The Stabilities of Meisenheimer Complexes. Part 33.[1] Kinetic Studies of the Formation of Isomeric σ-Adducts from 2,4,6-Trinitrobenzyl Chloride and Aliphatic Amines in Dimethyl Sulphoxide

Michael R. Crampton * **and Paul J. Routledge**
Department of Chemistry, University of Durham, Durham DH1 3LE
Peter Golding
Ministry of Defence, P.E.R.M.E., Waltham Abbey, Essex EN9 1BP

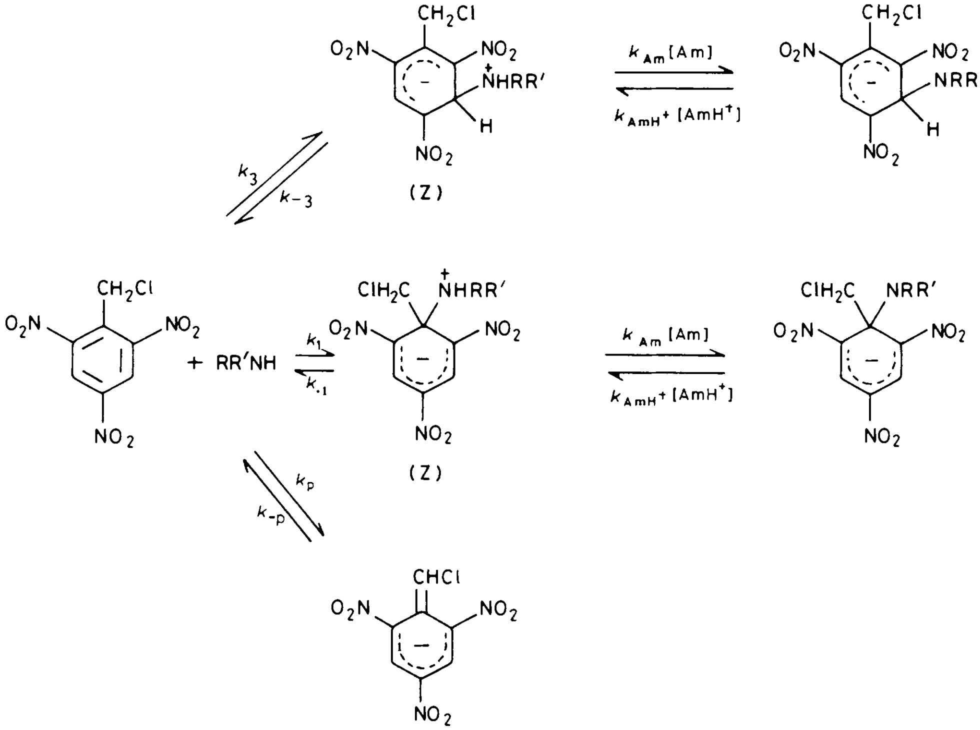
Kinetic and equilibrium data are reported for the reversible colour-forming reactions of 2,4,6-trinitrobenzyl chloride with some aliphatic amines in dimethyl sulphoxide and are compared with data for reactions of 1,3,5-trinitrobenzene. With n-butylamine and benzylamine three processes are observable: attack at the 3-position, attack at the 1-position, and transfer of a side-chain proton. For piperidine and pyrrolidine only two of these are observable, attack at the 1-position being disfavoured for steric reasons. The formation of anionic σ-adducts occurs *via* zwitterionic intermediates and it is shown that the proton-transfer step may be kinetically significant. Reductions of rate constants for proton-transfer below the values expected for diffusion-controlled reaction are attributed to steric effects which are increased when reaction involves secondary amines and when the CH_2Cl group is at the reaction site. Specific effects of chloride ions are noted and are attributed to their interaction with substituted ammonium ions.

The commercially important 2,2′,4,4′,6,6′-hexanitrostilbene may be prepared [2] by reaction of 2,4,6-trinitrobenzyl chloride with bases. Recent work [3] has shown that nitrogen bases may be particularly effective in this reaction.

In a preliminary study [4] of the reactions of 2,4,6-trinitrobenzyl chloride with aliphatic amines in dimethyl sulphoxide (DMSO) it was shown that, in the early stages, intensely coloured species are produced reversibly. Two types of process were identified: σ-adduct formation and transfer of a side-chain proton. Kinetic and equilibrium data relating to the latter process were reported.

Several studies have been reported [1,5-8] of the formation of anionic σ-adducts from 1,3,5-trinitrobenzene and amines in DMSO, and it has been shown that proton transfer from zwitterionic intermediates to amines may be kinetically significant. Here we report kinetic and equilibrium data for σ-adduct formation from 2,4,6-trinitrobenzyl chloride and four amines in DMSO. Our aims were to compare data with those for 1,3,5-trinitrobenzene and to examine the steric and electronic effects of the CH_2Cl group on σ-adduct formation.

Measurements were made spectroscopically. It is known [4] that σ-adducts give two bands in the visible region with maxima at 450—452 and 510—550 nm, whilst the conjugate base gives three bands with maxima at 373, 490, and 600 nm. We interpret our data according to Scheme 1. With the primary amine n-butylamine three reversible time-dependent processes



Scheme 1. Am = amine. Delocalisation involving exocyclic groups is not shown

are observed. Our analysis shows that these may be attributed to formation of the 3-adduct, followed by isomerisation to the 1-adduct, followed by equilibration with the conjugate base. With the secondary amines piperidine and pyrrolidine we observed only two of these processes. The missing process here is attack at the 1-position; the 1-adduct may be disfavoured because of the extreme steric congestion which would be caused by its formation.

Measurements in the presence of substituted ammonium ions were made using either the perchlorate or the chloride salts. The results provide further evidence [9] for the stabilisation of the substituted ammonium ions by association with chloride ions, $R'RNH_2^+ \cdots Cl^-$.

Experimental

2,4,6-Trinitrobenzyl chloride, m.p. 85 °C (lit.,[2] 85 °C), was available from previous work,[10] as were the amines.[1-4] Butylamine hydrochloride was prepared from the amine and gaseous hydrogen chloride in ether and was recrystallised from acetonitrile. Piperidine hydrochloride, benzylamine hydrochloride, and tetraethylammonium perchlorate were commercial ' pure ' specimens used as supplied. Piperidinium perchlorate, butylammonium perchlorate, benzylammonium perchlorate, and pyrrolidinium perchlorate were prepared in solution in dimethyl sulphoxide from weighed amounts of amine and perchloric acid; the pH values of these solutions were measured after reaction, and if necessary small quantities of acid or base were added until the theoretically calculated pH was obtained. The salt solutions so prepared contained less than 0.1% of free acid or amine.

Kinetic and equilibrium measurements were made with freshly prepared solutions of reagents using a Hi-Tech SF3L stopped-flow spectrophotometer or Pye-Unicam SP8-100 recording spectrometer. Rate coefficients at 25 °C are the means of five separate determinations and are precise to within ± 5%.

Results

Kinetic Analysis.—Rates of colour-forming reactions were measured under first-order conditions. For reactions of trinitrobenzyl chloride (TNBCl) with amines sufficient excess of amine was used so that >95% conversion into adduct was achieved at equilibrium. For reactions with buffers (amine plus amine salt) the buffer components were in large excess of the TNBCl concentration which was usually 1×10^{-5}M. Under these conditions [5] equation (1) applies.

$$\ln\left(\frac{OD_\infty}{OD_\infty - OD}\right) = k_{obs}\cdot t \qquad (1)$$

Equation (2) is the general rate expression for the reaction resulting in amine attack at the unsubstituted 3-position.[5] It is assumed that the zwitterionic forms may be treated as steady-state intermediates. For the reactions with amine (no added amine salt) equation (3) will apply, and if $k_{Am}[Am] \gg k_{-3}$ then we obtain equation (4). Inversion of equation (3) yields equation (5).

$$k_{obs} = \frac{k_3 k_{Am}[Am]^2 + k_{-3}k_{AmH^+}[AmH^+]}{k_{-3} + k_{Am}[Am]} \qquad (2)$$

$$k_{obs} = \frac{k_3 k_{Am}[Am]^2}{k_{-3} + k_{Am}[Am]} \qquad (3)$$

$$k_{obs} = k_3[Am] \qquad (4)$$

$$\frac{[Am]}{k_{obs}} = \frac{1}{k_3} + \frac{1}{K_3 k_{Am}[Am]} \qquad (5)$$

With the primary amines butylamine and benzylamine rapid reaction at the 3-position of TNBCl was followed by slower attack at the 1-position. The rates of these reactions were sufficiently different for them to be measured consecutively. Rate data for attack at the 1-position may be expressed [equation (6)] in terms of coefficients for the forward and the reverse reactions. It can be shown using standard methods [11] that, allowing for prior attack at the 3-position, the general rate expression is given by equation (7). For solutions containing no added amine salt, the k_r term becomes vanishingly small,

$$k_{obs} = k_f + k_r \qquad (6)$$

$$k_{obs} = \frac{k_1 k_{Am}[Am]^2}{(k_{-1} + k_{Am}[Am])\left(1 + K_{c.3}\dfrac{[Am]^2}{[AmH^+]}\right)} + \frac{k_{-1}k_{AmH^+}[AmH^+]}{k_{-1} + k_{Am}[Am]} \qquad (7)$$

$$k_{obs} = \frac{k_1 k_{Am}[Am]^2}{(k_{-1} + k_{Am}[Am])\left(1 + \dfrac{(OD)_3}{(OD_\infty)_3 - (OD)_3}\right)} \qquad (8)$$

$$k_{obs} = \frac{k_1[Am]^2}{\dfrac{k_{-1}}{k_{Am}} + [Am]} + \frac{\dfrac{k_{-1}k_{AmH^+}}{k_{Am}}[AmH^+]}{\dfrac{k_{-1}}{k_{Am}} + [Am]} \qquad (9)$$

and in some cases it was convenient for calculations to write the k_f term as shown in equation (8). Here $(OD)_3$ is the optical density at the completion of the faster reaction forming the 3-adduct and $(OD_\infty)_3$ is the appropriate value for complete conversion into the 3-adduct. We shall also use equation (9) which is the form, after rearrangement, of equation (7) appropriate to cases where there is little formation of the 3-adduct.

The rate expression relating to the transfer of the side-chain proton [equation (10)] has been given in previous work.[4]

$$k_{obs} = \frac{k_p[Am]}{1 + K_c\dfrac{[Am]^2}{[AmH^+]}} + k_{-p}[AmH^+] \qquad (10)$$

Equilibrium Constants.—We define by equation (11) an equilibrium constant $K_{c.3}$ for the overall conversion of TNBCl into its 3-amido adduct. This equilibrium constant is related by equation (12) to the equilibrium constant K_3 for formation of the zwitterionic intermediate, and to the acid dissociation constants of the zwitterion, K_a^Z, and protonated amine, $K_a^{AmH^+}$. Equation (13) relates $K_{c.3}$ to the rate coefficients associated with formation of the 3-adduct.

$$K_{c.3} = \frac{[\text{3-adduct}][AmH^+]}{[TNBCl][Am]^2} \qquad (11)$$

$$K_{c.3} = K_3 \cdot \frac{K_a^Z}{K_a^{AmH^+}} \qquad (12)$$

$$K_{c.3} = \frac{k_3}{k_{-3}} \cdot \frac{k_{Am}}{k_{AmH^+}} \qquad (13)$$

Expressions exactly analogous to (11)—(13) may be written for $K_{c.1}$, the equilibrium constant for reaction at the 1-position.

The results obtained with butylamine, benzylamine, piperi-

Table 1. Kinetic and equilibrium data for the reaction of TNBCl (5×10^{-6}M) and n-butylamine in DMSO at 25 °C

$[BuNH_2]$/M	k_{fast}/s^{-1}	k_3 [a]/l mol^{-1} s^{-1}	$(OD)_3$ [b]	k_{slow}/s^{-1}	k_{calc} [c]	$(OD)_1$ [d]
0.0004			0.0026	0.10	0.11	0.024
0.0005			0.0057	0.13	0.13	0.024
0.0006			0.0045	0.19	0.18	0.025
0.0008			0.0067	0.23	0.23	0.026
0.0010			0.0087	0.27	0.27	0.027
0.0020			0.0164	0.27	0.25	0.027
0.0040	10.6	2 660	0.0200			0.027
0.0060	20.0	3 330	0.0210			0.027
0.0080	24.2	3 020	0.0210			0.027
0.0100	33.6	3 360	0.0210			0.027

[a] Calculated using equation (4). [b] Optical density at completion of fastest reaction (450 nm). [c] Calculated from equation (8) with k_1 700 l mol^{-1} s^{-1} and k_{Am}/k_{-1} 2 000 l mol^{-1}. [d] Optical density at completion of slower reaction forming 1-adduct.

Table 2. Kinetic and equilibrium data for reaction of TNBCl with n-butylamine in DMSO containing n-butylammonium perchlorate (0.1M)

$[BuNH_2]$/M	$(OD)_3$ [a]	$K_{c,3}$/l mol^{-1}	$(OD)_1$	$K_{c,1}$/l mol^{-1}	k_{obs}/s^{-1}	k_{calc} [b]/s^{-1}
0.001			0.0039	23 000	2.2	2.2
0.002			0.0100	23 000	2.2	2.1
0.004			0.0173	29 000	2.9	2.9
0.006			0.0205		3.9	3.9
0.008			0.0209		4.9	4.9
0.010			0.0209		6.0	6.1
0.020	0.0045	76	0.021		10.3	9.9
0.030	0.0074	70	0.021		12.1	11.5
0.040	0.0106	77	0.021		12.0	11.7
0.050	0.0123	71	0.021		10.7	11.1
0.060	0.0137	69	0.021		10.5	10.5

[a] Optical density at completion of reaction giving 3-adduct. A Benesi–Hildebrand plot gives a value for $(OD_\infty)_3$ of 0.0192. [b] Calculated from equation (7) with k_1 630 l mol^{-1} s^{-1}, $K_{c,3}$ 73 l mol^{-1}, k_{Am}/k_{-1} 2 000 l mol^{-1}, and k_{AmH^+} 55 l mol^{-1} s^{-1}.

Table 3. Kinetic and equilibrium data for reaction of TNBCl with n-butylamine in DMSO containing n-butylammonium chloride (0.1M)

$[BuNH_2]$/M	(OD_3) [a]	$K_{c,3}$/l mol^{-1}	$(OD)_1$	$K_{c,1}$/l mol^{-1}	k_{obs}/s^{-1}	k_{calc} [b]
0.001			0.0056	37 000	1.49	1.50
0.002			0.0132	42 000	1.66	1.64
0.004			0.0175	31 000	2.6	2.55
0.006			0.0188	24 000	3.8	3.6
0.008			0.020		4.8	4.6
0.010			0.021		5.8	5.5
0.015	0.0057	160	0.021		7.8	7.2
0.020	0.0083	160	0.021		8.9	7.9
0.030	0.0128	170	0.022		8.3	8.4
0.040	0.0143	130	0.021		8.2	7.5

[a] Optical density at completion of reaction giving 3-adduct. A Benesi–Hildebrand plot gives a value for $(OD_\infty)_3$ of 0.021. [b] Calculated from equation (7) with k_1 630 l mol^{-1} s^{-1}, $K_{c,3}$ 150 l mol^{-1}, k_{Am}/k_{-1} 2 000 l mol^{-1}, and k_{AmH^+} 32 l mol^{-1} s^{-1}.

dine, and pyrrolidine are sufficiently different to warrant their separate treatment. Measurements made in the presence of substituted ammonium chloride or perchlorate salts indicate specific effects due to the anions present.

Reaction with n-Butylamine.—Two reactions giving σ-adducts were observed, followed by a very slow reaction, reported previously,[4] giving the conjugate base. We interpret the data according to Scheme 1. The data in Table 1 for attack at the 3-position show that at the base concentrations used $k_{Am}[Am] \gg k_{-3}$ so that equation (4) applies and yields a value for k_3 of 3 000 l mol^{-1} s^{-1}. If we set a lower limit for $k_{Am}[Am]/k_{-3}$ of 4 when $[BuNH_2] = 0.004$M then we calculate that $k_{Am}/k_{-3} > 1\,000$, and also $K_3k_{Am} > 3 \times 10^6$ l^2 mol^{-2} s^{-1}. The rate data for attack at the 1-position are interpreted using equation (8) with values of k_1 700 l mol^{-1} s^{-1} and k_{Am}/k_{-1} 2 000 l mol^{-1}.

Data obtained in the presence of 0.1M-butylammonium perchlorate are in Table 2. The attack at the 3-position was too fast to be measured but the optical densities at the completion of this reaction yielded a value for $K_{c,3}$ of 73 ± 4 l mol^{-1}. From the restricted data available we estimate a value for $K_{c,1}$ of $23\,000 \pm 5\,000$ l mol^{-1}, which may be compared with a value of 20 000 l mol^{-1} obtained previously.[4] The rate coefficients for formation of the 1-adduct pass through a maximum with increasing base concentration. We interpret the data according to equation (7). We first obtained a value for k_1 of 630 l mol^{-1} s^{-1} by using the data where $[BuNH_2] >$ 0.01M; here the condition $k_{Am}[Am] \gg k_{-1}$ will apply and also the k_r term will be negligible. We were then able to obtain a value of 0.0274 s^{-1} for the ratio $k_{-1}k_{AmH^+}/k_{Am}$ ($= k_1/K_{c,1}$). Finally we were able to make use of the fact that at low (<0.008M) amine concentrations little of the 3-adduct is initially present so that equation (9) will apply. Using the known values of k_1 and $k_{-1}k_{AmH^+}/k_{Am}$ we solved equation (9) for each amine concentration to obtain a value for k_{Am}/k_{-1} of 2 000 ± 500 l mol^{-1}. When these calculated parameters are used, equation (7) fits the data over the entire concentration range.

The data (Table 3) obtained in the presence of 0.1M-butylammonium chloride show significant differences from those obtained with the perchlorate salt. The value of $K_{c,3}$ is 150 ± 20 l mol^{-1}, and the value of $K_{c,1}$ is also higher than that obtained with the perchlorate. However, because of the extensive conversion into the 1 : 1 adduct at low amine concentrations the value of $K_{c,1}$ cannot be obtained with very high accuracy from the optical density data. The rate data obtained at the higher base concentrations yield a value for k_1 of 630 l mol^{-1} s^{-1}. We assume that the value of k_{Am}/k_{-1} will remain at 2 000 l mol^{-1}, and are then able to calculate a value for k_{AmH^+} of 32 l mol^{-1} s^{-1}. The value of $K_{c,1}$ obtained from the kinetic parameters is 40 000 l mol^{-1} ($= k_1k_{Am}/k_{-1}k_{AmH^+}$).

Table 4. Kinetic data for the fast reaction of TNBCl with benzylamine in DMSO at 25 °C, yielding the 3-adduct

$[PhCH_2NH_2]$/M	k_{fast}/s^{-1}	k_{calc} [a]	$(OD)_3$
0.010	5.9	5.9	0.025
0.015	9.6	10.1	0.028
0.020	14.9	14.8	0.026
0.030	23.0	24	0.029
0.040	33.1	34	0.028
0.060	53.3	54	0.028

[a] Calculated from equation (5) with k_3 1 000 l mol^{-1} s^{-1} and K_3k_{Am} 1.4 × 10^5 l^2 mol^{-2} s^{-1}.

Reaction with Benzylamine.—Two reactions giving σ-adducts were observed. Data obtained, without added salt, for the faster process yielding the 3-adduct are in Table 4. A plot of the data according to equation (5) gave values for k_3 1 000 l mol^{-1} s^{-1} and K_3k_{Am} 1.4 × 10^5 l^2 mol^{-2} s^{-1}. Thus in the amine concentration range used the proton-transfer step from the zwitterion to amine is partially rate-limiting. Data obtained in the presence of 0.1M-benzylammonium perchlorate are in Table 5. The optical densities at the completion of the faster σ-adduct-forming reaction yield a value for $K_{c,3}$ of 5 l mol^{-1}, and those at the end of the slower reaction give $K_{c,1}$ 1 000 l mol^{-1}. This latter value is significantly higher than that obtained in previous work.[4] We consider the present value to be the more reliable. As in the case of the reaction with butylamine and its perchlorate, sufficient data are available from the kinetics of the slower reaction to enable calculation of values for k_1 230 l mol^{-1} s^{-1}, $k_{-1}k_{AmH^+}/k_{Am}$ 0.23 s^{-1}, and k_{Am}/k_{-1} 200 l mol^{-1}. Combination of these values gives k_{AmH^+} 46 l mol^{-1} s^{-1}. Data calculated from equation (7) using these values gives excellent agreement with observed values.

The data measured with 0.1M-benzylammonium chloride are in Table 6. Calculations from these data were made independently from the measurements with the perchlorate salt. There are significant differences in the calculated values for $K_{c,3}$ 10 l mol^{-1}, $K_{c,1}$ 2 000 l mol^{-1}, $k_{-1}k_{AmH^+}/k_{Am}$ 0.125 s^{-1}, and k_{AmH^+} 25 l mol^{-1} s^{-1}. However, the values of k_1 and k_{Am}/k_{-1} are, within experimental error, unchanged.

For the solutions containing 0.1M-benzylammonium chloride we also measured the rate coefficients for the third (slowest) process yielding the conjugate base. Measurements were made at 620 nm using a conventional spectrophotometer. The results (Table 7) are well fitted by equation (10)

Table 5. Kinetic and equilibrium data for the reaction of TNBCl with benzylamine in DMSO containing benzylammonium perchlorate (0.1M)

$[PhCH_2NH_2]$/M	$(OD)_3$ [a]	$K_{c,3}$/l mol^{-1}	$(OD)_1$	$K_{c,1}$/l mol^{-1}	k_{obs}/s^{-1}	k_{calc} [b]
0.005			0.0051	1 000	2.9	2.9
0.0075			0.0088	940	2.8	2.9
0.01			0.0119	880	3.1	3.1
0.02			0.0200	910	4.2	4.6
0.04			0.0241	1 070	7.6	8.0
0.06			0.0250		11.9	11.1
0.08	0.0070	7.7	0.0250		13.2	13.4
0.10	0.0079	6.0	0.0259		15.2	14.7
0.15	0.0106	4.5	0.0255		16.1	15.8
0.20	0.0146	5.6	0.0259			

[a] Optical density at completion of reaction giving 3-adduct. A Benesi–Hildebrand plot gives a value for $(OD_\infty)_3$ of 0.021. [b] Calculated from equation (7) with k_1 230 l mol^{-1} s^{-1}, $K_{c,3}$ 5 l mol^{-1}, k_{Am}/k_{-1} 200 l mol^{-1}, and k_{AmH^+} 46 l mol^{-1} s^{-1}.

Table 6. Kinetic and equilibrium data for the reaction of TNBCl with benzylamine in DMSO containing 0.1M-benzylammonium chloride

$[PhCH_2NH_2]$/M	$(OD)_3$	$K_{c,3}$ [a]/l mol^{-1}	$(OD)_1$	$K_{c,1}$ [b]/l mol^{-1}	k_{obs}/s^{-1}	k_{calc} [c]
0.0025			0.0031	2 200	1.9	1.9
0.005			0.0084	2 000	1.8	1.9
0.0075			0.0123	1 800	2.0	2.1
0.01			0.0175	2 300	2.5	2.5
0.02			0.0223	2 000	4.1	4.0
0.04			0.0241		7.5	7.9
0.06	0.0059	12	0.0246		10.4	10.2
0.07	0.0072	11	0.0246			
0.08	0.0088	12	0.025		12.0	11.6
0.09	0.0092	10	0.024			
0.10	0.0101	10	0.025		12.8	12.0
0.15	0.0132	9	0.025			

[a] Calculated from equation (11) using a value for $(OD_\infty)_3$ of 0.020. [b] Calculated using a value for $(OD_\infty)_1$ of 0.025. [c] Calculated from equation (7) with k_1 250 l mol^{-1} s^{-1}, $K_{c,3}$ 10 l mol^{-1}, $k_{-1}k_{AMH^+}/k_{Am}$ 0.125 s^{-1}, and k_{Am}/k_{-1} 200 l mol^{-1}.

Table 7. Rate data for the deprotonation of TNBCl by benzylamine in DMSO containing 0.1M-benzylammonium chloride.

$[PhCH_2NH_2]$/M	k_{obs}/s^{-1}	k_{calc} ^{a}
0.001	0.0054	0.0057
0.002	0.0075	0.0087
0.004	0.0114	0.0125
0.006	0.0144	0.0140
0.008	0.0153	0.0143
0.01	0.0131	0.0138
0.02	0.0108	0.0100
0.04	0.0065	0.0065

[a] Calculated from equation (10) with values of k_p 3.4 l mol^{-1} s^{-1}, k_{-p} 0.024 l mol^{-1} s^{-1}, and $K_{c.1}$ 2 000 l mol^{-1}.

Table 8. Kinetic data for the reaction of TNBCl with piperidine in DMSO containing 0.1M-piperidinium perchlorate

[Piperidine]/M	0.01	0.015	0.02	0.03	0.04	0.05
k_{obs}/s^{-1}	30	36	41	50	69	94
k_{calc} ^{a}	31	34	39	50	69	93

[a] Calculated from equation (2) with K_3k_{Am} 2.6 × 10^4 l^2 mol^{-2} s^{-1}, k_{AmH^+} 280 l mol^{-1} s^{-1}, and $k_{Am}[Am] \ll k_{-3}$.

Table 9. Kinetic and equilibrium data for reaction of TNBCl with piperidine in DMSO containing piperidinium chloride (0.1M)

[Piperidine]/ M	k_{obs}/s^{-1}	k_{calc} ^{a}	$(OD)_3$	$K_{c.3}$ ^{b}/ l mol^{-1}
0.01	14.4	14.4	0.0079	258
0.02	21.6	21.6	0.0177	213
0.03	34.7	33.5	0.0246	197
0.04	51.0	50.5	0.0306	242
0.05	69	72	0.0325	217
0.06	102	99	0.0343	226

[a] Calculated from equation (2) with K_3k_{Am} 2.4 × 10^4 l^2 mol^{-2} s^{-1}, k_{AmH^+} 120 l mol^{-1} s^{-1}, and $k_{Am}[Am] \ll k_{-3}$. [b] Calculated from $(OD)_3$ values using a value of 0.0385 for complete conversion into 3-adduct.

with values of k_p 3.4 l mol^{-1} s^{-1}, k_{-p} 0.024 l mol^{-1} s^{-1}, and $K_{c.1}$ 2 000 l mol^{-1}.

Reaction with Piperidine.—Two reversible colour-forming reactions were observed. The visible spectra indicate that the faster process involves σ-adduct formation, and the slower process transfer of a side-chain proton. We will justify later our assumption that the σ-adduct is that formed by attack at an unsubstituted position (3-adduct) rather than by attack at the 1-position. Rate data for the faster reaction obtained in the presence of 0.1M-piperidinium perchlorate are in Table 8. A plot of k_{obs} *versus* the square of the piperidine concentration was linear indicating that in equation (2) the condition $k_{-3} \gg k_{Am}[Am]$ applies. The slope of this plot gave a value for K_3k_{Am} of 2.6 × 10^4 l^2 mol^{-2} s^{-1} and the intercept a value for k_{AmH^+} of 280 l mol^{-1} s^{-1}. Combination of these values gave $K_{c.3}$ 93 l mol^{-1}. The absence of curvature in this plot allows us to calculate an upper limit of 2 for k_{Am}/k_{-3}. Data obtained in the presence of 0.1M-piperidinium chloride are in Table 9. There is acceptable agreement between the values of $K_{c.3}$ calculated from the kinetic data, 200 l mol^{-1}, and the equilibrium data, 220 ± 30 l mol^{-1}.

Table 10. Kinetic data for the reaction of TNBCl with pyrrolidine in DMSO containing 0.1M-tetraethylammonium perchlorate

[Pyrrolidine]/M	0.002	0.004	0.006	0.008	0.010
k_{obs}/s^{-1}	2.2	7.7	18	28.7	43.6
k_{calc} ^{a}	2.2	8.2	17.3	29.2	43.3

[a] Calculated from equation (5) with K_3k_{Am} 5.8 × 10^5 l^2 mol^{-2} s^{-1} and k_3 1.7 × 10^4 l mol^{-1} s^{-1}.

Table 11. Kinetic and equilibrium data for reaction of TNBCl with pyrrolidine in the presence of pyrrolidinium perchlorate

[Pyrrolidine]/M	[Pyrrolidinium perchlorate] ^{a}/M	k_{obs}/ s^{-1}	k_{calc} ^{b}	OD_3 ^{c}	$K_{c.3}$ ^{d}
0.001	0.01	24	24		
0.002	0.01	26	25		
0.004	0.01	28	29	0.0134	260
0.006	0.01	36	37	0.0219	260
0.007	0.01	41	42	0.0246	250
0.008	0.01	48	48	0.0269	230
0.009	0.01	56	55	0.0297	240
0.010	0.01	64	61	0.0325	260
0.012	0.01	81	77	0.0348	240
0.004	0.02	53	51	0.0095	330
0.006	0.02	60	58	0.0134	240
0.008	0.02	69	67	0.0205	260
0.015	0.02	125	120	0.0337	260

[a] I = 0.1M with tetraethylammonium perchlorate. [b] Calculated from equation (2) with K_3k_{Am} 5.8 × 10^5 l^2 mol^{-2} s^{-1}, k_{AMH^+} 2 400 l mol^{-1} s^{-1}, and k_{Am}/k_{-3} 34 l mol^{-1}. [c] Measured at 450 nm at completion of rapid colour-forming reaction. [d] Calculated using a value for $(OD_\infty)_3$ of 0.045.

Table 12. Kinetic and equilibrium data for the reaction of TNBCl with pyrrolidine in the presence of pyrrolidinium perchlorate

[Pyrrolidine]/M	[Pyrrolidine perchlorate] ^{a}/M	k_{obs}/ s^{-1}	k_{calc} ^{b}	$(OD)_3$ ^{c}	$K_{c.3}$
0.006	0	18	17	0.043	
0.006	0.001	19	19	0.038	210
0.006	0.002	21	21	0.034	210
0.006	0.004	25	25	0.029	230
0.006	0.006	30	29	0.025	230
0.006	0.008	32	33	0.023	250
0.006	0.010	36	37	0.021	260
0.010	0	43	43		
0.010	0.001	44	45		
0.010	0.002	47	47		
0.010	0.004	51	50		
0.010	0.006	52	54		
0.010	0.008	57	57		
0.010	0.010	62	61		

[a] I = 0.1M with tetraethylammonium perchlorate. [b] Calculated from equation (2) with K_3k_{Am} 5.8 × 10^5 l^2 mol^{-2} s^{-1}, k_{AmH^+} 2 400 l mol^{-1} s^{-1} and k_{Am}/k_{-3} 34 l mol^{-1}. [c] Measured at 450 nm at completion of rapid colour forming reaction.

Reaction with Pyrrolidine.—As with piperidine, two reversible colour-forming reactions were observed. These are attributed to formation of the 3-adduct and to transfer of a side-chain proton. Data relating to the faster, adduct-forming reaction are in Tables 10—12. Measurements were made at constant ionic strength, 0.1M, using tetraethylammonium perchlorate as the neutral electrolyte. Data obtained in the absence of added pyrrolidinium salts are in Table 10. A linear plot of the data according to equation (5) yielded values for K_3k_{Am} (5.8 ± 0.5) × 10^5 l^2 mol^{-2} s^{-1} and k_3 (1.7 ± 1) × 10^4 l mol^{-1} s^{-1}. Combination of these values gave k_{Am}/k_{-3} 34 l mol^{-1}.

Extrapolation to zero amine concentration of data (Table 11) obtained in the presence of constant concentrations of

Table 13. Rate data for the deprotonation of TNBCl by pyrrolidine in DMSO containing 0.1M-pyrrolidinium perchlorate

[Pyrrolidine]/M	0.001	0.002	0.003	0.004	0.005	0.006	0.008
k_{obs}/s^{-1}	0.14	0.27	0.39	0.55	0.66	0.83	1.12

Table 14. Effects of chloride ions on equilibrium and rate data

	$K_{c.3}$ [a]/ l mol^{-1}	$K_{c.1}$ [a]/l mol^{-1}	k_1/ l mol^{-1} s^{-1}	k_{Am}/k_{-1}/ l mol^{-1}	k_{AmH^+}/ l mol^{-1} s^{-1}	K_3k_{Am}/ l^2 mol^{-2} s^{-1}	k_{AmH^+} [b]/ l mol^{-1} s^{-1}
Butylammonium perchlorate	73	23 000	630	2 000	55		
Butylammonium chloride	150	40 000	630	2 000	32		
Benzylammonium perchlorate	5	1 000	230	200	46		
Benzylammonium chloride	10	2 000	250	200	25		
Piperidinium perchlorate	93					2.6×10^4	280
Piperidinium chloride	200					2.4×10^4	120

[a] In the presence of chloride ions these data are re-defined as $(K_{c.3})_{Cl^-}$ or $(K_{c.1})_{Cl^-}$. [b] Attack at 3-position.

pyrrolidinium perchlorate yielded a value for k_{AmH^+} of 2 400 ± 100 l mol^{-1} s^{-1}. The kinetic parameters thus give a value for $K_{c.3}$ of 240 l mol^{-1}, in good agreement with that obtained from equilibrium optical densities.

Measurements were also made giving the variation of rate coefficients with concentration of amine perchlorate at constant amine concentrations. The data (Table 12) are fitted well using the parameters obtained previously.

Rata data for the slower reaction involving deprotonation of the substrate are in Table 13. A plot of k_{obs} *versus* amine concentration was linear with an intercept indistinguishable from zero. The slope of the plot gives a value for k_p of 140 l mol^{-1} s^{-1}.

Discussion

Effects of Chloride Ions.—In general we have worked at a total salt concentration of 0.1M using either perchlorate or chloride salts. Comparisons are available for reactions involving butylammonium, benzylammonium, and piperidinium salts. The data in Table 14 show that the equilibrium constants for overall conversion of TNBCl into its 3-adduct, $K_{c.3}$, and into its 1-adduct, $K_{c.1}$, have higher values in the presence of chloride ions than in the presence of perchlorate. A similar effect of chloride ions has been observed in the reactions of 1,3,5-trinitrobenzene with aniline in the presence of diazabicyclo-octane (DABCO),[9] and in the reaction of 1,3,5-trinitrobenzene with piperidine,[1] and has been attributed to association of Cl^- with the substituted ammonium ions ($RR'NH_2^+ \cdots Cl^-$). We assume that the perchlorate ions with much more dispersed charge will not interact strongly with the substituted ammonium ions. We can include the effect of chloride ions on the reaction of parent (P) with amine as shown in Scheme 2. It is readily shown that the overall equilibrium constant for adduct formation in the presence of chloride ions, $(K_{c.3})_{Cl^-}$, is related by equation (14) to the value of $K_{c.3}$ in the absence of chloride ions and to the equilibrium constant, K_{Cl^-}, for association of ammonium ions with chloride ions. An exactly analogous equation applies to reaction at the 1-position. Our measurements show that the effect of 0.1M-chloride ion is approximately to double the values of measured equilibrium constants giving values of *ca.* 10 l mol^{-1} for the association constants, K_{Cl^-}, for each of the substituted ammonium ions used.

$$\begin{tikzcd}
\mathrm{P} + 2\mathrm{RR'NH} + \mathrm{Cl}^- \arrow[r, shift left, "K_{c.3}"] & (\mathrm{P.NRR'})^- + \mathrm{RR'NH_2}^+ + \mathrm{Cl}^- \arrow[l, shift left] \arrow[d, shift left, "K_{Cl^-}"] \\
& \mathrm{RR'NH_2}^+ \cdots \mathrm{Cl}^- \arrow[u, shift left]
\end{tikzcd}$$

Scheme 2.

$$(K_{c.3})_{Cl^-} = K_{c.3}(1 + K_{Cl^-}[Cl^-]) \qquad (14)$$

The data in Table 14 show that values of k_1, k_{Am}/k_{-1}, and K_3k_{Am} are unaffected, within experimental error, by chloride ions. However, values of k_{AmH^+} are reduced by a factor of *ca.* 2 in the presence of 0.1M-chloride ions. These observations are compatible with association of the substituted ammonium ions with chloride resulting in lower rates of protonation of the anionic σ-adducts.

Attack at Unsubstituted Ring Positions.—In the subsequent discussion we shall use values of equilibrium and rate constants obtained using perchlorate salts where association effects are unimportant. In Table 15 kinetic and equilibrium data for reaction at the unsubstituted 3-position of TNBCl are compared with similar data[1,5] for reaction at an unsubstituted position of the 1,3,5-trinitrobenzene ring (TNB). Data in the first five rows of this Table are either directly determined values or are directly calculated from these values. Data in the last two rows are based on the assumption that the ratio of acidities $K_a^Z/K_a^{AmH^+}$ has a value of 500 which is independent of the nature of the amine and that of the substrate. That this ratio will have a value greater than unity is expected since it is known[12,13] that the trinitrocyclohexadienide group, although negatively charged, is electron-withdrawing relative to hydrogen. A value of 500 has been justified previously[5,7] for reactions of 1,3,5-trinitrobenzene and we would not expect the ratio to vary considerably for TNBCl.

The ratios of $K_{c.3}$ values for reactions of TNB and TNBCl vary from 14 to 23 depending upon the amine. The inductive withdrawal of the CH_2Cl group might be expected to enhance the stability of the 3-adducts formed from TNBCl relative to TNB. However, the steric bulk of the CH_2Cl group will force the nitro-groups at the 2- and 6-position from the ring plane, so that they cannot exert their maximum electron-withdrawing influence. Similarly, 3-alkoxy adducts formed from TNBCl have lower stabilities[10] than those formed from TNB. The kinetic data in Table 15 show that decreases in the value of k_3, the rate coefficient for attack of amine on the substrate, account almost entirely for the decreased stabilities of the TNBCl adducts.

Values of $K_{c.3}$ decrease in the order pyrrolidine > piperidine > butylamine > benzylamine and largely reflect the

Table 15. Comparison of kinetic and equilibrium parameters for reaction at unsubstituted ring positions of TNBCl and 1,3,5-trinitrobenzene (TNB)

		Benzylamine[a]	n-Butylamine[a]	Pyrrolidine[b]	Piperidine[b]
k_3/l mol^{-1} s^{-1}	TNBCl	1 000	3 000	1.7×10^4	$>1.3 \times 10^4$
	TNB	13 000	45 000	7.5×10^5	$>2 \times 10^5$
K_3k_{Am}/l^2 mol^{-2} s^{-1}	TNBCl	1.4×10^5	$>3.0 \times 10^6$	5.8×10^5	2.6×10^4
	TNB	1.6×10^6	5.5×10^7	1.0×10^7	6×10^5
k_{Am}/k_{-3} (l mol^{-1})	TNBCl	140	>1 000	34	<2
	TNB	120	1 200	14	<10
$K_{c,3}$/l mol^{-1}	TNBCl	5	73	240	93
	TNB	105	1 000	3 500	2 140
k_{AmH^+}/l mol^{-1} s^{-1}	TNBCl[c]	3×10^4	$>4 \times 10^4$	2 400	280
	TNB	1.5×10^4	6×10^4	3 000	280
k_{Am}[d]/l mol^{-1} s^{-1}	TNBCl	1.5×10^7	$>2 \times 10^7$	1.2×10^6	1.4×10^5
	TNB	7.5×10^6	3×10^7	1.5×10^6	1.4×10^5
k_{-3}[d]/s^{-1}	TNBCl	1×10^5	2×10^4	3.5×10^4	$>7 \times 10^4$
	TNB	6×10^4	2.3×10^4	1×10^5	$>4.7 \times 10^4$

[a] Data for reaction with TNB from ref. 5. [b] Data for reaction with TNB from ref. 1. [c] For the benzylamine and butylamine cases this is calculated as $K_3k_{\text{Am}}/K_{c,3}$. [d] These data are based on the assumption that $K_a^{\text{Z}}/K_a^{\text{AmH}^+}$ has the value 500.

Table 16. Summary of kinetic and equilibrium data for formation of 1-adducts

	n-Butylamine	Benzylamine
k_1/l mol^{-1} s^{-1}	630	230
k_{Am}/k_{-1} (l mol^{-1})	2 000	200
$K_{c,1}$/l mol^{-1}	23 000	1 000
k_{AmH^+}/l mol^{-1} s^{-1}	55	46
k_{Am}[a]/l mol^{-1} s^{-1}	2.7×10^4	2.3×10^4
k_{-1}[a]/s^{-1}	13	110

[a] These values are calculated using $K_a^{\text{Z}}/K_a^{\text{AmH}^+}$ 500. We assume that the presence of the CH_2Cl group will not greatly affect the electron-withdrawing capability of the cyclohexadienide ring.

basicity order of the amines.[14,15] The reactivity order of the amines, k_3 values, parallels that obtained for S_NAr substitution of 1-chloro-2,4-dinitrobenzene in ethanol.[16]

Values of k_{Am} for proton transfer from zwitterion to amine, and k_{AmH^+} for proton transfer from substituted ammonium ions to anionic adducts are, for a given amine, almost identical for TNBCl and TNB. The reduction in value of k_{Am} below that expected for diffusion-controlled reaction has been attributed previously[5,7] to steric factors in that the reactive site is crowded and cannot be easily approached by bases larger than the hydroxide ion. The decreases in value of k_{Am} in the series primary amine > pyrrolidine > piperidine reflects increased steric hindrance. In the present case attack occurs at an unsubstituted ring position between two nitro-groups for both TNBCl and TNB so that the steric situation at the reaction site is similar for the two substrates. In fact the similarity in values with pyrrolidine and with pyridine is very strong evidence that the adduct-forming reaction we have studied involves attack at the 3-position rather than at the 1-position.

Attack at the 1-Position.—For butylamine and benzylamine we also observe attack at the 1-position carrying the CH_2Cl group. Data relating to this process are in Table 16. Values of the equilibrium constant $K_{c,1}$ are larger than $K_{c,3}$ by factors of 300 for butylamine and 200 for benzylamine. The values of the rate coefficient k_1 are smaller than k_3 by factors of *ca.* 5. These changes reflect the steric and electronic effects of the CH_2Cl group. The increases in value of the equilibrium constants largely reflect the relief of steric strain, present in the parent molecule, when the CH_2Cl group is bent from the ring plane. The nitro-groups at the 2- and 6-position are then able to become coplanar with the ring and exert their maximum electron withdrawal. An additional factor may be the inductive withdrawal by the CH_2Cl group. That attack is slower at the 1-position than the 3-position may be attributed to *F*-strain[17] (steric hindrance to the approach of the reagent).

Values of the rate coefficients, k_{Am} and k_{AmH^+}, relating to the proton-transfer steps, are reduced by factors of *ca.* 10^3 when reaction occurs at the 1-position. The presence of the CH_2Cl group at the reaction site causes an additional unfavourable steric effect.

The failure to observe 1-adducts with the secondary amines may be due to thermodynamic or kinetic factors. It might be argued that the presence of two very bulky groups, CH_2Cl and the piperidide group, at the same carbon atom, will create such a sterically crowded environment as to render production of such an adduct thermodynamically unfavourable. Recent work[18] has shown the large steric requirements of cyclic secondary amines, particularly piperidine. Some support for this view comes from the observation[19] that the bulky sulphite ion will attack only unsubstituted positions in the TNBCl ring. Also there is evidence[20] that 1,1-dialkoxy adducts become relatively less favoured than their 1,3-isomers as the steric bulk of the alkoxy groups increases. Alternatively the 1-adducts from piperidine and pyrrolidine and TNBCl may have greater thermodynamic stability than their 3-isomers but the rate of their formation may be reduced to such an extent that the transfer of the side-chain proton to form the conjugate base takes precedence.

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