Complexation catalysis: effective charge development in the aminolysis of phenyl esters in chlorobenzene catalysed by crown ethers

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Kinetics of the butylaminolysis of substituted phenyl acetates in chlorobenzene in the presence of a variety of crown ethers obey the following rate law.

$$\text{Rate} = k_b[\text{BuNH}_2]^2[\text{Ester}] + k_c[\text{BuNH}_2][\text{Crown}][\text{Ester}]$$

The individual rate constants fit Brønsted-type relationships:

$$\log k_b = -0.75\,\text{p}K_a + 4.21$$
$$\log k_c = -0.58\,\text{p}K_a + 3.41 \quad [\text{18-crown-6}]$$
$$\log k_c = -0.61\,\text{p}K_a + 3.18 \quad [\text{12-crown-4}]$$

where $\text{p}K_a$ refers to the ionization of the phenol in aqueous solution.

The Brønsted β_{1g} values for k_b and k_c are calibrated with the value of β_{eq} recently determined for acetyl transfer between phenolate ions in chlorobenzene. The sensitivity, β_{1g}, of k_c is consistent with the rate-limiting formation of a crown ether–zwitterion adduct with subsequent fast (non-rate-limiting) ArO–C bond fission. The Brønsted data for k_b when calibrated by β_{eq} is consistent with rate-limiting proton transfer from zwitterion to base.

18-Crown-6 enables proton transfer to occur between phenol and butylamine in chlorobenzene according to the equation:

$$\text{BuNH}_2 + \text{ArOH} + \text{Crown} \rightleftharpoons \text{Bu–NH}_3{}^+\cdot\text{Crown} + \text{ArO}^-$$
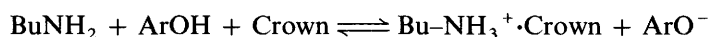
The equilibrium constant (K) for the above reaction with a series of substituted phenols has a Brønsted selectivity (β) of 2.1 compared with that for the ionization of phenols in water.

The provision of microscopic solvation by a host molecule to a reactant guest is one of the factors contributing to kinetic advantage in catalysis mediated by complexation. Crown ethers and glymes catalyse the aminolysis of esters in aprotic solvents such as chlorobenzene and the catalytic effect is due to the complexation between crown ether and the zwitterionic adduct.[1–4] This system is a convenient vehicle for investigating microscopic solvation at developing cationic centres such as might occur in complexation catalysis. Many of the quantitative kinetic studies of aminolyses in non-aqueous solutions have employed chlorobenzene[1–6] and since the effective charge has recently[7] been measured for the transfer of the acetyl group from substituted phenyl acetates to the acetate ion in this solvent we are now in a good position to provide further useful mechanistic information. The effective charge development (β_{eq}) for the transfer equilibrium provides a calibration[7b] for reactions of substituted phenyl acetates in chlorobenzene, the solvent often used to study aminolysis kinetics under aprotic conditions.

Aminolysis of esters in aqueous solution involves formation of a zwitterionic adduct (T$^\pm$, Scheme 1, path I) whose pathway for decomposition to products can depend on the presence of proton acceptor agents and on the basicity of the leaving group.[8–10] A similar mechanistic scheme is thought to occur for aminolyses in non-aqueous solvents and the solvating power of solvent and additives (such as crown ether or glymes) are then important in predicting the detailed decomposition pathway of T$^\pm$ for such solvents as chlorobenzene, which could have little intrinsic solvating power for developing ions. Aminolyses in aprotic, weakly polar solvents are likely to be dominated by the formation of ion pairs due to the weak solvating power of the medium. Additives such as crown ethers which can supply microscopic solvation to the developing ions could act as

Scheme 1
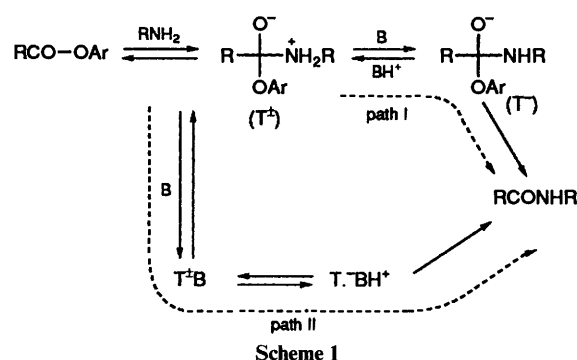
catalysts for aminolyses under these conditions. The effect of substituents on the kinetics has been investigated for both aqueous[10] and aprotic solvents[1,4] for aminolyses of substituted phenyl esters.

In this study we have looked at the kinetics of butyl-aminolysis of substituted phenyl acetates in chlorobenzene solvent catalysed by a variety of crown ethers. Our purpose was to investigate the function of crown ethers in catalysis in aprotic media by application of the newly available calibration data. The information is of use in the wider context of microscopic solvation in complexation catalysis.

Experimental

Materials
Substituted phenyl acetates were from previous studies in this laboratory.[11] Crown ethers were purchased from Aldrich and phenols were obtained commercially and purified prior to use by either recrystallization from a suitable solvent or by

sublimation. Chlorobenzene (BDH) was fractionally distilled and that fraction having bp 131–132 ° was employed in the kinetic studies. Butylamine was redistilled from KOH pellets, from CaH_2 and then stored in a darkened bottle prior to use.

Kinetics

The kinetics of the reaction of butylamine with substituted phenyl acetates were measured by the addition of an aliquot [ca. 20 μL (1 μL = 1 mm³)] of a solution of the ester in chlorobenzene on the flattened tip of a glass rod to a chlorobenzene solution (2.5 cm³) of butylamine and crown ether of known concentrations in a silica cell held at 25 °C in a Perkin-Elmer Lambda 5 UV–VIS spectrophotometer. The absorbance change at an appropriate wavelength (determined from a preliminary wavelength scanning experiment) was recorded as a function of time and first-order rate constants were calculated with standard software with a desk-top computer.

The dependence of the catalytic rate constants on butylamine concentration was determined by varying the butylamine concentration against a fixed concentration of the crown.

Ionization of phenols in chlorobenzene

Spectroscopic studies of the ionization of substituted phenols in the presence of increasing concentrations of 18-crown-6 were carried out with 0.1 mol dm⁻³ butylamine solutions containing a suitable concentration of the phenol by adding aliquots of a 0.1 mol dm⁻³ solution of 18-crown-6. After each addition the ultra-violet–visible spectrum was scanned to determine the absorbance due to the production of the complexed butylammonium phenolate.

Molecular modelling

The complex between 18-crown-6 and the zwitterion adduct of phenyl acetate with butylamine was modelled by optimization of the charged complex by the HYPERCHEM software package using the Polak–Ribiere conjugate gradient method and an AMBER force field with distance dependent dielectric applied. The zwitterion (T^+) was manually docked over the crown ether ring placing the N-hydrogens into the ring plane. Geometry optimization was carried out by molecular mechanics using a steepest descent followed by conjugate gradient minimizer. Initially, the crudely optimized complex was subjected to a 1-SCF CNDO/2 calculation to provide more precise charges on all atoms.

Results

The reactions of butylamine with the aryl acetates in chlorobenzene solution obeyed excellent first-order kinetics to at least 90% of the total reaction. The reaction of 4-nitrophenyl acetate in the absence of crown ether is second-order in amine concentration (Fig. 1). The reaction rates were found to depend upon both the concentration of added crown ether and the concentration of butylamine. Examples of the plots obtained against butylamine concentration (constant crown concentration) and against crown concentration (at constant butylamine concentration) are illustrated in Figs. 2 and 3, respectively; the kinetics fit the rate eqn. (1). Values for the catalytic rate con-

$$k_{obs} = k_b[BuNH_2]^2 + k_c[BuNH_2][Crown] \qquad (1)$$

stant k_c were determined from plots of pseudo-first-order rate constants against crown ether concentration with butylamine concentration set at 0.10 mol dm⁻³ (see e.g. Fig. 3). In all cases good linear plots were obtained over the crown ether concentration range employed and values of k_c agree with those determined by Hogan and Gandour[2] in those cases where comparison is possible. Values for k_b, the base-catalysed rate constant, were obtained from the intercept at zero crown
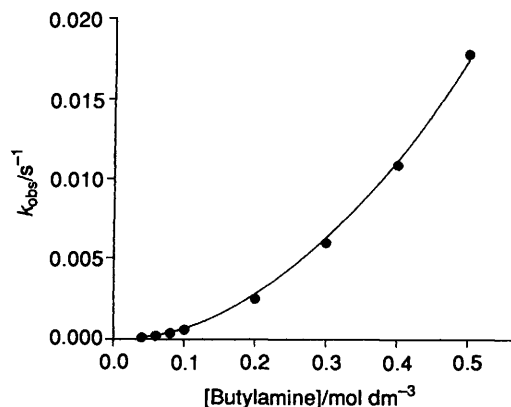

Fig. 1 Plot of k_{obs} vs. [butylamine] for butylaminolysis of 4-nitrophenyl acetate in chlorobenzene solution; the line is drawn from eqn. (1) with parameter (k_b) taken from Table 2
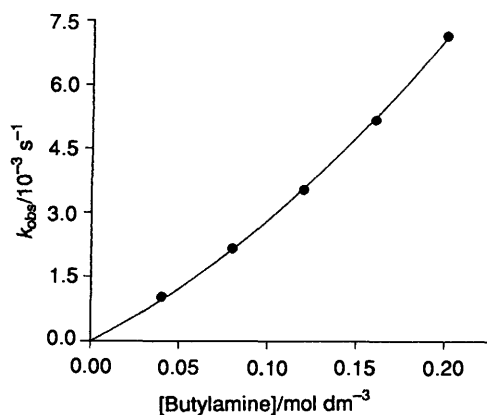

Fig. 2 Plot of k_{obs} vs. [butylamine] for butylaminolysis of 4-nitrophenyl acetate in 0.08 mol dm⁻³ 18-crown-6 in chlorobenzene solution; the line is drawn from eqn. (1) with parameters from Table 2
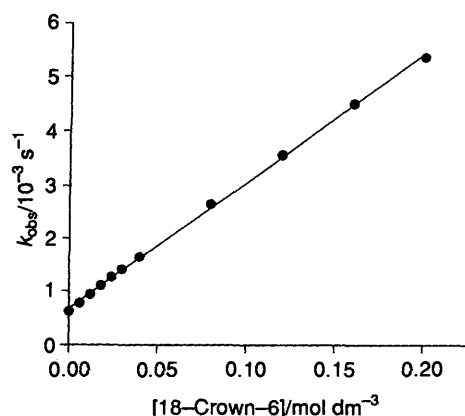

Fig. 3 Plot of k_{obs} vs. [18-crown-6] for butylaminolysis of 4-nitrophenyl acetate in 0.10 mol dm⁻³ butylamine in chlorobenzene solution; the line is drawn from eqn. (1) with parameters from Table 2

concentration and were checked by direct measurement. Table 1 shows the data for catalysis of the butylaminolysis of 4-nitrophenyl acetate by a series of crown ethers with varying ring sizes. The results of this study indicate that 12-crown-4 and 18-crown-6 are the most useful of the crowns for detailed mechanistic study. The data for the reaction of butylamine with substituted phenyl acetates in chlorobenzene solution in the presence of 18-crown-6 and 12-crown-4 are recorded in Table 2.

The base-catalysed butylaminolysis (k_b) of substituted phenyl acetates and reactions in the presence of 12-crown-4 and 18-

Table 1 Kinetic data for the butylaminolysis of 4-nitrophenyl acetates in chlorobenzene solution in the presence of a variety of crown ethers[a]

Crown ether	N[b]	$k_c/dm^6\,mol^{-2}\,s^{-1}$	[Crown]/10^{-4} mol dm^{-3}[c]	$(k_{obs}/[But-NH_2])/$ $10^{-4}\,dm^3\,mol^{-1}\,s^{-1}$[d]	λ/nm[e]
DiBz-18-c-6	4	0.073 ± 0.0019[f]	6–24	6.6–7.8	315
DiBz-24-c-8	5	0.095 ± 0.0013	5–25	6.6–8.5	315
DiBz-30-c-10	5	0.266 ± 0.0132	3.3–16.4	7.5–10.7	315
Benzo-15-c-5	5	0.042 ± 0.0054	10–50	7.1–8.6	315
15-C-5	5	0.098 ± 0.0024	40–202	10.6–25	400
12-C-4		0.105 [g,h]			
18-C-6		0.239 [g,i]			

[a] 25 °C; 0.1 mol dm^{-3} BuNH$_2$. [b] Number of data points not including duplicates. [c] Range of crown concentrations. [d] Range of observed pseudo-first-order rate constants. [e] Wavelength of kinetic study. [f] Hogan and Gandour[2] find 0.034 dm^6 mol^{-2} s^{-1}. [g] From Table 2. [h] Hogan and Gandour[2] find 0.070 dm^6 mol^{-2} s^{-1}. [i] Hogan and Gandour[2] find 0.220 dm^6 mol^{-2} s^{-1}.

Table 2 Kinetic data for the butylaminolysis of phenyl acetates in chlorobenzene solution in the presence of 18-crown-6 and 12-crown-4 [a]

Phenol	pK_a[b]	[Ester]/ 10^{-4} mol dm^{-3}	N[d]	$k_b/10^{-3}\,dm^6\,mol^{-2}\,s^{-1}$[e]	$k_c/10^{-3}\,dm^6\,mol^{-2}\,s^{-1}$[f]	$k_{obs}/10^{-4}\,s^{-1}$[g]	λ/nm[h]	[Crown]/ mol dm^{-3}
Reactions catalysed by 12-crown-4								
2-Cl, 4-NO$_2$	5.45	0.10	6	1530 ± 8	970 ± 34	153–250	385	0–0.1
2,3,5-Cl$_3$	6.43	3.00	6	230 ± 0.7	160 ± 10	23.2–39.1	293	0–0.1
2,4,5-Cl$_3$	6.72	3.07	6	130 ± 0.3	98 ± 4.0	12.7–22.6	296	0–0.1
4-NO$_2$	7.14	0.80	6	62 ± 0.08	105 ± 9.1	6.18–27.3	315	0–0.2
2,5-Cl$_2$	7.51	8.00	6	37 ± 0.2	33 ± 1.1	3.66–7.03	287	0–0.1
4-CN	7.95	0.24	6	18 ± 0.06	31 ± 1.8	1.80–5.01	286	0–0.1
3-NO$_2$	8.38	9.00	6	9.4 ± 0.07	13 ± 0.4	0.94–2.48	335	0–0.1
Reactions catalysed by 18-crown-6								
2-Cl, 4-NO$_2$	5.45	0.10	5		2170 ± 51	199–374	400	0.02–0.1
2,3,5-Cl$_3$	6.43	3.00	5		370 ± 2.3	30.7–60.0	293	0.02–0.1
2,4,5-Cl$_3$	6.72	3.07	5		235 ± 5.4	17.6–36.5	297	0.02–0.1
4-NO$_2$	7.14	0.80	10		239 ± 2.2	7.68–53.7	400	0.006–0.2
2-NO$_2$	7.20	1.70	5		214 ± 4.8	3.03–4.71	430	0.02–0.1
2,5-Cl$_2$	7.51	8.00	5		136 ± 1.3	5.28–11.3	282	0.02–0.1
4-CN	7.95	0.24	5		56 ± 1.5	1.54–7.15	283	0.02–0.1
3-NO$_2$	8.38	9.00	5		37 ± 1.4	1.86–4.63	350	0.02–0.1

[a] General conditions: 25 °C, 0.1 mol dm^{-3} BuNH$_2$. [b] pK_a of phenol in water. [c] Concentration of substituted phenyl acetate in the reaction cell. [d] Number of runs not including duplicates. [e] Overall third-order rate constant for butylamine-catalysed butylaminolysis. [f] Overall third-order rate constant for crown-catalysed reactions. [g] Range of observed rates or rate constants. [h] Wavelength for kinetic runs.

crown-6 obey the Brønsted equations well [eqns. (2)–(4)]. The

$$\log k_b = (-0.75 \pm 0.02)pK_a + (4.21 \pm 0.16),$$
$$r = 0.9977, n = 7 \quad (2)$$

$$\log k_c = (-0.58 \pm 0.04)pK_a + (3.41 \pm 0.31),$$
$$r = 0.9826, n = 8, \text{[18-Crown-6]} \quad (3)$$

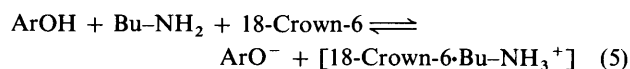$$\log k_c = (-0.61 \pm 0.05)pK_a + (3.18 \pm 0.39),$$
$$r = 0.9802, n = 7, \text{[12-Crown-4]} \quad (4)$$

data, where comparable, show good agreement with the results of Hogan and Gandour.[4] These Brønsted dependencies are illustrated in Fig. 4.

The butylaminolysis of phenyl acetates in the presence of 18-crown-6 gives rise to phenolate ion as judged from the ultraviolet–visible spectrum of the product whereas the 12-crown-4 catalyst gives the neutral phenol. This result is judged to come from the complexation of the butylammonium ion by the former crown, but not by the latter. The phenolate ion is observed as the product in catalysis by 15-crown-5, but all the other crowns studied give neutral phenol as the product. The addition of 4-nitrophenol to chlorobenzene containing butylamine and 18-crown-6 or 15-crown-5 gives the phenolate anion whereas the other crowns studied here do not cause ionization. The complexation phenomenon may be employed to determine the equilibrium constant (K) for the transfer of a proton from a phenol to butylamine according to eqn. (5).
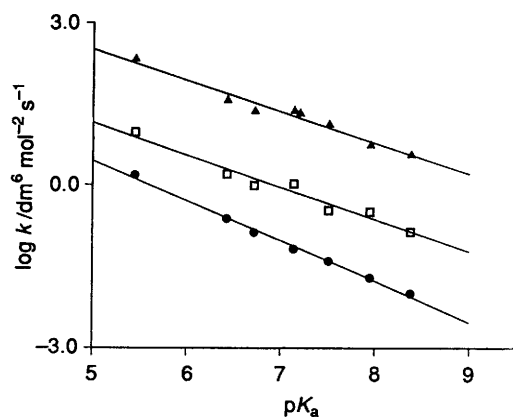
Fig. 4 Brønsted dependence for butylaminolysis of substituted phenyl acetates in chlorobenzene solution with no added crown ether (●), catalysed by 18-crown-6 (▲) and catalysed by 12-crown-4 (□). The data are taken from Table 2 and the lines are drawn from eqns. (2), (3) (× 100) and (4) (× 10), respectively. The identities of the phenyl acetates for ▲ are, in increasing order of pK_a of the phenol: 2-Cl, 4-NO$_2$; 2,3, 5-Cl$_3$; 2,4,5-Cl$_3$; 4-NO$_2$; 2-NO$_2$; 2,5-Cl$_2$; 4-CN; 3-NO$_2$.

$$\text{ArOH} + \text{Bu-NH}_2 + \text{18-Crown-6} \rightleftharpoons$$
$$\text{ArO}^- + [\text{18-Crown-6·Bu-NH}_3{}^+] \quad (5)$$

The absorbance (A), measured at a suitable wavelength, changes according to eqn. (6) and an example is shown in Fig. 5; the results fitted to this equation are collected in Table 3. The concentration of butylamine is such that its depletion by reaction with ArOH is negligible; moreover the phenol
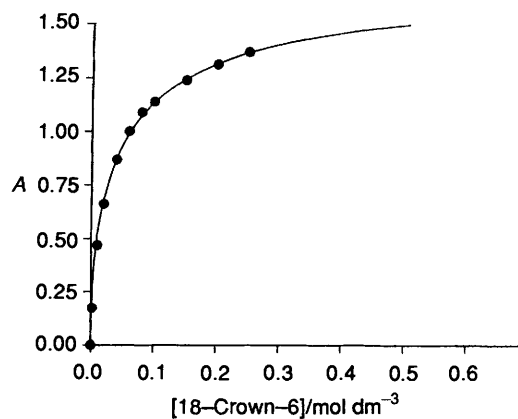
Fig. 5 Plot of absorbance at 400 nm $vs.$ [18-crown-6] for the addition of 18-crown-6 to 3-Me-4-NO_2-phenol (8×10^{-5} mol dm^{-3}) in 0.1 mol dm^{-3} butylamine in chlorobenzene solution; the line is drawn from eqn. (6) with parameters from Table 3

Fig. 6 Plot of log K $vs.$ pK_a of phenol in water. The data is from Table 3 and the line is drawn from eqn. (7). The identities of the phenols are, in order of increasing pK_a: 3,4-$(NO_2)_2$; 2-Cl, 4-NO_2; 4-NO_2; 3-Me, 4-NO_2; 4-Cl, 3-NO_2; 3-NO_2.

concentration is less than that of the crown (for all except the lowest concentrations). Thus the concentration of ArO⁻ (A − A_0) and the butylammonium–crown complex are identical enabling eqn. (6) to be fitted without recourse to extensive

$$K = [ArOH][Bu\text{-}NH_2][Crown]/[ArO^-][Crown\text{-}Bu\text{-}NH_3]$$
$$= (A_\infty - A)[Bu\text{-}NH_2][Crown]/(A - A_0)^2 =$$
$$K_a^{ArOH}K' \quad (6)$$

analytical techniques; the concentration of free ArOH is (A_∞ − A). Values of K fit a Brønsted correlation [eqn. (7) and Fig. 6] where pK_a is for the ionization of the appropriate phenol in water.

$$\log K = (2.10 \pm 0.14)\, pK_a - (17.55 \pm 1.00)$$
$$(r = 0.9907, n = 6) \quad (7)$$

The results of the molecular mechanics calculations on the structure of the complex between the zwitterion and 18-crown-6 are summarized by a drawing of the 3D structure **I**. The main features of the structure are the distances between oxygens (a), (b), (c) and (d) from the hydrogen (g) at 2.436, 2.695, 2.991, 2.427 Å respectively and the distance (2.926 Å) between hydrogen (e) and oxygen (c).

I
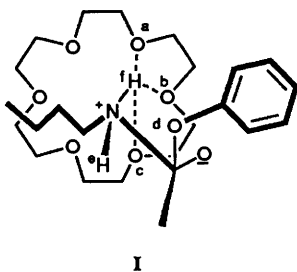
Discussion

Aminolysis in chlorobenzene without glymes or crowns

The mechanism for aminolysis of esters in aqueous solvent has been thoroughly discussed by Jencks and his co-workers.[8a,b] We shall use Leffler α data[7a,12] for these known mechanisms as standards for the mechanistic interpretation of such data for aminolysis in other solvents. The existence of a base term for various aminolysis reactions in aqueous solution is generally consistent with rate-limiting proton transfer in the scheme. Rate-limiting fission of the ArO–C bond demands that the return step
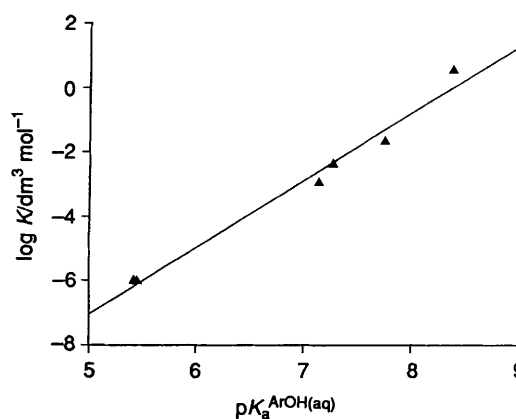
to the zwitterion (T⁻ + BH⁺ ⟶ T± + B) would have to be included in the overall kinetic equation; only specific base catalysis would then be observed because the base concentration term would be cancelled by the conjugate acid term ([BH⁺]) in the denominator of the rate equation. Dependence on '[OH⁻]' or 1/[H⁺] would result because of the ratio [B]/[BH⁺] in the overall kinetic equation. Rate-limiting ArO–C bond fission could retain a general base term in the kinetic equation if diffusion of T⁻·HB⁺ were slow compared with the reverse reaction. T⁻·HB⁺ to T±·B. This condition is unlikely to hold in the case of aqueous or highly solvating solvents but could be true in aprotic non-polar solvents (see later).

Knowledge of effective charge development (obtained from either β or ρ) is only useful for discussing the extent of bond change in the transition state when it is compared with the value for the overall equilibrium reaction (β_{eq} or ρ_{eq}) where the change in bonding is complete. The comparison may be done conveniently using Leffler's parameter ($\alpha = \beta/\beta_{eq}$ or ρ/ρ_{eq}).[7a,12] Studies of the aminolyses of phenyl acetates in aqueous solution enable us to estimate the value of α_{1g} to be expected when the proton transfer step is rate limiting. The rate constants (k_b) for ammonia-catalysed ammonolysis of phenyl acetates[10] have $\beta_{1g} = -0.2$, which, when compared with the corresponding β_{eq} for the transfer (-1.7) gives a Leffler parameter $\alpha_{1g} = 0.12$ which is consistent with only little leaving group fission in the transition state of a mechanism involving rate-limiting proton transfer.

The kinetics of ester aminolysis in chlorobenzene are second-order in amine concentration which is consistent with a rate-limiting proton transfer step (Scheme 1, path II). General base catalysis has been observed in other aminolyses of esters in non-aqueous solutions.[13–17] Even though the rate expression for butylaminolysis contains two butylamine concentration terms it is possible that the rate-limiting step in chlorobenzene could be ArO–C fission. The conjugate acid (BH⁺) of the base (B) which accepts the proton from T± could remain associated with the T⁻ species as an ion pair in an aprotic solvent; the complex T⁻·HB⁺ would break up by diffusion more slowly than ArO–C bond fission due simply to the lack of solvating power of the medium. Whereas in highly solvating solvents, such as water, the diffusion step is generally faster than bond fission it is conceivable for non-polar aprotic solvents that the return reaction (BH⁺·T⁻ ⟶ B·T±) within the complex could be faster than ArO–C bond fission which would then be the rate-limiting step. This mechanism can be excluded by comparison of the Leffler exponents for variation of the leaving group with that ($\alpha_{1g} = 0.12$) when proton transfer is known to be

Table 3 Data for binding of butylammonium phenolates by 18-crown-6 in chlorobenzene solution[a]

Phenol	[BuNH$_2$][b]	N[c]	pK$_a$[d]	[ArOH]/ 10^{-4} mol dm^{-3} [e]	K/10^{-6} dm^3 mol^{-1}	(A$_\infty$ − A$_0$)[f]	λ/nm[g]	[Crown]/ 10^{-2} mol dm^{-3} [h]	A[i]
3,4-NO$_2$	0.01	12	5.42	0.80	0.965 ± 0.069	1.42 ± 0.004	420	0.01–1.0	0.18–1.6
2-Cl, 4-NO$_2$	0.01	15	5.45	0.20	0.933 ± 0.145	1.20 ± 0.02	400	0.004–2.5	0.42–1.28
4-NO$_2$	0.1	16	7.14	0.80	1150 ± 130	1.25 ± 0.02	400	0.02–10	0.09–1.15
3-Me, 4-NO$_2$	0.1	11	7.27	0.80	4290 ± 140	1.69 ± 0.01	410	0.2–25	0.17–1.40
4-Cl, 3-NO$_2$	0.1	11	7.75	0.80	21300 ± 5800	0.25 ± 0.01	410	0.4–25	0.08–0.22
3-NO$_2$	1.0	9	8.38	5.00	(3.72 ± 0.14) × 10^6	0.43 ± 0.08	375	5–100	0.06–0.4

[a] General conditions: 25 °C. [b] Butylamine concentration, measurements taken after addition of aliquots of 0.1 mol dm^{-3} solution of 18-crown-6 in chlorobenzene. [c] Number of data points not including duplicates. [d] pK$_a$ of phenol in water; values from S. A. Ba-Saif, M. A. Waring and A. Williams, *J. Am. Chem. Soc.*, 1990, **112**, 8115; *J. Chem. Soc., Perkin Trans. 2*, 1991, 1653. [e] Concentration of phenol in the reaction cell. [f] A$_\infty$ = absorbance maximum (calculated from fit); A$_0$ = absorbance at [crown] = 0 mol dm^{-3} (observed). [g] Wavelength at which measurements of absorbance were taken. [h] Range of 18-crown-6 concentrations. [i] Range of observed absorbance values at the given wavelength.

rate-limiting, albeit for a different solvent. It is not possible to compare the β_{1g} value for k_c, the butylaminolysis of phenyl acetates in chlorobenzene, directly with the value for ammonolysis in aqueous solution and the β values require calibration by the β_{eq} values for transfer of acetyl to phenoxide ions in water (1.7)[7a] and chlorobenzene (2.6),[7b] respectively. Butylaminolysis in chlorobenzene has a Leffler value of α_{1g} = 0.75/2.6 = 0.29 which indicates that the relative effective charge development of the aryl oxygen has not changed substantially compared with that for water consistent with rate-limiting formation of the ion pair (T$^-$·BuNH$_3$$^+$). It is likely that decomposition of T$^-$ occurs prior to expulsion of the butylammonium ion from the ion pair (T$^-$·BuNH$_3$$^+$).

Data for k_b for pyrrolidinolysis in acetonitrile[5] indicate a β_{1g} value of −2.7; we do not yet have a value for β_{eq} for this solvent which we can use to calibrate the effective charge from this parameter. The pyrrolidinolysis in chlorobenzene gives k_b values leading to a β_{1g} of 1.8 and the corresponding Leffler parameter (α_{1g} = 0.69) is consistent with a substantial build up of charge on the aryl oxygen in the transition state of the rate-limiting step and we conclude that the rate-limiting step in this reaction is ArO–C bond fission. The kinetics point to a transition-state composition involving two amines consistent with rate-limiting fission of T$^-$ within the encounter complex BH$^+$·T$^-$ (Scheme 1, path II).

An alternative explanation of the low α value for k_b for the butylaminolysis reaction is that the decomposition of T$^-$ could be rate-limiting with proton transfer to the departing aryl oxygen thus reducing the development of effective charge. This possibility is consistent with a favourable proton transfer from the butylammonium ion to the phenolate ion in the solvent under scrutiny. Although we do not possess data for the ionization constants of phenols and butylammonium ion for chlorobenzene solution the latter is assumed to be the more acidic because of the lack of reaction between phenols and butylamine in that solvent.

Aminolysis catalysed by glymes and crown ethers

Few kinetic studies have addressed the catalytic influence of glymes and crown ethers in aprotic solvents.[1-4] The rate law for butylaminolysis of phenyl acetates in the presence of 18-crown-6 possesses a term which is first-order in both butylamine and 18-crown-6 concentration and this requires that the crown is included in the composition of the transition state for the rate-limiting step. The β_{1g} value of −0.58 observed for this term indicates that less charge development is occurring on the leaving oxygen than in the base-catalysed reaction channel. The Leffler α_{1g} values of the respective solvents indicates that similar low effective charge development occurs on the oxygen in the transition state of the rate-limiting step (α_{1g} = 0.58/2.6 = 0.22) compared with the general base-catalysed reactions in water

and chlorobenzene (0.12 and 0.29, respectively). Such low values of Leffler's α_{1g} are not consistent with rate-limiting fission of the ArO–C bond in the crown ether case and we conclude that in butylaminolysis formation of the crown complex with T$^\pm$ adduct is rate limiting.

The Hammett selectivity data reported by Gandour and Hogan[4] may be converted readily to the appropriate Brønsted β_{1g} parameters and these range from −0.87 to −1.12; the corresponding α_{1g} parameters, ranging from 0.3 to 0.43, are in agreement with the mechanism proposed,[4] but support proton transfer as the rate-limiting step rather than ArO–C fission. The variation in α_{1g} for the glymes[17] and crowns (this work) would appear to indicate shifts in transition-state structure and it is likely that relatively subtle effects (such as change in amine structure) could easily switch the timing of steps within the proposed mechanism (Scheme 2).

(A) RCONHR + Crown + HOAr

(B) RCONHR$^+$ RNH$_3$$^+$ crown + ArO$^-$
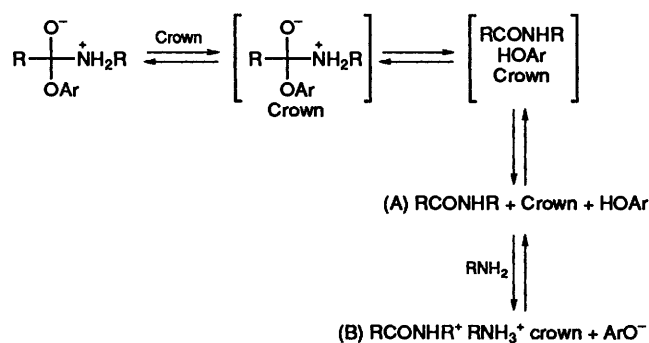
Scheme 2

The steps subsequent to the rate-limiting formation of the association complex with the zwitterion (T$^\pm$) and the crown are 'kinetically invisible' and are not subject to experimental verification in this work. It is unlikely that the crown acts as a proton transfer agent in a similar manner to that of regular bases because it is a very weak base.

Scheme 2 involves the initially forming phenolate ion's accepting a proton from the ammonium ion before the system can become a protonated amide. Those crowns which catalyse the formation of amide and neutral phenol involve a path which stops at (A) in Scheme 2 whereas 18-crown-6 and 15-crown-5 involve an ionization step where the initially formed phenol reacts with butylamine and crown to give the ammonium–crown cation and phenolate ion (B).

It is conceivable that the values of α_{1g} for k_c much less than unity are due to proton transfer in the transition state reducing the effective charge on the aryl oxygen and that the rate-limiting step is indeed the collapse of the tetrahedral intermediate. The modelled structure of the complex between the zwitterion and

the crown indicates that one of the hydrogens of the nitrogen is between 2.4 and 2.7 Å from two ether oxygens of the crown and some 2.4 Å from the phenolic oxygen. This indicates that it is reasonable to suppose that the aromatic oxygen could become protonated by direct transfer in the collapse of the zwitterion to product. However, it is unclear as to the function of the crown ether in the mechanism because a similar pathway would be open to an aminolysis reaction involving neither general base nor crown catalysis.

An alternative mechanism involves rate-limiting expulsion of phenolate ion from the $T^{\pm}$·crown complex; the high energy requirement of the incipient $RCONH_2{}^+R$ species[18] could be satisfied by interaction with the crown within the complex. This mechanism, with ArO–C bond fission in the transition state would require substantial interaction between the oxyanion and the ammonio proton to satisfy the observed small α_{1g}. A mechanism involving prior complexation of the crown with amine or crown with ester is quite possible, but not likely to be an important component since there would appear to be no driving force for each of these association reactions. Such steps are, moreover, unlikely to be rate limiting.

Proton transfer between phenol and butylamine

Ease of formation of the phenolate ions from solutions of phenols and butylamine in chlorobenzene solution is a function of crown ether structure. Hogan and Gandour[2,3] delineate the structural requirements of the polyether-type catalyst and it is possible that the same structural features are responsible for the ability of the polyethers to facilitate proton transfer from phenol to butylamine in chlorobenzene solutions as exemplified in eqn. (5).

The parameter K [defined in eqn. (6)] can be expressed as a function of the ionization constant of the phenol (K_a^{ArOH}); K' [see eqn. (6)] is an equilibrium constant independent of the substitutent. The Brønsted exponent for the correlation of log K and the pK_a of phenols in water [eqn. (7)] indicates that the value of log K is some 2.1 times more sensitive to the substituent than is the value of the pK_a of phenol in water and this gives rise to a measure of the effective charge for the ionization in the chlorobenzene system. The greater development of effective charge is expected because of localization due to poorer solvating power of the chlorobenzene than that of water and this is seen with the selectivity of the ionization of phenols in dimethylsulfoxide,[19] acetonitrile[20] and the gas phase.[19] The

proton transfer reaction could involve simply the formation of the ion pair between complexed crown and phenolate ion in which case the effective charge development on the free phenoxide ion in chlorobenzene should be greater than 2.1.

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