Aromatic Nucleophilic Substitution Reactions of 1,2-Dinitrobenzene with Aliphatic Primary Amines in n-Hexane; Catalysis by Non-nucleophilic Bases

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The kinetics of the reactions of 1,2-dinitrobenzene with n-butyl-, s-butyl-, isobutyl-, n-propyl-, and isopropyl-amine in n-hexane at various temperatures have been investigated. The second-order rate coefficients for these reactions increase linearly with the amine concentrations. The values of the ratio of the rate constant for the catalysed process to the rate constant of the uncatalysed step $[k_3^{RNH_2}/k_2]$ are dependent on temperature, so that it is possible to minimize the catalysed or uncatalysed processes simply by temperature variation. Kinetic studies in the presence of non-nucleophilic bases [pyridine, triethylamine (TEA), and tributylamine (TBA)] confirmed the proposal that all these reactions are base-catalysed even for the cases where $k_3^{RNH_2}/k_2$ is less than 50. The role that electron donor–acceptor complex formation between reactants may play in the mechanism of these reactions is discussed. The influence of electronic and steric effects in the amine structure on the catalytic rate constant has been analysed. It has been shown that the catalysed step is disfavoured by electron-donating substituents and that it is inhibited by steric hindrance. The studies with the addition of the bulky bases TEA and TBA confirmed these conclusions.

It is well known that a nitro group *ortho* to electron-withdrawing groups (in general nitro groups) in an aromatic compound can be readily replaced by nucleophilic reagents.[1–][10] Most of the studies of this reaction have been performed with anionic nucleophiles, in protic or aprotic solvents. The use of aliphatic amines as nucleophiles in non-polar solvents is less common.[2,6,7,10] In the latter cases typical aromatic nucleophilic substitutions (S_NAr) have been reported for the denitration reaction; mechanisms involving either base catalysis[6] or spontaneous decomposition of the anionic intermediate have been proposed.[2] In addition, examples are known where no direct replacement of the nitro group occurs,[7] although these reactions are base catalysed.

The typical S_NAr mechanism[11] when aliphatic amines are the nucleophiles and 1,2-dinitrobenzene (1,2-DNB) is the aromatic substrate can be represented as in Scheme 1. Application of the steady-state hypothesis to this mechanism gives equation (i), where k_A is the observed second-order rate constant and B_i is the nucleophile or any base added to the reaction medium.

$$k_A = \frac{k_1(k_2 + \sum_i k_3^{B_i}[B_i])}{k_{-1} + k_2 + \sum_i k_3^{B_i}[B_i]}$$ (i)

Recently, we have reported a kinetic study of the reaction of n-butylamine with 1,2-DNB in n-hexane.[12] A base-catalysed S_NAr mechanism was proposed ($k_2 + k_3^{B_i}[B_i] \ll k_{-1}$). Previous studies on the formation of electron donor–acceptor (EDA) complexes between aliphatic amines as *n* donors and cyano- and nitro-substituted benzenes as π acceptors[13] had raised the question of the role that the EDA complexes between the reactants might play in S_NAr. Since 1,2-DNB forms relatively strong complexes with respect to other aromatic dinitro compounds (1,3- and 1,4-DNB) with secondary and tertiary amines in n-hexane,[13] it is considered that such complexes are also formed with primary amines. However the role of the complexes in the reaction studied[12] was not kinetically distinguishable. In addition, studies of the substitution of 1,2-DNB by piperidine in n-hexane have shown that the reaction follows a wholly base-catalysed S_NAr mechanism.[14] The curvilinear dependence of k_A on the concentration of piperidine
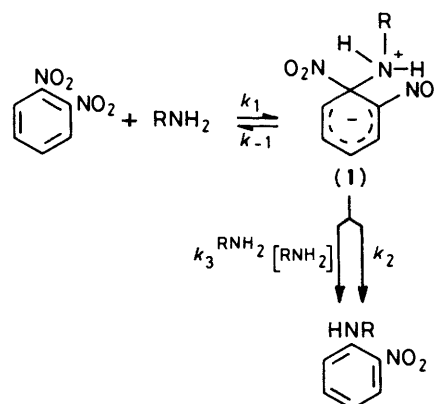

Scheme 1.

(Pip) was explained in terms of formation of an EDA complex (1,2-DNB–Pip) prior to the formation of the σ intermediate.

Following this line of work, we report now studies on the reactions of 1,2-DNB with other primary aliphatic amines: n-propylamine, isopropylamine, isobutylamine, and s-butylamine in n-hexane as solvent. Our aim was to determine the electronic and steric effects that the amine structure might have on the reaction rates and the mechanisms of catalysis. The influence of addition of non-nucleophilic bases such as pyridine (Py), triethylamine (TEA), and tributylamine (TBA) was also studied, in order to obtain further information on the catalysis mechanism. The role of EDA complexes in these reactions was also analysed.

Moreover, we propose an alternative method of calculation of the values of the kinetic parameters, when the plot of k_A against amine concentration is linear. This enables an improved estimate of the intercept of such plots to be made, particularly when the value is very small. Thus the studies of the reaction of 1,2-DNB with Bu^nNH_2[12] have been extended.

Results and Discussion

The substrate 1,2-DNB gave the corresponding *N*-alkyl-2-nitroaniline on treatment with Pr^nNH_2, Pr^iNH_2, Bu^nNH_2,

Scheme 2.
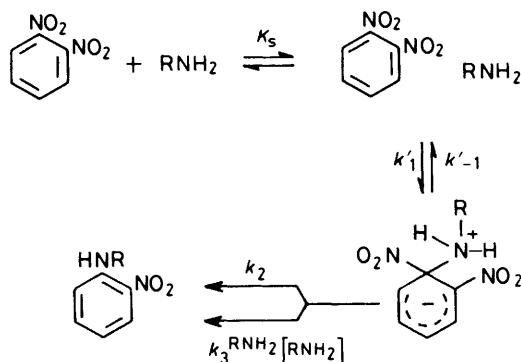
Bu^{i}NH$_2$, or Bu^{s}NH$_2$ in n-hexane, in quantitative yield as shown by t.l.c. and u.v.–visible spectroscopic analysis of the reaction mixtures.

If our previous proposal[14] of the formation of one EDA complex of the 1,2-DNB with the amine prior to the intermediate (1) is applied, Scheme 1 becomes Scheme 2.

The expression of k_A for this mechanism is given in equation (ii), where k_ψ is the observed pseudo-first-order rate constant.

$$k_A = \frac{k_\psi}{[\text{RNH}_2]} = \frac{k'_1 K_s k_2 + k'_1 K_s k_3^{\text{RNH}_2}[\text{RNH}_2]}{(k'_{-1} + k_2 + k_3^{\text{RNH}_2}[\text{RNH}_2])(1 + K_s[\text{RNH}_2])} \tag{ii}$$

The values of k_ψ and k_A obtained for the substitution of 1,2-DNB by amines in n-hexane at different amine concentrations and temperatures are collected in Table 1. The values of k_A increase linearly with amine concentration [equation (iii)].

$$k_A = k'_2 + k'_3[\text{RNH}_2] \tag{iii}$$

Following Bernasconi's treatment,[11e] the linear relationship of k_A with base concentration can be rationalized by assuming that $k_3^{\text{RNH}_2}[\text{RNH}_2] \ll (k_{-1} + k_2)$ and $k_2 \ll k_{-1}$; furthermore the mechanism given in Scheme 2 means that $K_s[\text{RNH}_2] \ll 1$. Then equation (ii) can be written as equation (iv), which gives $k_3^{\text{RNH}_2}/k_2$ from experimental k'_2 and k'_3 values (the uncatalysed and catalysed constants, respectively).

$$k_A = \frac{k_\psi}{[\text{RNH}_2]} = \frac{k'_1 K_s k_2}{k'_{-1}} + \frac{k'_1 K_s k_3^{\text{RNH}_2}[\text{RNH}_2]}{k'_{-1}} \tag{iv}$$

Bunnett[11d] favours a value of $k_3^{\text{RNH}_2}/k_2 > 50$ as a test for the presence and importance of the catalysed process, to avoid confusion with variation due to medium changes where $k_3^{\text{RNH}_2}/k_2$ is expected to be 5 or less. The cases where the values of $k_3^{\text{RNH}_2}/k_2$ are between these limits must be carefully analysed before any conclusions are reached.

When the data were processed to calculate $k_3^{\text{RNH}_2}/k_2$ through linear plots and equation (iv), we observed that, since k_2 was rather small, the intercepts were small and small variations in the calculated values of k_A gave, for the same reaction, values of $k_3^{\text{RNH}_2}/k_2$ that could be accommodated very easily by either base-catalysed or uncatalysed reactions.

Equation (iv) is derived by dividing equation (v) by [RNH$_2$],

$$k_\psi = k'_2[\text{RNH}_2] + k'_3[\text{RNH}_2]^2 \tag{v}$$

with consequent loss in sensitivity. Thus the values of k'_2 and k'_3 could be calculated by fitting the experimental k_ψ values with [RNH$_2$] through equation (v) by a least-squares procedure. The results are shown in Table 2. Graphical

representation of the experimental data (k_ψ vs. [RNH$_2$]) through equation (v) allowed us to detect readily those experiments that presented serious experimental errors and which should be disregarded and repeated.

Table 2 shows that the values of $k_3^{\text{RNH}_2}/k_2$ at room temperature (27 °C) for some of the systems are lower than 50. In some cases (e.g. Pr^{i}NH$_2$-1,2-DNB) the value is so low that the existence of base catalysis becomes very doubtful. However kinetic studies in the presence of non-nucleophilic bases (see below) lead us to presume that these reactions are actually base-catalysed.

When we compare the values of $k_3^{\text{RNH}_2}/k_2$ at 27 °C (Table 2) with data for the reaction of 1,2-DNB with piperidine in n-hexane, where the uncatalysed step (k_2) is not detected[14] at the same temperature, it is readily recognized that the secondary amine is more prone to base catalysis than the primary aliphatic amines of comparable basicity, as shown for S_NAr of a nitro-substituted compound with aliphatic amines in benzene.[15]

From studies of temperature effects on k'_3 the activation parameters collected in Table 3 were calculated. They show relatively low $\Delta H^\neq$ and large negative $\Delta S^\neq$ values. These values are consistent with the complexity of the proposed mechanism. It is interesting that similar values were obtained for the reaction of 2-fluoro-6-nitrobenzothiazole with aliphatic amines in benzene;[16] it was suggested that some pre-equilibrium association between reactants should be considered, although no direct evidence was obtained.

The values of k'_2 and k'_3 are influenced differently by increasing temperature, so that it is possible to minimize the catalysed or uncatalysed process by temperature variations. Similar effects have been observed in the amino-substitution of 2-fluoro-6-nitrobenzothiazole in benzene.[16]

On the other hand, in support of the idea of EDA complex formation prior to formation of the intermediate (1) (Scheme 2), the absorbance of the reaction mixtures, extrapolated to zero time of reaction, showed an appreciable deviation from additivity with respect to the absorbances of the components alone in the region λ 290—300 nm. These characteristics were also observed for the system Pip–1,2-DNB.[14] The equilibrium constant for the system Pr^{i}NH$_2$-1,2-DNB was calculated by the method previously described[13a,b] and a value of $K_s = 0.16 \pm 0.04$ dm^3 mol^{-1} at 27 °C was obtained. If we compare this value with that obtained at the same temperature for the system Pip–1,2-DNB[14] ($K_s = 0.55 \pm 0.05$ dm^3 mol^{-1}) we can explain why in the latter case k_A vs. [Pip] shows a downward curvature, whereas for Pr^{i}NH$_2$-1,2-DNB, where K_s is much smaller, a linear dependence is expected since the condition $K_s[\text{RNH}_2] \ll 1$ for equation (ii) is fulfilled.

Amino Substitution of 1,2-DNB in the Presence of Non-nucleophilic Bases.—These studies were performed for the reactions of 1,2-DNB with Pr^{i}NH$_2$ and Bu^{n}NH$_2$, and Py, TEA, and TBA were used as added bases. The results are shown in Table 4.

On addition of Py the rates of all these reactions are enhanced in proportion to the initial amount of Py. To fit the experimental data equation (iv) becomes equation (vi) where

$$k_A = k''_3 + k'_3{}^{\text{Py}}[\text{Py}] \tag{vi}$$

$k''_3 = k'_1 K_s k_2/k'_{-1} + k'_1 K_s k_3^{\text{RNH}_2}/k'_{-1}$ and $k'_3{}^{\text{Py}} = k'_1 K_s k_3^{\text{Py}}/k'_{-1}$. An evaluation by least-squares methods leads to a value of $k'_3{}^{\text{Py}}$ for the system Pr^{i}NH$_2$-1,2-DNB of $(0.32 \pm 0.03) \times 10^{-4}$ dm^6

mol^{-2} s^{-1} ($r = 0.9990$) and for the system Bu^nNH_2–1,2-DNB of $(7.10 \pm 0.05) \times 10^{-4}$ ($r = 0.9991$). Since $k_3^{Py}/k_3^{Pr^iNH_2} = 1.8 \pm 0.4$ and $k_3^{Py}/k_3^{Bu^nNH_2} = 1.6 \pm 0.4$ the catalytic power of Py is seen to be higher than that of the amine used. The fact that Py seems to be a better catalyst than the primary amines cannot be explained by the mechanism proposed by Bunnett and Davies,[17] since the basicity of Py has been demonstrated to be much lower than that of some primary amines (e.g. Bu^nNH_2) in non-polar solvents.[18] The mechanisms proposed for reaction in these solvents have been modifications

Table 1. Rates of reactions between 1,2-DNB (ca. 10^{-4}M) and primary amines in n-hexane at various temperatures

T 17.0 ± 0.5 °C

$[Bu^nNH_2]$/M	0.10	0.20	0.30	0.35	0.41	0.50	0.55	0.60	0.65
$10^5 k_\psi$/s^{-1}	0.33	1.13	2.75	3.78	4.81	7.65	9.20	11.90	13.10
$10^5 k_A$/s^{-1} dm³ mol^{-1}	3.3	5.6	9.2	10.8	11.7	15.3	16.7	19.8	20.1

T 37.5 ± 0.5 °C

$[Bu^nNH_2]$/M	0.05	0.05	0.07	0.10	0.12	0.15	0.21	0.25	0.30	0.50
$10^5 k_\psi$/s^{-1}	0.36	0.32	0.44	0.60	1.52	1.79	3.50	4.86	7.20	17.30
$10^5 k_A$/s^{-1} dm³ mol^{-1}	7.2	6.4	6.2	6.0	12.6	11.9	16.7	19.4	24.0	34.6
$[Bu^nNH_2]$/M	0.60	0.70	0.80	1.00						
$10^5 k_\psi$/s^{-1}	26.00	34.30	44.10	65.50						
$10^5 k_A$/s^{-1} dm³ mol^{-1}	43.3	49.0	55.1	65.5						

T 18.5 ± 0.5 °C

$[Bu^iNH_2]$/M	0.10	0.20	0.30	0.40	0.50	0.60
$10^5 k_\psi$/s^{-1}	0.14	0.58	1.24	2.11	3.40	5.11
$10^5 k_A$/s^{-1} dm³ mol^{-1}	1.4	2.9	4.1	5.3	6.8	8.5

T 27.5 ± 0.5 °C

$[Bu^iNH_2]$/M	0.10	0.20	0.30	0.38	0.40	0.50	0.60
$10^5 k_\psi$/s^{-1}	0.27	0.99	1.82	2.66	3.27	5.27	7.27
$10^5 k_A$/s^{-1} dm³ mol^{-1}	2.7	5.0	6.0	7.1	8.2	10.6	12.1

T 43.5 ± 0.5 °C

$[Bu^iNH_2]$/M	0.20	0.30	0.40	0.50	0.60
$10^5 k_\psi$/s^{-1}	1.96	3.77	6.28	9.34	12.90
$10^5 k_A$/s^{-1} dm³ mol^{-1}	9.8	12.6	15.7	18.7	21.5

T 27.2 ± 0.5 °C

$[Bu^sNH_2]$/M	0.40	0.55	0.60	0.60	0.65	0.70	0.75	0.78	0.80	0.85	0.90
$10^6 k_\psi$/s^{-1}	3.33	5.30	6.49	6.64	7.58	8.66	9.98	10.84	11.34	12.48	14.65
$10^6 k_A$/s^{-1} dm³ mol^{-1}	8.3	9.6	10.8	11.1	11.7	12.4	13.3	13.9	14.2	14.7	16.3

T 37.7 ± 0.5 °C

$[Bu^sNH_2]$/M	0.30	0.40	0.48	0.50	0.60	0.70	0.75	0.80	0.90
$10^6 k_\psi$/s^{-1}	3.33	5.12	6.41	7.5	9.97	12.82	14.95	17.95	21.56
$10^6 k_A$/s^{-1} dm³ mol^{-1}	11.1	12.8	13.3	15.0	16.6	18.3	19.9	22.4	24.0

T 45.0 ± 0.5 °C

$[Bu^sNH_2]$/M	0.20	0.25	0.30	0.45	0.55	0.70	0.80
$10^6 k_\psi$/s^{-1}	2.68	3.96	4.90	9.81	13.72	20.59	26.26
$10^6 k_A$/s^{-1} dm³ mol^{-1}	13.4	15.8	21.8	24.9	29.4	32.8	

T 27.0 ± 0.5 °C

$[Pr^nNH_2]$/M	0.20	0.24	0.30	0.30	0.35	0.40	0.45	0.50
$10^5 k_\psi$/s^{-1}	1.46	2.21	3.22	3.05	4.41	5.89	7.47	9.12
$10^5 k_A$/s^{-1} dm³ mol^{-1}	7.3	9.2	10.7	10.2	12.6	14.7	16.6	18.2

T 36.5 ± 0.5 °C

$[Pr^nNH_2]$/M	0.10	0.20	0.30	0.40	0.50
$10^5 k_\psi$/s^{-1}	0.56	2.15	4.82	8.76	13.15
$10^5 k_A$/s^{-1} dm³ mol^{-1}	5.6	10.7	16.1	21.9	26.3

T 51.5 ± 0.5 °C

$[Pr^nNH_2]$/M	0.10	0.20	0.30	0.31	0.40	0.50
$10^5 k_\psi$/s^{-1}	1.28	3.76	9.26	10.37	14.86	23.49
$10^5 k_A$/s^{-1} dm³ mol^{-1}	12.8	18.8	30.9	33.4	37.1	47.0

T 18.0 ± 0.5 °C

$[Pr^iNH_2]$/M	0.30	0.37	0.40	0.50	0.59	0.60	0.60	0.61	0.70	0.80	0.90
$10^6 k_\psi$/s^{-1}	1.54	2.25	2.46	3.84	4.99	5.17	5.61	5.62	7.47	8.96	11.20
$10^6 k_A$/s^{-1} dm³ mol^{-1}	5.1	6.1	6.2	7.7	8.5	8.6	9.3	9.2	10.7	11.2	12.4

Table 1 (*continued*)

$T\ 27.4 \pm 0.5\ °C$

$[Pr^iNH_2]$/M	0.20	0.30	0.31	0.40	0.50	0.50	0.60	0.65	0.70	0.70	0.77
$10^6 k_\psi/s^{-1}$	0.99	2.36	2.06	4.17	5.76	6.40	8.55	8.45	10.07	11.08	12.89
$10^6 k_A/s^{-1}\ dm^3\ mol^{-1}$	4.9	7.9	6.6	10.4	11.5	12.8	14.2	13.0	14.4	15.8	16.7
$[Pr^iNH_2]$/M	0.80	0.92	1.00	1.00	1.00	1.00					
$10^6 k_\psi/s^{-1}$	13.61	18.14	20.62	20.61	20.96	20.62					
$10^6 k_A/s^{-1}\ dm^3\ mol^{-1}$	17.0	19.7	20.6	20.6	20.9	20.6					

$T\ 44.0 \pm 0.5\ °C$

$[Pr^iNH_2]$/M	0.10	0.21	0.31	0.40	0.45	0.50	0.55	0.60	0.65
$10^6 k_\psi/s^{-1}$	0.92	2.75	5.16	8.57	10.74	12.39	14.46	17.50	19.28
$10^6 k_A/s^{-1}\ dm^3\ mol^{-1}$	9.2	13.1	16.6	21.4	23.9	24.8	26.3	29.1	29.7

Table 2. Regression analysis of k_ψ for the reactions of 1,2-DNB with primary aliphatic amines in n-hexane by equation (v)

Amine	T/°C	$10^4 k'_2/$ $s^{-1}\ dm^3\ mol^{-1}$	$10^4 k'_3/$ $s^{-1}\ dm^6\ mol^{-2}$	$k_3^{RNH_2}k_2^{-1}/$ $mol^{-1}\ dm^3$	$10^4\sigma^a$	$F(1, n-2, k'_2 = 0)^b$	$F(1, n-2, 0.005)^c$	n^d
Bu^nNH_2	17.0 ± 0.5	0	3.03	∞	0.1			9
	27.0 ± 0.5^e	0	4.58	∞	0.1	0.259	4.317	8
	37.5 ± 0.5	0.54	6.10	11	0.05	91.24	3.428	14
Bu^iNH_2	18.5 ± 0.5	0	1.38	∞	0.1			6
	27.5 ± 0.5	0.014	2.01	150	0.005	0.003	4.773	7
	43.5 ± 0.5	0.375	2.95	8	0.007	7.57	7.453	5
Bu^sNH_2	27.2 ± 0.5	0.010	0.164	15	0.002	38.6891	3.690	11
	37.0 ± 0.5	0.031	0.230	7	0.004	30.0761	4.029	9
	45.0 ± 0.5	0.076	0.312	4	0.006	322.11	4.773	7
Pr^nNH_2	27.0 ± 0.5	0	3.66	∞	0.01			8
	36.5 ± 0.5	0.07	5.16	69	0.03	0.0086	7.453	6
	51.5 ± 0.5	0.47	8.44	17	0.05	0.0370	5.598	6
Pr^iNH_2	18.0 ± 0.5	0.010	0.122	9	0.003	36.1575	3.690	11
	27.4 ± 0.5	0.028	0.177	6	0.005	671.83	3.285	17
	44.0 ± 0.5	0.066	0.366	5	0.005	965.689	4.029	9

^{a} Standard deviations. ^{b} F Values of the correlation calculated with $k'_2 = 0$. ^{c} Tabulated F values for the 99.5% confidence level; note that if this value is smaller than the calculated F value the hypothesis $k'_2 = 0$ can be disregarded. ^{d} Number of points. ^{e} Data from ref. 12.

Table 3. Activation parameters on the basis of k'_3 for reactions of 1,2-DNB with primary aliphatic amines in n-hexane^a

Amine	$\Delta H^{\ddagger}$/kJ mol^{-1}	$\Delta S^{\ddagger}$/J mol^{-1} K^{-1}
Bu^nNH_2	22 ± 2	-224 ± 3
Bu^iNH_2	20 ± 3	-239 ± 6
Bu^sNH_2	26 ± 1	-242 ± 6
Pr^nNH_2	25 ± 1	-218 ± 1
Pr^iNH_2	30 ± 1	-227 ± 1

^{a} At 25 °C.

of Bunnett's mechanism, whereby because of the strength of electrostatic forces in solvents of low dielectric constant, reaction takes place within aggregates. Thus, for non-polar solvents, catalysis by Py would be observed if heteroconjugation occurred between the conjugate acid of the nucleophile and Py, and the heteroconjugate participated in electrophilic catalysis of departure of a leaving group.[18] The latter mechanism is a particular case of the one we proposed for catalysis by Py in the piperidinodenitration of 1,2-DNB in n-hexane,[14] where we consider that the actual catalyst is the hydrogen-bonded dimer of the aliphatic amine with Py. In this case the same reasoning is applicable.

Although 1,2-DNB forms an EDA complex with Py in n-hexane[14] as observed for reaction of Pip–1,2-DNB, this side reaction does not seem to have any detectable effect on the kinetics of the reaction.

The value of K_s for the EDA complex Py–1,2-DNB is small enough (0.30 ± 0.03) to ensure that the curvilinear dependence

which may be expected when the term $K_s[Py]$ is introduced into equation (ii) is not observed.

The results of the kinetic studies of the reactions of 1,2-DNB with Bu^nNH_2 in the presence of TEA and TBA are collected in Table 4. The amines TEA and TBA are rather bulky non-nucleophilic bases and the reactions were expected to show steric effects. Table 4 shows that these bases do not catalyse the reactions but exhibit small inhibition effects which exceed experimental error.

The absence of catalysis can be explained by considering that the steric hindrance reduces the catalytic power of the relatively strong bases, which also have no hydrogen atoms to perform bifunctional catalysis. From comparison of the catalytic power of different amines, Frenna *et al.* consider that the tertiary amines can be effective catalysts only if the steric interactions are low.[19]

Correlations of the Rate Constants with the Structures of the Amines.—A simple inspection of the values of the rate constants, both k'_2 and k'_3, in Table 2, and the studies with non-nucleophilic bases, show that steric effects may play an important role in the uncatalysed and catalysed processes of these reactions. It is also well known that the reactivity of aliphatic amines towards lone-pair acceptors is generally governed by the polar and steric effects of the three N-substituents.[20-23]

The electronic effects of the N-substituents on a rate constant can be interpreted by means of equation (vii), where $\Sigma\sigma^*$ is the

$$\log k = \rho^* \Sigma\sigma^* + c \qquad (vii)$$

Table 4. Kinetic data for the reactions of 1,2-DNB with Bu^nNH_2 and Pr^iNH_2 in n-hexane in the presence of non-nucleophilic bases

$[Bu^nNH_2] = 0.608M$; T 27.0 ± 0.5 °C

[Py]/M	0.00	0.12	0.25	0.37
$10^4 k_A/s^{-1}$ dm³ mol⁻¹	2.4	3.2	4.2	5.0

$[Bu^nNH_2] = 0.594M$; T 27.0 ± 0.5 °C

[TEA]/M	0.00	0.20	0.40	0.40	0.60	0.65	0.80	0.80	1.00	1.20
$10^4 k_A/s^{-1}$ dm³ mol⁻¹	2.7	2.7	2.6	2.6	2.6	2.6	2.5	2.4	2.5	2.4

$[Bu^nNH_2] = 0.594M$; T 27.0 ± 0.5 °C

[TBA]/M	0.00	0.10	0.21	0.30	0.42
$10^4\ k_A/s^{-1}$ dm³ mol⁻¹	2.7	2.6	2.5	2.4	2.3

$[Pr^iNH_2] = 0.601M$; T 27.0 ± 0.5 °C

Py/M	0.00	0.10	0.20	0.30
$10^6 k_A/s^{-1}$ dm³ mol⁻¹	13.4	16.4	19.0	21.2

Table 5. Values of log k'_3 and substituent parameters

Amine	log k'_3	$\Sigma\sigma^{*a}$	$E_s^{c\ a}$
Bu^nNH_2	−3.34	0.85	−0.71
Bu^iNH_2	−3.70	0.855	−0.66
Bu^sNH_2	−4.80	0.77	−1.74
Pr^nNH_2	−3.44	0.865	−0.70
Pr^iNH_2	−4.74	0.79	−1.24

[a] From Table IV of Ref. 25b.

summation of the Taft σ^* values of the three N-substituents,[20] ρ^* is the susceptibility constant, and c is the intercept.

In order to obtain some idea of how the electronic factors can influence the catalytic decomposition of the intermediate (1), we correlated the values of k'_3 by use of equation (vii). The values of $\Sigma\sigma^*$ used are shown in Table 5.

A positive value of ρ^* (16.0; $r = 0.9640$) was obtained. However the value is too high and the correlation is not very satisfactory. These facts are taken as an indication that steric factors should also be considered and included in the correlation. This can be done by introducing into equation (vii) a new parameter, such as the E_s^c, Hancock's corrected steric constant[24,25] for the alkyl substituents (Table 5). However, the values of E_s^c are difficult to apply to the properties of aliphatic amines; several approximations have been proposed.[25] The problems are to determine which is the 'site of reaction' and the fact that the steric effects of the three N-substituents are not additive, even for primary amines. This approach requires the use of multiparametric equations,[25b] for which at present we have insufficient data.

Nevertheless, for the correlation in equation (vii), we can see that a positive value of ρ^* shows that the catalysed step is favoured by electron-withdrawing N-substituents while electron-donating N-substituents disfavour it.

Opposite electronic effects have been found[26-28] for the catalysed and uncatalysed rate constants for S_NAr of ortho-nitro aromatic compounds with substituted anilines as nucleophiles and catalysts. High negative ρ^* values for the process measured by the catalytic rate constant (k_3^{Bi}) for the reaction between 1-fluoro-2,4-dinitrobenzene and ring-substituted anilines in tetrahydrofuran seem to indicate that the usually accepted mechanism of a base-catalysed step is not operating in this case.[26] However, strong steric inhibition was clearly observed when N-methyl-substituted anilines were used as catalysts.[26,27]

Substituent effects investigated through Hammett plots for the uncatalysed and catalysed rate constants of the reactions of anilines with phenyl 2,4,6-trinitrophenyl ether in benzene[29] showed that ρ^* was high and negative but smaller for the

uncatalysed reaction and consequently less sensitive to electron-donating substituents. The proposed mechanism of catalysis for this case involves a cyclic transition state.

A comparison of the S_NAr processes for aliphatic amines and aromatic amines seems not very reasonable, at least at this stage, since for the known reactions the electronic requirements seem to be different. This point is now under investigation.

With respect to steric effects (although we were not able to quantify them), it is easily recognized from the data in Table 5 that branching on the N-alkyl substituents slow down the catalysed step; this effect is particularly strong for Bu^sNH_2 and Pr^iNH_2 compared with the unbranched homologues. Also, although the E_s^c values (Table 5) are quite different, it appears that the steric effect of Bu^s is very similar to that of the Pr^i, at least for these reactions.

The fact that Bu^sNH_2 and Pr^iNH_2 seem to have the same steric effects can be rationalized by considering that α-methyl branching is the only significant effect. Rotation around the N–C axis would mask other steric effects.[25b] A similar effect of α-methyl branching is shown in the depression by steric hindrance of the uncatalysed and base-catalysed steps of amine substitutions of 2-fluoro-6-nitrobenzothiazole in benzene.[16] Moreover, larger differences are observed for the more rigid piperidine system than for butylamine.

An interesting example of the importance of steric effects with respect to electronic effects was observed[10] when the nature of the products of the reactions of amines with 1,2,3,4-tetrachloro-5,6-dinitrobenzene was investigated. Primary amines reacted by displacing a nitro group, whereas acyclic secondary amines, in general, reacted by replacing a chlorine atom from a position ortho to a nitro group. The results were rationalized in terms of the predominance of steric over electronic factors. In these examples the aromatic amines seem to give 'anomalous' results.

Recently, important steric effects have been observed for the base-catalysed step of S_NAr of 1-fluoro-4-nitrobenzene by aliphatic amines in aprotic solvents; this has been explained by considering that the power of bulky amines to act as a hydrogen-bond-acceptor catalyst is strongly reduced.[29] On the other hand it might be expected that the catalysed step is highly influenced by steric factors if the amine is acting as bifunctional catalyst.[16]

Thus, in agreement with our results and in view of the non-polar character of the solvent, n-hexane ($\pi^* = -0.08$),[30] we propose a mechanism of catalysis in which the second molecule of amine acts as a bifunctional catalyst within aggregates of conveniently oriented charged and dipolar species.[31] Since the nucleophile is a primary amine it is expected that within the aggregate the transfer of a proton will be fast and followed by slow electrophilically catalysed leaving-group expulsion.

The mechanism of the uncatalysed process involves a transfer of an ammonium proton to the leaving group. Comparison with the results for piperidinodenitration of 1,2-DNB[14] showed the trend predicted that aliphatic secondary amines require more catalysis than primary ones.[15]

The effect of α-branching in the primary amines in decreasing k_2' values is probably a result of increasing k_{-1} via steric hindrance, despite the electronic effect of the alkyl group. The effect of α-branching in the amine would be more noticeable for bulkier leaving groups.[32]

Experimental

Materials.—n-Hexane (Mallinckrodt), 1,2-DNB (Fluka), Bu^nNH_2 (Riedel), Pr^nNH_2 (Riedel), Pr^iNH_2 (Fluka), Bu^iNH_2 (Aldrich), Bu^sNH_2 (Aldrich), TEA (Fluka), TBA (Riedel), and Py (Carlo Erba) were purified as previously described.[13,14]

Kinetic Measurements.—The reactions were performed by following the increase in absorbance at the visible absorption maximum of the N-alkyl-2-nitroaniline over at least three half-lives. A Cary 17 spectrophotometer was used with 1 cm thermostatically controlled cells.

When the reactions were too slow ($[RNH_2] \leqslant 0.3M$) the initial rates method was employed, with A_t vs. t plots showing good linearity up to at least 3% reaction. At 0.3M amine the two methods gave the same constant within experimental error ($\pm 4\%$).

In all cases pseudo-first-order kinetics were observed. Standard solutions of the reactants were prepared in n-hexane as solvent at room temperature. The reactions were run by mixing known amounts of the solutions (at controlled temperature) and delivering them into a 10 ml volumetric flask. The mixture was shaken, the flask was filled with solvent; one portion was introduced into a cell and the other kept in a 5 ml volumetric flask filled up to the mark and set aside for later determination of the infinity absorbance value, A_∞. In all cases, this value was determined experimentally for each run at the working temperature. The final spectrum of the reaction mixture always matched within $\pm 3\%$ that of a solution corresponding to 100% formation of the corresponding N-alkyl-2-nitroaniline.

For each system representative kinetic runs were carried out recording the whole u.v.–visible spectrum at different times; two isosbestic points were detected. The same behaviour was observed when the reactions were performed with addition of non-nucleophilic bases. The occurrence of the isosbestic points is good evidence that competing reactions are absent.[33]

To determine EDA complex formation constants a u.v. spectrophotometric method described previously[13,14] was used.

Calculations.—Data processing was performed with a Digital PDP 11/34 computer. Computer programs are available by writing to J. J. S.

Synthesis, Purification, and Characterization of Products.—N-Alkyl-2-nitroanilines were prepared by reactions of 1,2-DNB (100 mg, 6 mmol) with the neat amines (60 mmol) at room temperature. Reaction was complete within a few minutes as established by following the disappearance of 1,2-DNB by t.l.c. [silica gel F_{254} with benzene–light petroleum (1:1) as solvent]. The reaction mixture was then treated with light petroleum and the organic layer was washed with water and dried (Na_2SO_4). The organic solution was eluted with light petroleum through silica gel (Carlo Erba) and then evaporated to give an orange oil (average yield 60%). The structures of the products are fully supported by ¹H n.m.r. and mass spectra.

¹H N.m.r. spectra were obtained with a Bruker X-60

instrument and the mass spectra with a Finnigan 3300 spectrometer.

N-Butyl-2-nitroaniline was previously characterized by u.v.–visible and ¹H n.m.r. spectrometry;[12] m/z 194 (41%, M^+), 195 (20, $M + 1$), 196 (2.3, $M + 2$), 193 (4, $M - H$), 165 (3, $M - C_2H_5$), 151 (100, $M - C_3H_7$), 135 (6, $M - C_3H_7 - O$), 133 (6, $M - C_3H_7 - H_2O$), 121 (11, $M - OC_4H_9$), 106 (20, $M - OC_4H_9 - NH$), and 93 (48, $M - C_3H_7 - NO - CO$).

N-Isobutyl-2-nitroaniline showed $\lambda_{max.}$ (n-hexane) 412 nm (log ε 3.84); δ(Cl_4C, standard Me_4Si) 1.03 [6 H, d, C $(CH_3)_2$], 2.00 (1 H, m, HC), 3.06 (2 H, m, CH_2), 8.05 (1 H, br s, NH), and 6.58 (2 H, m), 7.28 (1 H, m) and 8.05 (1 H, m) (aromatics); m/z 194 (11, M^+), 151 (100, $M - C_3H_7$), 127 (2, $M - NO_2H$), 135 (4, $M - OC_4H_9$), and 93 (28, $M - OC_4H_7 - CO$).

N-s-Butyl-2-nitroaniline showed $\lambda_{max.}$ (n-hexane) 412 nm (log ε 3.89); δ(Cl_4C, standard Me_4Si) 0.99 (3 H, t, CH_3), 1.63 (2 H, m, CH_2), 3.62 (1 H, m, CH), 1.20 (3 H, d, CH_2), 7.95 (1 H, br s, NH), and 6.62 (2 H, m), 7.33 (1 H, m), and 8.08 (1 H, m) (aromatics); m/z 194 (26, M^+), 179 (3, $M - CH_3$), 165 (100, $M - C_2H_5$), and 135 (5, $M - C_2H_5 - NO$).

N-Isopropyl-2-nitroaniline showed $\lambda_{max.}$ (n-hexane) 408 nm (log ε 3.81); δ(Cl_4C, standard Me_4Si) 1.28 [6 H, d, $(CH_3)_2$], 3.72 (1 H, m, CH), 7.97 (1 H, br s, NH), and 6.60 (2 H, m), 7.30 (1 H, m), and 8.06 (1 H, m) (aromatics); m/z 180 (42, M), 165 (100, $M - CH_3$), 147 (17, $M - CH_3 - OH_2$), 135 (15, $M - CH_3 - NO$), 119 (40, $M - CH_3 - NO_2$), 118 (34, $M - CH_3 - NO_2H$), and 107 [30, $M - NHCH(CH_3)_2$].

N-Propyl-2-nitroaniline showed $\lambda_{max.}$ (n-hexane) 408 nm (log ε 3.84); δ(Cl_4C, standard Me_4Si) 1.22 (3 H, t, CH_3), 1.63 (2 H, m, CH_2), 3.22 (2 H, m, NCH_2), 7.98 (1 H, br s, NH), and 6.57 (2 H, m), 7.2 (1 H, m), and 8.05 (1 H, m) (aromatics); m/z 180 (42, M^+), 151 (100, $M - C_2H_5$), 134 (2, $M - NO_2$), 133 (3, $M - H - NH_2$), 121 (10, $M - C_2H_5 - NO$), 105 (19, $M - C_2H_5 - NO_2$), 104 (16, $M - C_2H_5 - NO_2 - H$), and 92 (8, C_6H_6N).

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