# Kinetic and Equilibrium Acid–Base Properties of Strong Naphthalenediamine Bases

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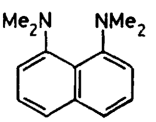
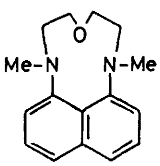
The kinetic and equilibrium acid-base properties of two derivatives of the strong base 1,8-bis(dimethylamino)-naphthalene (1), p*K* 12.1, have been investigated. When the nitrogen atoms are bridged as in 2,3,6,7-tetrahydronaphthaleno[1,8-*hi*][1,4,8]oxadiazecine (2), p*K* 12.9, the basicity is increased. For 1,8-dimorpholinonaphthalene (3), p*K* 7.49, the basicity is much lower than for (1) but still four p*K* units higher than for *N*-phenylmorpholine. The rate coefficients for proton transfers from the protonated amines (1) and (2) to hydroxide ion in 30% (v/v) $Me_2SO$–$H_2O$ have values of $6.1 \times 10^5$ and $6.2 \times 10^3$ dm$^3$ mol$^{-1}$ s$^{-1}$ respectively and for (3) in aqueous solution proton transfer from the protonated amine to phosphate dianion occurs with a rate coefficient of $1.2 \times 10^3$ dm$^3$ mol$^{-1}$ s$^{-1}$. The low rates and high basicities are due to stabilisation of the protonated amines by strong intramolecular hydrogen bonds.

FOLLOWING the discovery [1] of the unusually high basicity of 1,8-bis(dimethylamino)naphthalene (1) we have investigated the kinetic and equilibrium acid–base properties of various related 1,8-diaminonaphthalenes. The high basicity of (1), p*K* 12.1,[2] has been attributed [1] to the relief of strain which accompanies formation of the intramolecularly hydrogen-bonded naphthylammonium ion. Thermodynamically favourable proton removal by hydroxide ion from the protonated amine occurs with a rate coefficient which is five orders of magnitude below the diffusion-limited rate expected for the reaction of an ammonium ion with hydroxide ion and this has also been explained by the presence of a strong intramolecular hydrogen bond in the protonated amine.[2] The introduction of more bulky groups as for example in 1,8-bis(diethylamino)naphthalene leads to an increase in basicity and a further reduction in the rate coefficient for proton removal from the ammonium ion.[3] Substitution of methoxy-groups into the 2- and 7-positions has even more dramatic effects as illustrated by the basicity of 1,8-bis(diethylamino)-2,7-dimethoxynaphthalene (p*K* *ca.* 16.3) and in this case the half-life of the acid–base reaction between the protonated amine and hydroxide ion is in the range of seconds.[4] We now report our studies with 2,3,6,7-tetrahydronaphthaleno-[1,8-*hi*][1,4,8]oxadiazecine (2) and 1,8-*NN*-dimorpholinonaphthalene (3).



(1)



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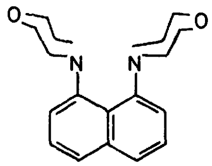
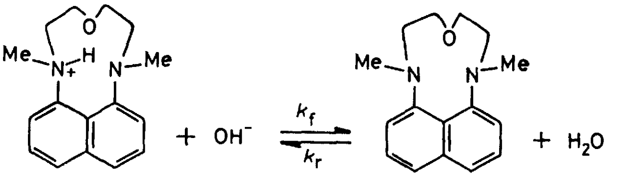


(3)

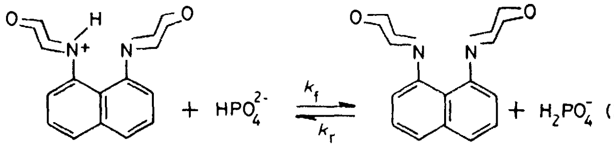
## EXPERIMENTAL AND RESULTS

*Materials.*—Substrates (2) and (3) were prepared by Dr. R. W. Alder, University of Bristol, and details will be published separately.[5]

*Equilibrium Measurements.*—(a) 2,3,6,7-*Tetrahydronaphthaleno*[1,8-hi][1,4,8]*oxadiazecine* (2). Equilibrium (1) was studied at 25.0 °C and ionic strength 0.1 mol dm$^{-3}$ in 30% v/v $Me_2SO$–$H_2O$. This solvent was chosen because previous studies with 1,8-bis(dimethylamino)naphthalene [3] had shown that 30% $Me_2SO$–$H_2O$ was more suitable for kinetic measurements than a wholly aqueous medium. The trifluoroacetate salt of protonated (2) was dissolved in 30% v/v $Me_2SO$–$H_2O$ to give a solution of concentration $2.7 \times 10^{-5}$ mol dm$^{-3}$. The absorbance due to the amine at 335 nm was measured in optical cells of pathlength 4 cm in the presence of sodium hydroxide concentrations in the range 0.001—0.01 mol dm$^{-3}$ and at ionic strength 0.10 mol dm$^{-3}$ adjusted by addition of potassium chloride. At 335 nm the free base absorbs strongly ($\varepsilon$ $7.2 \times 10^3$ dm$^3$ mol$^{-1}$ cm$^{-1}$) and the protonated form has low absorbance. The absorbance readings were used to calculate the ratio of the concentrations of the protonated and unprotonated forms and hence a value for the equilibrium constant for equilibrium (1) was obtained. The results are given in Table 1.



(1)



(2)

(b) 1,8-*Dimorpholinonaphthalene* (3). Equilibrium (2) was studied in aqueous phosphate buffer solutions at 25.0 °C and ionic strength 0.10 mol dm$^{-3}$. The buffer solutions were made up to have various buffer ratios ($[H_2PO_4^-]/[HPO_4^{2-}]$) and gave pH values in the range 6.8—7.8. Appropriate volumes of solutions of monosodium dihydrogenorthophosphate (0.05 mol dm$^{-3}$) and dipotassium monohydrogenorthophosphate (0.05 mol dm$^{-3}$) were mixed and potassium chloride was added to maintain constant ionic strength. The pH values were checked with an EIL model 7060 pH meter and found to be in agreement with literature values.[6] The amine (3) was introduced by injecting 0.01 cm$^3$ of a methanol solution of the hydrochloride salt into 50 $cm^3$ of each buffer to give a total amine concentration of $4.1 \times 10^{-6}$ mol $dm^{-3}$. The absorbance of the solutions was measured at 237 and 320 nm in optical cells of 4 cm path length. At 237 and 320 nm the free base absorbs strongly ($\varepsilon$ $4.0 \times 10^4$ and $8.8 \times 10^3$ $dm^3$ $mol^{-1}$ $cm^{-1}$, respectively) and the protonated amine shows only weak absorbance ($\varepsilon$ *ca.* $0.42 \times 10^4$ and *ca.* $0.37 \times 10^3$ $dm^3$ $mol^{-1}$ $cm^{-1}$, respectively). The absorbance readings at these wavelengths in the presence of different phosphate buffer ratios are shown in Table 1 and these results were used to calculate a value $K$ of $0.164 \pm 0.009$ for equilibrium (2). The value[7] p$K$ 7.20 for $H_2PO_4^-$ at infinite dilution was converted to p$K$ 6.70 at ionic strength 0.1 mol $dm^{-3}$ using the Debye–Hückel approximation. This value was combined with the result $K$ 0.164 for equilibrium (2) to give p$K$ $7.49 \pm 0.03$ for 1,8-dimorpholinonaphthalene at ionic strength 0.1 mol $dm^{-3}$.

TABLE 1

Equilibrium results

(*a*) Amine (2)

30% (v/v) $Me_2SO$–$H_2O$, ionic strength 0.1 mol $dm^{-3}$, 25 °C

$BH^+ + OH^- \rightleftharpoons B + H_2O$ $K = [B]/[BH^+][OH^-] = 400 \pm 70$ $mol^{-1}$ $dm^3$, $pK_{BH^+} = 12.9 \pm 0.2$

| $10^3[OH^-]$/mol $dm^{-3}$ | 0 | 1.0 | 2.0 | 3.0 | 4.0 | 6.0 | 8.0 | 10.0 | 100 |
|---|---|---|---|---|---|---|---|---|---|
| Absorbance at 335 nm | 0.020 | 0.200 | 0.329 | 0.413 | 0.462 | 0.604 | 0.622 | 0.630 | 0.781 |
| $[B]/[BH^+]$ | | 0.310 | 0.683 | 1.07 | 1.39 | 3.30 | 3.79 | 4.04 | |
| $K$/$mol^{-1}$ $dm^3$ | | 310 | 342 | 356 | 346 | 549 | 473 | 404 | |

(*b*) Amine (3)

Aqueous solution, ionic strength 0.1 mol $dm^{-3}$, 25.0 °C

$BH^+ + HPO_4^{2-} \rightleftharpoons B + H_2PO_4^-$ $K = [B][H_2PO_4^-]/[BH^+][HPO_4^{2-}] = 0.164 \pm 0.009$, $pK_{BH^+} = 7.49 \pm 0.03$

| $[H_2PO_4^-]/[HPO_4^{2-}]$ | Acid | Base | 1.00 | 0.60 | 0.40 | 0.30 | 0.20 | 0.16 | 0.10 |
|---|---|---|---|---|---|---|---|---|---|
| Absorbance at 237 nm | 0.068 | 0.650 | 0.149 | 0.203 | 0.243 | 0.275 | 0.333 | 0.355 | 0.422 |
| $[B]/[BH^+]$ | | | 0.162 | 0.302 | 0.430 | 0.552 | 0.836 | 0.973 | 1.55 |
| $K$ | | | 0.162 | 0.181 | 0.172 | 0.166 | 0.167 | 0.156 | 0.155 |
| p$K$ | | | 7.49 | 7.44 | 7.46 | 7.48 | 7.48 | 7.51 | 7.51 |
| Absorbance at 320 nm | 0.006 | 0.145 | 0.024 | 0.037 | 0.048 | 0.057 | 0.069 | 0.071 | 0.093 |
| $[B]/[BH^+]$ | | | 0.149 | 0.287 | 0.433 | 0.580 | 0.829 | 0.878 | 1.67 |
| $K$ | | | 0.149 | 0.172 | 0.173 | 0.174 | 0.166 | 0.141 | 0.167 |
| p$K$ | | | 7.53 | 7.46 | 7.46 | 7.46 | 7.48 | 7.55 | 7.48 |

*Kinetic Measurements.*—(a) *Amine* (2). Chemical relaxation times were determined for equilibrium (1) by the temperature-jump technique at 25 °C. Solutions of the amine ($8 \times 10^{-5}$ mol $dm^{-3}$) in 30% v/v $Me_2SO$–$H_2O$ containing sodium hydroxide at concentrations in the range 0.005—0.02 mol $dm^{-3}$ and with the ionic strength 0.1 mol $dm^{-3}$ were subjected to a 3.1 °C temperature jump brought about by a 14 kV discharge from a 0.05 $\mu$F capacitor. The equilibrium was disturbed in favour of products and the increase in absorbance at 335 nm which accompanied the increase in concentration of the free amine was measured with time. Measurements were also made with a constant concentration of sodium hydroxide (0.0025 mol $dm^{-3}$) and at various amine concentrations in the range $4 \times 10^{-5}$—$2 \times 10^{-4}$ mol $dm^{-3}$ and the relaxation times were found to be independent of the total amine concentration. The dependence of reciprocal relaxation time on hydroxide ion concentration for equilibrium (1) is given by equation (3). The results are plotted in Figure 1 and values of $k_r[H_2O]$ of $15 \pm 2$ $s^{-1}$ and $k_f$ of $6.2 \pm 0.4 \times 10^3$ $dm^3$ $mol^{-1}$ $s^{-1}$ were

$$\tau^{-1} = k_r[H_2O] + k_f[OH^-] \qquad (3)$$

calculated. The ratio of rate coefficients $k_f/k_r[H_2O]$ of $413 \pm 60$ $dm^3$ $mol^{-1}$ is compatible with the value of the equilibrium constant $K$ of $400 \pm 70$ $dm^3$ $mol^{-1}$ obtained from equilibrium measurements.

To confirm that the observed chemical relaxations referrred to equilibrium (1), relaxation amplitudes were measured using solutions identical to those used for measuring relaxation times. A maximum was observed in the amplitude of relaxation as the hydroxide ion concentration was varied. Under our reaction conditions it is predicted that the maximum amplitude for equilibrium (1) should be observed when the free amine and protonated form are present in equal concentrations. The hydroxide ion concentration at which this occurs can be calculated from the equilibrium constant for the reaction and the result is in good agreement with the hydroxide ion concentration (0.0025 mol $dm^{-3}$) at which a maximum in the amplitude was observed experimentally.

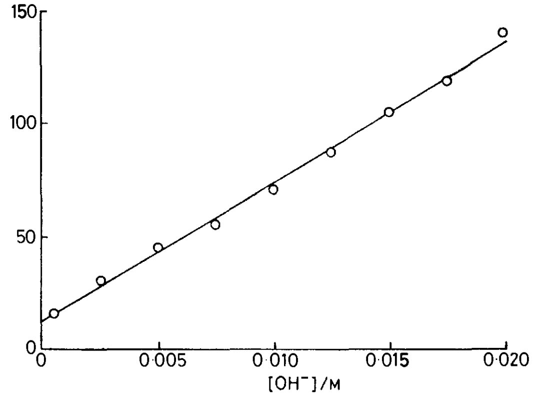


FIGURE 1 Variation of the reciprocal relaxation time for the equilibrium between protonated (2) and hydroxide ion in 30% v/v $Me_2SO$–$H_2O$

(b) 1,8-*Dimorpholinonaphthalene* (3). The kinetics of reaction (2) were studied by the temperature-jump method. Measurements were made with a total concentration of 1,8-dimorpholinonaphthalene of $5 \times 10^{-6}$ mol $dm^{-3}$ in the presence of varying concentrations of phosphate buffer. Results were obtained at two buffer ratios, $[H_2PO_4^-]/[HPO_4^{2-}]$ 1.0 and 0.50 at a constant ionic strength of 0.1 mol $dm^{-3}$. The reaction solutions thermostatted at 20.2 °C were subjected to a temperature jump of 4.8° brought about by a 40 kV discharge from a 0.05 $\mu$F capacitor to give a final reaction temperature of 25 °C. The equilibrium was disturbed in favour of products and the increase in concentration of the free base was monitored at 237 nm.

A few measurements were made at 320 nm and were in good agreement with the measurements at 237 nm. The dependence of reciprocal relaxation time on buffer concentration at the two buffer ratios is shown in Figure 2.

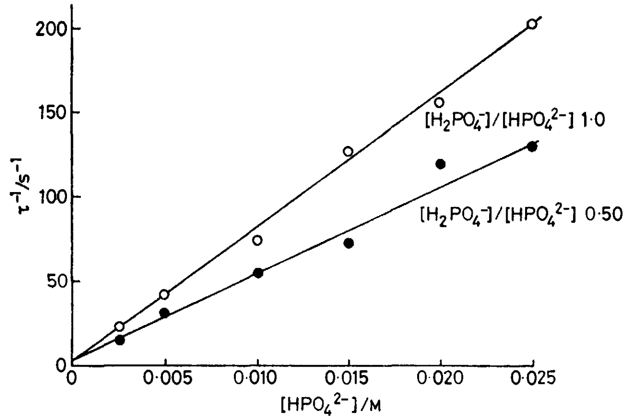


FIGURE 2 Dependence of the reciprocal relaxation time on buffer concentration for the protonation of (3) in aqueous orthophosphate buffers

For the equilibrium between the protonated and unprotonated forms of 1,8-dimorpholinonaphthalene in phosphate buffer the reciprocal relaxation time is given by equation (4) in which the rate coefficients $k_{OH^-}$ and $k_{H_2O}$

$$\tau^{-1} = k_{OH^-}[OH^-] + k_{H_2O}[H_2O] + (k_f + rk_r)[HPO_4^{2-}] \quad (4)$$

refer to deprotonation by hydroxide ion and $r$ is the buffer ratio, $r = [H_2PO_4^-]/[HPO_4^{2-}]$. At fixed buffer ratio the reciprocal relaxation time increases linearly with buffer concentration as shown in Figure 2. At each buffer ratio the values of $k_f$ and $k_r$ were calculated by combining the gradient of the plot of reciprocal relaxation time against buffer concentration with the result $k_f/k_r$ 0.164 determined from equilibrium measurements. The data at the two buffer ratios were in good agreement and gave average values of $k_f$ of $1.21 \pm 0.05 \times 10^3$ dm$^3$ mol$^{-1}$ s$^{-1}$ and $k_r$ of $7.5 \pm 0.3 \times 10^3$ dm$^3$ mol$^{-1}$ s$^{-1}$.

## DISCUSSION

The kinetic and equilibrium data for the diamines (2) and (3) are compared in Table 2 with the results previously obtained[3] for 1,8-bis(dimethylamino)naphthalene (1). For (1) and (2) in 30% v/v $Me_2SO-H_2O$ the equilibrium constants for reaction of the protonated amines with hydroxide ion have values of 2 800 and 400 dm$^3$ mol$^{-1}$, respectively, which means that under these conditions (2) is a stronger base than (1) by a factor of 7. Assuming that a similar factor applies to the basicities in aqueous solution, the aqueous basicity of (2) can be estimated as p$K$ 12.9 ± 0.2 from the value p$K$ 12.1 ± 0.1 which was measured for (1) in aqueous solution.[2] The amines (1) and (2) are very much stronger bases than *NN*-dimethylaniline (p$K$ 5.2 [8,9]) and (3) is a stronger base than *N*-phenylmorpholine (p$K$ 3.2[9]). The results in Table 2 also show that the rates of ionisation of the protonated amines are lower than the diffusion-limited rate coefficients (*ca.* $1 \times 10^{10}$ dm$^3$ mol$^{-1}$ s$^{-1}$) expected for thermodynamically favourable proton removal from a protonated amine. The low rates and high basicities can both be explained by the presence of strong intramolecular hydrogen bonds in the protonated amines. Evidence for hydrogen bonds in the ammonium ions is provided by the large downfield shift of the acidic proton in the n.m.r. spectrum, for example a chemical shift, δ 19.5, was observed[1] for the acidic proton in protonated 1,8-bis(dimethylamino)naphthalene.

We have obtained results[10] which have been confirmed[11] showing that, in the mechanism of proton transfer from related naphthylammonium ions, the intramolecularly hydrogen-bonded species first rearranges to give a low concentration of an open form which is hydrogen-bonded externally to solvent and then proton transfer occurs from this species to base. Overall the proton transfer reaction is slow because the mechanism involves a low concentration intermediate. If it is assumed that proton transfer from the open form is diffusion limited, the rate coefficient for the overall reaction will be lower than the diffusion limit by a factor which is equal to the value of the equilibrium constant between closed and open forms of the ammonium ion. However it is likely that attack on the open form by base is sterically hindered[3] and this may reduce the rate coefficient for this step below the diffusion-limited value. If the lowering in rate of the overall reaction is assumed to result entirely from the unfavourable equilibrium we can estimate that the equilibrium constants between closed and open forms of the ammonium ions have values of *ca.* $10^5$ and $10^7$ for (1) and (2) respectively. For

TABLE 2

Summary of kinetic and equilibrium results

$$BH^+ + X^- \underset{k_r}{\overset{k_f}{\rightleftharpoons}} B + HX$$

$$K = [HX][B]/[BH^+][X^-]$$

| B | p$K$ | $X^-$ | Solvent | $K$/dm$^3$ mol$^{-1}$ | $10^3$ $k_f$/dm$^3$ mol$^{-1}$ s$^{-1}$ | $10^3$ $k_r$/s$^{-1}$ |
|---|---|---|---|---|---|---|
| Amine (1) [a] | 12.1 ± 0.1 | $OH^-$ | $H_2O$ | 52 ± 13 | 190 ± 40 | 3.9 ± 0.4 |
| | | $OH^-$ | 30% v/v $Me_2SO-H_2O$ | 2 800 ± 200 | 610 ± 50 | 0.20 ± 0.03 |
| Amine (2) | 12.9 ± 0.2 | $OH^-$ | 30% v/v $Me_2SO-H_2O$ | 400 ± 70 | 6.2 ± 0.4 | 0.015 ± 0.002 |
| Amine (3) | 7.49 ± 0.03 | $HPO_4^{2-}$ | $H_2O$ | 0.164 ± 0.009 [b] | 1.21 ± 0.05 | 7.5 ± 0.3 [c] |

[a] Results from ref. 3. [b] $K = [B][H_2PO_4^-]/[BH^+][HPO_4^{2-}]$. [c] dm$^3$ mol$^{-1}$ s$^{-1}$.

(3) since proton transfer is occurring to phosphate dianion and the diffusion limit for this reaction will be somewhat lower than for reaction with hydroxide ion it is estimated that the unfavourable equilibrium between closed and open forms of the ammonium ion reduces the rate coefficient for the overall proton transfer by a factor of *ca.* $1 \times 10^5$ in this case. The acidities of the closed forms of the protonated amines (1)—(3) will be reduced by similar factors compared with the acidities of the open forms and therefore the protonated amines will be weaker acids than expected in the absence of intramolecular hydrogen bonding. This will amount to acid-weakening effects on the protonated amines or base-strengthening effects on the amines of 5.0, 7.0, and 4.7 p$K$ units respectively for (1)—(3). The effect for (2) is larger than for (1) and (3) and this may be the result of stabilisation of the closed form of the protonated amine because of the presence of the oxygen atom in the vicinity of the hydrogen-bonded proton. The amounts by which the actual p$K$ values for (1)—(3) differ from the p$K$ values observed for related amines which are unable to form intramolecular hydrogen bonds in the protonated forms are roughly similar to the predicted differences. Thus (1) and (2) are 6.9 and 7.7 p$K$ units respectively more strongly basic than *NN*-dimethylaniline and (3) is 4.3 units more strongly basic than *N*-phenylmorpholine.

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[1/700 *Received*, 1*st May*, 1981]

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