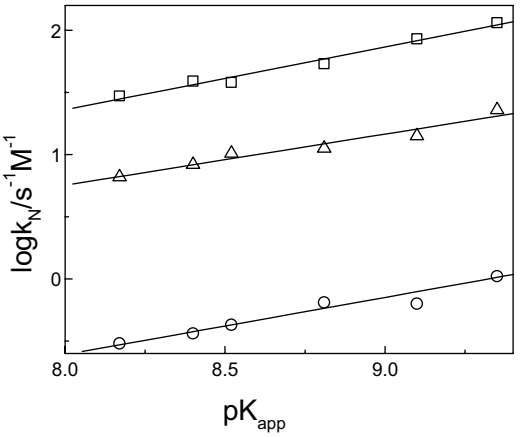


Figure 4. Brønsted-type plots for the reactions of PAA with NPA (○), DNPA (△) and TNPA (□) in aqueous solution at 25.0 °C and an ionic strength of 0.1 M (KCl)

0.48 and 0.39, respectively). The slopes are also in accordance 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),[18] the reactions of quinuclidines with these two substrates ($\beta = 0.54$ and 0.47, respectively)[19] and those of anilines with the latter compound ($\beta = 0.54$).[20] These β value are also in agreement with those found in the concerted reactions of SA amines and anilines with 4-methylphenyl 2,4-dinitrophenyl carbonate and 4-chlorophenyl 2,4-dinitrophenyl carbonate in 44 wt% ethanol–water ($\beta = 0.44$–0.68).[7c] It is known that the linearity of the Brønsted plot and the slope value are not sufficient to prove that a mechanism is concerted.[21] Also, it must be ensured that there is no break in the Brønsted-type plot for a hypothetical stepwise mechanism.[21]

Stepwise aminolyses of aryl acetates (with monomeric amines) show values of pK_a° (pK_a at the curvature center of the Brønsted-type plot) about 4–5 pK units greater than the pK_a of the conjugate acid of the leaving group.[2]

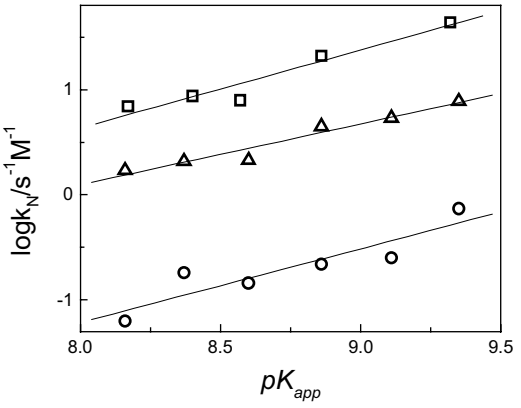


Figure 5. Brønsted-type plots for the reactions of PAA with NPC (○), DNPC (△) and TNPC (□) in aqueous solution at 25.0 °C and an ionic strength of 0.1 M (KCl)

However, when the amine group is in the backbone of the polymer this difference is about 3–3.5 pK units.[8b] In the case of the reaction of PAA with NPA, the curvature of the Brønsted plot should be centered at p$K_{app} > 10$ (pK_a of 4-nitrophenol ≈ 7),[22] which lies outside the pK_{app} range used. Nevertheless, if the mechanism were stepwise, the rate-determining step would be the expulsion of the nucleofuge and the β value should be 0.8–1.1.[2] The β value obtained (0.5) is relatively low, suggesting that the concerted mechanism governs the PAA aminolysis of NPA. In the case of the reactions of PAA with DNPA and TNPA the curvature should be located at p$K_{app} \approx 7.0$–7.5 (pK_a of 2,4-dinitrophenol ≈ 4)[22] and 3.3–3.8 (pK_a of 2,4,6-trinitrophenol $= 0.3$),[22] respectively. Both values are smaller than the lowest pK_a of the experimental pK_a range, indicating that, at the pK_a range employed, the Brønsted slope would correspond to that where the first step is rate-determining (β_1).[2] However the experimental slope values found ($\beta = 0.4$ and 0.5 for the reactions of DNPA and TNPA, respectively) are larger than those reported for β_1 (0.1–0.3),[2] suggesting a concerted mechanism for the reactions of PAA with those substrates.

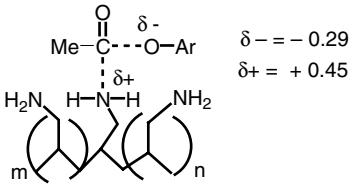
In the case of the reactions of the carbonate series, the β values are in upper limit of those found for the aminolysis (monomeric amines) of carbonyl compounds when the mechanism is concerted.[2d,4b,7c] The same argumentation about the absence of curvature in the reactions of PAA with acetates can be made concerning the reactions of PAA with aryl methyl carbonates in order to show that the latter reactions are also concerted. Furthermore, it is well known that for a stepwise mechanism, the replacement of Me by MeO destabilizes the tetrahedral intermediate.[18] This is due to an inductive electron-withdrawing effect of the MeO group in the putative tetrahedral intermediate, which enhances the push exerted by O^- in the intermediate to expel either the amine or the nucleofuge.[18] Therefore, if the mechanism for the reactions of PAA with the acetates is concerted, then it should be also concerted for the reactions with carbonates.

The dependence of the nucleophilic rate constant (k_N), obtained for the reactions of PAA with the acetate series, on the pK_a of the amine (pK_{app}) and the pK_a of the leaving group (pK_{lg}) is given by Eqn (3) ($R^2 = 0.94$, $n = 18$) and that for carbonates by Eqn (4) ($R^2 = 0.939$, $n = 18$):

$$\log k_N = (0.45 \pm 0.13)\mathrm{p}K_{app} - (0.29 \pm 0.02)\mathrm{p}K_{lg} - (2.0 \pm 1.0) \quad (3)$$

$$\log k_N = (0.71 \pm 0.13)\mathrm{p}K_{app} - (0.28 \pm 0.02)\mathrm{p}K_{lg} - (4.8 \pm 1.1) \quad (4)$$

The values for the sensitivity to the nucleophile ($\beta_{nuc} = 0.45$ and 0.71 for acetates and carbonates,



Scheme 2. Transition state for the reactions of PAA with aryl acetates

respectively) were discussed earlier and those for the sensitivity to the leaving group ($\beta_{lg} = -0.29$ and -0.28) are near the expected value for a concerted mechanism.[23] Scheme 2 shows the transition state for the acetate esters with PAA.

Logarithmic plots of the experimental nucleophilic rate constant values against those calculated with Eqns (3) and (4) (not shown) are linear withal a slope of unity and zero intercept.

The pyridinolyses of NPA,[2c] DNPA,[2d] TNPA,[2f] NPC,[3a] DNPC[3b] and TNPC[2f] are stepwise, whereas the reactions of these substrates with PAA are concerted (this work). The change in mechanism for the latter reactions can be attributed to greater instability of the tetrahedral intermediate formed with the polyamine or else to a transition state for the concerted path that is more stable (relative to reactants) than that for the stepwise reaction. In the same way, the reactions of DNPC with anilines,[4a] DNPA with SA amines[2e] and NPC with SA amines and quinuclidines[4b] are stepwise, in contrast to the reactions of these substrates with PAA, which are concerted. These results show the destabilization of the putative tetrahedral intermediate formed with PAA.

It is known that SA amines and quinuclidines destabilize the putative tetrahedral intermediate relative to anilines and pyridines owing to a better leaving ability of the two former amines from the intermediate. The sequence of leaving abilities of monomeric amines is quinuclidines > SA amines > anilines > pyridines.[19] Therefore, considering that the mechanism of the title reactions is concerted, it is possible that the leaving ability of PAA from the putative tetrahedral intermediate is the greatest compared with monomeric amines. Therefore, the stability of tetrahedral intermediates would decrease in the sequence pyridines > anilines > SA amines > quinuclidines > PAA.

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