the corresponding trapping agent was heated at 100 °C in Me_2SO for 0.25, 0.50, 1, 2, 4, 10, 20, and 48 h, respectively. Each time, both solid phases (precursor and trapping) were separated, washed, and radioassayed and so was the liquid phase. Thus, we were able to draw plots of ln A_0/A against t (eq 1) to deduce directly k_1, its value being very similar in all cases. As we already knew simultaneous concentrations of ketone moiety in trapping resin and in solution, we calculated k_2 and k_3. As expected, k_3 is also similar in every instance, whereas k_2 is dependent on the trapping agent.

Polyphasic Dynamic Reactor (PDR). Two 25-mL round-bottomed flasks A and C (Figure 1) are connected by means of a 15 mm long tube B with an internal diameter of 6 mm. Outside, both flasks are also connected by an adjustable peristaltic pump, which regulates the flow rate in the whole system. In the top of each flask, a reflux condenser can be installed. Every flask connection is made by sintered-glass plates.

Calibration of the PDR can be easily done by using a coloring matter which allows the liquid running through conduit B to be seen. In this way, we were able to draw plots of the run-time against the flow.

Lifetime Measurements. In a series of experiments, a suspension of polymeric precursor I (0.1 g) in Me_2SO was heated and stirred at 100 °C in vessel A of the PDR. Trapping agent IV (0.1 g) was also stirred in vessel C. Reagent solution flowed from A to C through B. The run-time through this conduit was adjusted by the peristaltic pump at 3.0, 4.2, 5.3, 6.0, 8.1, 9.1, 10.2, 11.3, 12.6, 13.8, and 15 s, respectively. Each time, resin in vessel C was filtered, washed, and analyzed by hydrolysis and IR. We realized that cyclopentadienone was not trapped by IV for run-times of 13.8 or 15 s. Instead, adducts between IV and the ketone appeared when we experimented with the other run-times. Consequently, cyclopentadienone must have a lifetime between 12.6 and 13.8 s under these conditions.

Registry No. III, 611-13-2; IV, 42507-71-1; VIII, 3052-50-4; IX, 930-88-1; X, 18707-60-3; XI, 88855-00-9; XIII, 1515-76-0; cyclopentadienone, 13177-38-3.

General Base Catalysis, Isotope Effects, Activation Parameters, and the Mechanism of Removal of the Hydrogen-Bonded Proton from Protonated 1,8-Bis(diethylamino)-2,7-dimethoxynaphthalene

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Abstract: The equilibrium between 1,8-bis(diethylamino)-2,7-dimethoxynaphthalene and the intramolecularly hydrogen-bonded protonated amine in the presence of phenol buffers is established very slowly in 70% Me_2SO–H_2O (v/v) with half-lives in the range of minutes. Evidence is presented to show that deprotonation of the protonated amine occurs through a non-hydrogen-bonded open form from which the proton is removed by base. The rate of the overall reaction is reduced because the non-hydrogen-bonded species is present as a low-concentration intermediate and because proton removal from this intermediate is sterically hindered. These factors are of roughly similar importance. The conclusion is also reached that strain in the amine and the presence of the intramolecular hydrogen bond in the protonated amine contribute about equally to the unusually high basicity of 1,8-bis(diethylamino)-2,7-dimethoxynaphthalene, $pK_a = 16.3$.

In recent years a number of proton transfers involving oxygen and nitrogen acids and bases have been found which do not fit into the classification described by Eigen[1] as normal proton-transfer behavior and observed[1,2] for most oxygen and nitrogen acids. Although this classification is of immense value in making predictions about proton transfers, particularly with reference to these reactions as steps in multistep mechanisms,[3] it is the exceptions to this classification which are perhaps, now, of more interest. Unusual acid–base systems for which proton transfer is exceptionally slow and basicity is high include the [1.1.1]-cryptand[4] and 1,6-diazabicyclo[4.4.4]tetradecane.[5] Several other examples of nitrogen bases which show high basicity but for which the kinetics of proton transfer have not yet been studied in detail are also known.[6] Our interest in this area has concerned the unusual acid–base properties of diaminonaphthalenes,[7] and in this paper we describe our studies with 1,8-bis(dimethylamino)-2,7-dimethoxynaphthalene and 1,8-bis(diethylamino)-2,7-dimethoxynaphthalene.

1,8-Bis(diethylamino)-2,7-dimethoxynaphthalene ($pK_a = 16.3$)[8] shows unusually high basicity for an aromatic amine. Thus in the protonated amine the proton is very tightly bound and requires strongly basic conditions for its removal. In suitable Me_2SO–H_2O mixtures containing hydroxide ion, proton removal from the protonated amine is thermodynamically favorable but the reaction occurs very slowly and can be followed by using a conventional UV spectrophotometer, for example $t_{1/2} = 22$ s in 50% Me_2SO–H_2O (v/v) in the presence of 0.1 mol dm^{-3} sodium hydroxide.[8] 1,8-Bis(dimethylamino)-2,7-dimethoxynaphthalene is also strongly basic ($pK_a = 16.1$),[8] but proton removal from the protonated amine is more rapid, for example, $t_{1/2} = 15$ ms with 0.1 mol dm^{-3} sodium hydroxide in 60% Me_2SO–H_2O (v/v). Previous papers on 1,8-bis(diethylamino)-2,7-dimethoxynaphthalene have dealt with the hydroxide ion catalyzed proton transfer. In the present paper we are concerned with general base catalysis, isotope effects, and activation parameters. General base catalysis of the reaction of

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(1) Eigen, M. *Angew. Chem., Int. Ed. Engl.* **1964**, *3*, 1–19.

(2) Eigen, M.; Kruse, W.; Maass, G.; De Maeyer, L. *Prog. React. Kinet.* **1964**, *2*, 285–318.

(3) Jencks, W. P. *Acc. Chem. Res.* **1976**, *9*, 425–432.

(4) Cheney, J.; Lehn, J.-M. *J. Chem. Soc., Chem. Commun.* **1972**, 487–489. Smith, P. B.; Dye, J. L.; Cheney, J.; Lehn, J.-M. *J. Am. Chem. Soc.* **1981**, *103*, 6044–6048.

(5) Alder, R. W.; Casson, A.; Sessions, R. B. *J. Am. Chem. Soc.* **1979**, *101*, 3652–3653.

(6) Oediger, H.; Möller, F.; Eiter, K. *Synthesis* **1972**, *4*, 591–598. Heinzer, F.; Soukup, M.; Eschenmoser, A. *Helv. Chim. Acta* **1978**, *61*, 2851–2874. Barton, D. H. R.; Elliott, J. D.; Géro, S. D. *J. Chem. Soc., Perkin Trans. 1*, **1982**, 2085–2090.

(7) Hibbert, F. *Acc. Chem. Res.*, in press.

(8) Alder, R. W.; Goode, N. C.; Miller, N.; Hibbert, F.; Hunte, K. P. P.; Robbins, H. J. *J. Chem. Soc., Chem. Commun.* **1978**, 89–90. Hibbert, F.; Hunte, K. P. P. *J. Chem. Soc., Perkin Trans. 2* **1983**, 1895–1899.

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1,8-bis(dimethylamino)-2,7-dimethoxynaphthalene has been studied previously,[9] and a preliminary report of solvent isotope effects on the reaction has been published.[10] In the present work general base catalysis is extended to two further bases. The purpose of the work is to compare the behavior of the two amines and to provide information about the mechanism of proton removal from protonated 1,8-bis(diethylamino)-2,7-dimethoxynaphthalene and therefore to understand why proton transfer occurs so very slowly. We are also able to reach some conclusions about the exceptional basic strength of the amines.

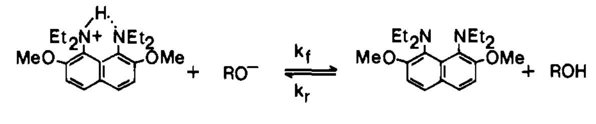
Experimental Section

Materials. Samples of 1,8-bis(dimethylamino)-2,7-dimethoxynaphthalene and 1,8-bis(diethylamino)-2,7-dimethoxynaphthalene were prepared as described previously and purifed by recrystallization and sublimation.[8,11] Liquid phenols and trifluoroethanol were purified by distillation under nitrogen, and solid phenols were recrystallized. Dimethyl sulfoxide (Analar) was refluxed with calcium hydride and distilled under a reduced pressure of nitrogen.

Kinetic Measurements. Temperature-jump measurements were made with use of the instrument manufactured by Messanlagen Studiengesellschaft. Temperature jumps of 3.7 °C were obtained by a 30 kV discharge from a 0.01 μF capacitor. The output of absorbance against time from the temperature-jump instrument was stored with a transient waveform recorder (Physical Data Inc.) and played back to an Apple II microcomputer. The data (4000 points averaged to 250) were treated by least-squares analysis, and for each reaction solution the average of at least five determinations of the relaxation time was taken. Stopped-flow experiments were conducted with a Durrum Model D-150. For determination of activation parameters, temperatures were measured accurately with a chromel-alumel thermocouple placed in the reaction solution.

Results

General Base Catalyzed Proton Transfer. 1,8-Bis(diethylamino)-2,7-dimethoxynaphthalene. Proton transfer between 1,8-bis(diethylamino)-2,7-dimethoxynaphthalene and three phenols was studied in 70% Me_2SO-H_2O (v/v) at 15.5 °C and at ionic strength 0.1 mol dm^{-3} by making spectrophotometric measurements at 350 nm where the amine absorbs strongly. Equilibrium constants for reaction 1 were determined from the measured



(1)

absorbance of solutions containing relatively low total concentrations of the amine (ca. 2 × 10^{-5} mol dm^{-3}) in the presence of excess buffers (ca. 0.04 mol dm^{-3}) at several buffer ratios. The buffers were made up by adding standard solutions of sodium hydroxide to a weighed amount of the phenol. The buffer concentrations were sufficiently low that no complications from buffer association arose.[9,12] The results of the equilibrium measurements are given in Table Ia.

Kinetic measurements of reaction 1 were made by adding a concentrated solution of the appropriate phenol in Me_2SO to a thermostated solution of the amine in Me_2SO-H_2O containing sodium hydroxide. The conversion of the amine into the protonated form was observed by following the decrease in absorbance at 350 nm with time. Some of the reactions were quite slow. For example, when 2-methylphenol (0.02 mol dm^{-3}) was introduced into a solution containing 1,8-bis(diethylamino)-2,7-dimethoxynaphthalene and sodium hydroxide (0.01 mol dm^{-3}) together with potassium chloride (0.09 mol dm^{-3}) the resulting reaction to give an equilibrium concentration of the protonated amine occurred with a half-life of 51 s. In 2-chlorophenol buffers the reactions were more rapid and the stopped-flow method was needed. The approach to equilibrium in experiments of this type is given in eq 2 and 3 assuming that the reaction between phenol and hydroxide ion occurs rapidly. The rate of proton removal from the

$$-\ln([B] - [B]_e) = k_{obsd}t + \text{constant} \tag{2}$$

$$k_{obsd} = [RO^-](k_f + k_r[ROH]/[RO^-]) \tag{3}$$

protonated amine by hydroxide ion is small compared with the rate of the buffer catalyzed reaction under our experimental conditions. In eq 2, [B] represents the concentration of 1,8-bis(diethylamino)-2,7-dimethoxynaphthalene present at time t during the reaction and $[B]_e$ is the concentration of the free amine when equilibrium is reached. For each kinetic run the first-order rate coefficient (k_{obsd}) was calculated as the gradient of a linear plot of ln ($A - A_e$) against time where A_e is the absorbance at 350 nm after equilibrium has been reached and A is the absorbance at time t during reaction. For each phenol the variation of k_{obsd} with buffer concentration was investigated at two buffer ratios. At each buffer ratio the value of the gradient of the accurately linear plot of k_{obsd} against buffer concentration was combined with the value of the equilibrium constant of the reaction to give values for k_f and k_r. The average values of the rate coefficients for each phenol are shown in Table Ia.

Table I. General Base Catalyzed Proton Transfer

(a) 1,8-Bis(diethylamino)-2,7-dimethoxynaphthalene

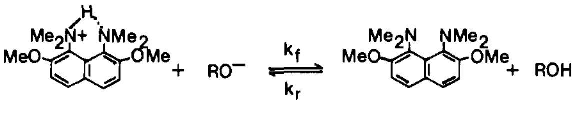
base	K	k_f, dm^3 mol^{-1} s^{-1}	k_r, dm^3 mol^{-1} s^{-1}	ref
OH^-	2500 ± 1000	6.5 ± 0.3	0.0026 ± 0.0005	*a, d*
$2-MeC_6H_4O^-$	0.27 ± 0.02	0.30 ± 0.05	1.05 ± 0.09	*a*
$C_6H_5O^-$	0.062 ± 0.005	0.51 ± 0.02	8.2 ± 0.4	*a*
$2-ClC_6H_4O^-$	0.007 ± 0.003	0.48 ± 0.1	69 ± 10	*a*

(b) 1,8-Bis(dimethylamino)-2,7-dimethoxynaphthalene

base	K	k_f, dm^3 mol^{-1} s^{-1}	k_r, dm^3 mol^{-1} s^{-1}	ref
$CF_3CH_2O^-$	22 ± 4	122 ± 7	6 ± 1	*b*
$2,6-(Me_2CH)_2-C_6H_3O^-$	1.9 ± 0.1	89 ± 10	47 ± 5	*b*
$2-MeC_6H_4O^-$	0.50 ± 0.03	160 ± 30	320 ± 50	*c*
	0.39 ± 0.02	166 ± 20	420 ± 70	*b*
$C_6H_5O^-$	0.23 ± 0.02	250 ± 100	1100 ± 300	*c*
	0.15 ± 0.03	280 ± 40	1800 ± 200	*b*
$4-ClC_6H_4O^-$	0.09 ± 0.03	300 ± 50	3300 ± 500	*c*
$2-ClC_6H_4O^-$	0.018 ± 0.005	350 ± 100	19000 ± 4000	*c*

[a] Present work in 70% Me_2SO-H_2O (v/v) at 15.5 °C and ionic strength 0.1 mol dm^{-3}. [b] Present work in 70% Me_2SO-H_2O (v/v) at 25.0 °C and ionic strength 0.1 mol dm^{-3}. [c] Previous results[9] in 70% Me_2SO-H_2O (v/v) at 25.0 °C and ionic strength 0.5 mol dm^{-3}. [d] For base = OH^-, k_r is in s^{-1}.

1,8-Bis(dimethylamino)-2,7-dimethoxynaphthalene. The kinetics of the protonation-deprotonation of 1,8-bis(dimethylamino)-2,7-dimethoxynaphthalene in 70% Me_2SO-H_2O (v/v) in the presence of four phenol buffers, eq 4, was studied previously[9] with use of the temperature-jump method. In the present work similar



(4)

procedures have been used to study the reaction in the presence of further buffers, trifluoroethanol and 2,6-diisopropylphenol, in order to extend the basicity range of the buffer catalysts. Experiments with two of the previous buffers, phenol and 2-methylphenol, were repeated under slightly different reaction conditions. The kinetic and equilibrium results are given in Table Ib.

Isotope Effects. Equilibrium and kinetic solvent isotope effects on proton removal from protonated 1,8-bis(dimethylamino)-2,7-dimethoxynaphthalene by hydroxide ion and by several phenolate bases have been measured previously in 70% Me_2SO-L_2O (L = H or D).[10] For comparison we have now made similar mea-

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(9) Hibbert, F.; Robbins, H. J. *J. Am. Chem. Soc.* **1978**, *100*, 8239-8244.

(10) Hibbert, F.; Robbins, H. J. *J. Chem. Soc., Chem. Commun.* **1980**, 141-142.

(11) Alder, R. W.; Bryce, M. R.; Goode, N. C.; Miller, N.; Owen, J. *J. Chem. Soc., Perkin Trans. 1* **1981**, 2840-2847.

(12) Bernasconi, C. F.; Terrier, F. *J. Am. Chem. Soc.* **1975**, *97*, 7458-7466.

Table II. Equilibrium and Kinetic Solvent Isotope Effects on Proton Removal from Protonated 1,8-Bis(diethylamino)-2,7-dimethoxynaphthalene by Base

base	$K(H_2O)$	$K(H_2O)/K(D_2O)$	$k_f(H_2O)/k_f(D_2O)$
OH^-	2500 ± 500	ca. 0.4	1.01 ± 0.1
$2\text{-MeC}_6H_4O^-$	0.27 ± 0.02	0.60 ± 0.1	1.3 ± 0.3

surements for the much slower reaction involving proton removal from protonated 1,8-bis(diethylamino)-2,7-dimethoxynaphthalene by hydroxide ion and 2-methylphenolate ion in 70% (v/v) Me_2SO-L_2O at 15.5 °C and at an ionic strength of 0.1 mol dm^{-3}. Equilibrium constants for the reactions were determined spectrophotometrically by measuring the absorbance at 350 nm due to the free amine in the presence of varying concentrations of sodium hydroxide or in the presence of 2-methylphenol and 2-methylphenolate ion at different buffer ratios. The hydroxide ion catalyzed reaction was followed kinetically by observing the slow increase in absorbance at 350 nm which occurred when varying concentrations of sodium hydroxide (0.001 to 0.005 mol dm^{-3}) were introduced into a solution of the protonated amine in 70% (v/v) Me_2SO-H_2O. The reactions were slow with half-lives in the range 10–60 s. The observed rate coefficient (k_{obsd}) for the approach to equilibrium is given by eq 5, and a value for k_{OH^-}

$$k_{obsd} = k_{OH^-}[OH^-] + k_{H_2O}[H_2O] \qquad (5)$$

which refers to the rate coefficient for proton removal by hydroxide ion was determined as the gradient of a linear plot of k_{obsd} against hydroxide ion concentration. A similar procedure was used to determine a value for k_{OD^-} from measurements in 70% (v/v) Me_2SO-D_2O. The isotope effect on the reaction catalyzed by 2-methylphenolate was measured by using the procedure described in the previous section with either 70% (v/v) Me_2SO-H_2O or 70% (v/v) Me_2SO-D_2O as solvent. The results are given in Table II.

Activation Parameters. The temperature dependence of the rate coefficient (k_{OH^-}) for the hydroxide ion catalyzed proton removal from protonated 1,8-bis(dimethylamino)-2,7-dimethoxynaphthalene was measured in 60% Me_2SO-H_2O (v/v) at ionic strength 0.1 mol dm^{-3}. The temperature-jump method was used to investigate the dependence of the reciprocal relaxation time (τ^{-1}) on hydroxide ion concentration, eq 6, at six temperatures in the range 10–33 °C. The values of k_{OH^-} determined at each temperature were used to obtain the activation parameters in Table III.

$$\tau^{-1} = k_{OH^-}[OH^-] + k_{H_2O}[H_2O] \qquad (6)$$

Similar measurements taken on a conventional spectrophotometer were made for the slower reaction of protonated 1,8-bis(diethylamino)-2,7-dimethoxynaphthalene with hydroxide ion in 60% and 70% Me_2SO-H_2O (v/v), and the results are given in Table III.

Discussion

The data which have been obtained allow conclusions to be reached about the exceptional basicity and low rates of proton transfer exhibited by 1,8-bis(diethylamino)-2,7-dimethoxynaphthalene and 1,8-bis(dimethylamino)-2,7-dimethoxynaphthalene. The basicity of the two amines is roughly similar, and aqueous pK_a values of 16.1 and 16.3 were previously estimated.[8] This means that toward water, 1,8-bis(diethylamino)-2,7-dimethoxynaphthalene is a factor of ca. 2 more basic than 1,8-bis(dimethylamino)-2,7-dimethoxynaphthalene. A similar difference in basicity is observed toward phenols as shown by the results in Table I. The equilibrium constants for proton removal from phenols by the amines in 70% Me_2SO-H_2O (v/v) are a factor of 1.5 to 2.0 larger for 1,8-bis(diethylamino)-2,7-dimethoxynaphthalene than for 1,8-bis(dimethylamino)-2,7-dimethoxynaphthalene. Kinetically the amines are rather different. Proton removal from protonated 1,8-bis(diethylamino)-2,7-dimethoxynaphthalene by phenolate ions in 70% Me_2SO-H_2O (v/v) occurs 550 times more slowly than the corresponding reaction of 1,8-bis(dimethylamino)-2,7-dimethoxynaphthalene. For proton removal by hydroxide ion in 60% Me_2SO-H_2O (v/v) the difference in rate coefficients is ca. 130.[8]

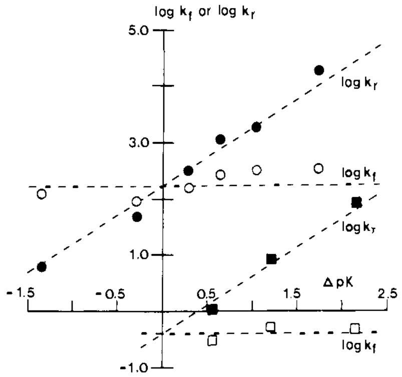
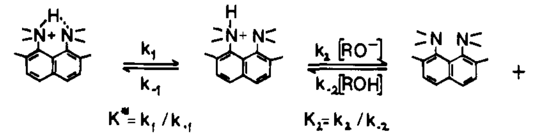


Figure 1. Forward (k_f) and reverse (k_r) rate coefficients for the deprotonation of protonated 1,8-bis(dimethylamino)-2,7-dimethoxynaphthalene (○ and ●) and 1,8-bis(diethylamino)-2,7-dimethoxynaphthalene (□ and ■) with bases.

The kinetic results for the two amines in phenol buffers have one significant feature in common. A change in basic strength of the phenolate ion and the consequent change in the equilibrium constant for proton transfer bring about a negligibly small change in the rate coefficient (k_f) for proton removal from the protonated amines. As the base is changed from trifluoro ethoxide to 2-chlorophenolate, the equilibrium constant (K) for proton removal from 1,8-bis(dimethylamino)-2,7-dimethoxynaphthalene changes over 1000-fold, but k_f shows a scattered variation of ca. 3-fold around an average value k_f ca. 150 dm^3 mol^{-1} s^{-1}. For reaction of 1,8-bis(diethylamino)-2,7-dimethoxynaphthalene in the presence of three different base catalysts, a change in the equilibrium constant (K) of ca. 40-fold leaves the value of k_f largely unaltered, with an average value of k_f ca. 0.4 dm^3 mol^{-1} s^{-1}. These results are illustrated in Figure 1 in which values of log k_f and log k_r are plotted against $\Delta pK = \log K = pK(\text{diamine}) - pK(\text{ROH})$.

A detailed explanation of the kinetic results is provided by the mechanism in eq 7. Evidence that proton removal from intramolecularly hydrogen-bonded acids occurs by this scheme, as opposed to a direct attack by base on the hydrogen-bonded proton, has been obtained previously,[9,12–15] and the present data provide support. If it is assumed that the open form of the protonated amine is present in low concentration (K* < 1) and that the rate at which this species reverts back to the closed form is more rapid than proton loss to give products ($k_{-1} > k_2[RO^-]$), the expressions in eq 8–10 are obtained. For the base catalysts studied in this work, the equilibrium constant (K) for proton transfer is in the range $0.007 < K < 22$, and since the value of K^* is extremely low, it follows that the value of K_2 is much greater than unity. Hence proton removal by base (RO^-) from the non-hydrogen-bonded intermediate in eq 7 is thermodynamically favorable for the reactions studied. If this proton removal behaved as a normal proton transfer in the Eugen sense, then the value of the forward rate coefficient (k_2), and hence the value of k_f, would remain constant



(7)

$$K = K^*K_2 \qquad (8)$$

$$k_f = K^*k_2 \qquad (9)$$

$$k_r = k_{-2} \qquad (10)$$

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(13) Hibbert, F.; Awwal, A. J. Chem. Soc., Perkin Trans. 2 1978, 939–945.

Table III. Activation Parameters for Hydroxide Ion Catalyzed Deprotonation[a]

	solvent	k_{OH^-}, dm^3 mol^{-1} s^{-1}	$\Delta G^{\ddagger}$, kJ mol^{-1}	$\Delta H^{\ddagger}$, kJ mol^{-1}	$-T\Delta S^{\ddagger}$, kJ mol^{-1}
1,8-bis(dimethylamino)-2,7-dimethoxynaphthalene	60% Me_2SO-H_2O(v/v)	640 ± 40	57.0	34 ± 4	23 ± 4
1,8-bis(diethylamino)-2,7-dimethoxynaphthalene	60% Me_2SO-H_2O(v/v)	3.7 ± 0.4	69.8	37 ± 7	33 ± 7
	70% Me_2SO-H_2O(v/v)	10.6 ± 0.5	67.1	35 ± 4	32 ± 4

[a] 25.0 °C, ionic strength 0.1 mol dm^{-3}.

and the value of the reverse rate coefficient ($k_{-2} = k_r$) would vary inversely with the value of K. These situations correspond to a value of the Brønsted exponent for the forward reaction of $\beta = 0$ and for the reverse reaction of $\alpha = 1.0$. The experimental data for the two amines are given in the form of an Eigen plot in Figure 1, and the lines are drawn with slopes of $\beta = 0.0$ and $\alpha = 1.0$.[16] Although proton removal from the intermediate in eq 7 for both amines clearly exhibits the main features of a normal proton transfer, an argument will be presented to show that the rate coefficients for this process are several orders of magnitude below those expected for a diffusion-controlled reaction. The original data for 1,8-bis(dimethylamino)-2,7-dimethoxynaphthalene[9] have been extended by Kresge to weaker bases.[14] For catalysis by weaker bases the proton-transfer step in eq 7 becomes less thermodynamically favorable. For catalysis by sufficiently weak bases, proton removal from the intermediate becomes unfavorable ($K_2 = k_2/k_{-2} < 1.0$) and hence the value of k_2, and also the value of k_f, then decreases as the catalyst is made weaker. This brings about curvature in the Eigen plot which begins for bases for which the condition $K_2 = 1.0$ and $K = K^*$ applies. For proton removal from an intramolecularly hydrogen-bonded acid occurring by eq 7, curvature in the Eigen plot is displaced from the point $\Delta pK = 0$ at which curvature is observed for a normal acid. This displacement occurs by an amount equal to $\Delta pK = -\log K^*$ and therefore depends upon the strength of the hydrogen bond. In the reaction of 1,8-bis(dimethylamino)-2,7-dimethoxynaphthalene in aqueous solution, curvature in the Eigen plot was observed for catalysis by bases with pK = ca. 9.5. Since the result pK_a = ca. 16.1 was found for 1,8-bis(dimethylamino)-2,7-dimethoxynaphthalene, curvature in the Eigen plot is observed for proton transfers with equilibrium constant K = ca. 2.5×10^{-7}. It follows that the equilibrium constant between open and closed forms has a value K^* ca. 2.5×10^{-7}. For catalysis by strong bases in aqueous solution a constant value of k_f ca. 1.0 dm^3 mol^{-1} s^{-1} was observed. It is therefore deduced that when proton removal from the open form of the protonated amine is thermodynamically favorable the reaction occurs with a rate coefficient k_2 = ca. 4.0×10^6 dm^3 mol^{-1} s^{-1}. In the present work with 1,8-bis(dimethylamino)-2,7-dimethoxynaphthalene in 70% Me_2SO-H_2O (v/v) a constant value of k_f ca. 150 dm^3 mol^{-1} s^{-1} is observed for proton removal by strong base catalysts. The difference between this result and the value in aqueous solution probably arises from a weakening of the intramolecular hydrogen bond in the presence of the superior hydrogen-bond acceptor (Me_2SO)[17] and hence reflects a difference in the value of K^* in the different solvents. This means that for proton transfer involving 1,8-bis(dimethylamino)-2,7-dimethoxynaphthalene in 70% Me_2SO-H_2O (v/v) the results $K^* = 4.0 \times 10^{-5}$ and $k_2 = 4.0 \times 10^6$ dm^3 mol^{-1} s^{-1} can be deduced. Values of K^* and k_2 for the much less reactive 1,8-bis(diethylamino)-2,7-dimethoxynaphthalene can also be estimated. Since the pK_a values of the two amines are similar, it will be assumed that the values of K^* for the intramolecular hydrogen bonds are also similar so that a value of K^* = ca. 2×10^{-5} will be taken for 1,8-bis(diethylamino)-2,7-dimethoxynaphthalene in 70% Me_2SO-H_2O (v/v) to allow for the twofold difference in basicity of the amines. It follows from this value and the value of the rate coefficient observed for proton removal from protonated 1,8-bis(diethylamino)-2,7-dimethoxynaphthalene by strong bases that proton transfer from the non-hydrogen-bonded intermediate in this case occurs with a rate coefficient k_2 = ca. 2×10^4 dm^3 mol^{-1} s^{-1}. Therefore for both amines thermodynamically favorable proton removal from the intermediate open forms occurs with rate coefficients which are well below the diffusion limit. Crystal structures show that there is considerable increase in strain in going from the protonated[18] to the free base form[19] of 1,8-bis(dimethylamino)naphthalene, and hence it seems reasonable to attribute the depression in the rate of proton removal from the non-hydrogen-bonded intermediate to a transition-state steric effect which is greater for 1,8-bis(diethylamino)-2,7-dimethoxynaphthalene than for 1,8-bis(dimethylamino)-2,7-dimethoxynaphthalene. For the amines overall proton transfer is slow because reaction occurs through a low concentration intermediate and because proton removal from this intermediate is slow. These factors make roughly equal contributions.

The values deduced for the equilibrium constants between open and closed forms of the protonated amines are related to the strength of the intramolecular hydrogen bonds. For 1,8-bis(dimethylamino)-2,7-dimethoxynaphthalene in aqueous solution the result $K^* = 2.5 \times 10^{-7}$ was deduced. This means that the protonated amine is stabilized by ca. 6.5 pK units compared with a protonated amine which is unable to form an intramolecular hydrogen bond, and hence this factor probably accounts for about half of the enhancement in basicity of these amines over typical aromatic amines. The remainder arises because, compared with most amines, 1,8-bis(dimethylamino)-2,7-dimethoxynaphthalene and 1,8-bis(diethylamino)-2,7-dimethoxynaphthalene are destabilized by unique steric interactions. For both amines relief of strain occurs on protonation.

The kinetic solvent isotope effects observed for proton removal from protonated 1,8-bis(diethylamino)-2,7-dimethoxynaphthalene by hydroxide ion and by 2-methylphenolate ion given in Table II are similar to the results previously obtained for 1,8-bis(dimethylamino)-2,7-dimethoxynaphthalene.[9] It has been shown[20] that the solvent kinetic isotope effect on proton transfer involving oxygen or nitrogen acids and bases goes through a sharp maximum value of ca. 3 as the pK values of the acids and bases are varied, and the maximum isotope effect occurs when the donor and acceptor are closely matched in pK, at ΔpK = ca. 0. When ΔpK falls outside the range $-3 < \Delta pK < 3$, the solvent isotope effect on the reaction is close to unity. The small solvent isotope effects observed for the reaction of the naphthalenediamines are therefore consistent with the mechanism in eq 7 since the proton-transfer step is well removed from the condition ΔpK ca. 0 and because the isotope effect on the equilibrium between open and closed forms of the protonated amines is expected to be small, $K^*(H_2O)/K^*(D_2O)$ = ca. 1.0.

Activation parameters for the hydroxide ion catalyzed deprotonations, Table III, show that the enthalpy and entropy terms are about equal. The difference in rate coefficients for proton

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(14) Kresge, A. J.; Powell, M. F. *J. Am. Chem. Soc.* **1981**, *103*, 972–973.

(15) Hibbert, F., Hunte, K. P. P. *J. Chem. Soc., Perkin Trans. 2* **1981**, 1562–1565. Awwal, A.; Burt, R.; Kresge, A. J. *Ibid.* **1981**, 1566–1571.

(16) Linear regression analysis of the data for 1,8-bis(diethylamino)-2,7-dimethoxynaphthalene gives $\beta = 0.11$ and $\alpha = 1.14$ and for 1,8-bis(dimethylamino)-2,7-dimethoxynaphthalene the data at 25 °C and ionic strength 0.1 mol dm^{-3} give $\beta = 0.11$ and $\alpha = 1.04$.

(17) Kamlet, M. J.; Taft, R. W. *J. Am. Chem. Soc.* **1976**, *98*, 377–383.

(18) Truter, M. R.; Vickery, B. L. *J. Chem. Soc., Dalton Trans.* **1972**, 395–403.

(19) Einspahr, H.; Robert, J.-B.; Marsh, R. E.; Roberts, J. D. *Acta Crystallogr., Sect. B* **1973**, *29B*, 1611–1617.

(20) Bergman, N.-Å.; Chiang, Y.; Kresge, A. J. *J. Am. Chem. Soc.* **1978**, *100*, 5954–5956. Cox, M. M.; Jencks, W. P. *Ibid.* **1978**, *100*, 5956–5957. Fischer, H.; De Candis, F. X.; Ogden, S. D.; Jencks, W. P. *Ibid.* **1980**, *102*, 1340–1347. Chiang, Y.; Kresge, A. J.; Holzwarth, J. F. *J. Chem. Soc., Chem. Commun.* **1982**, 1203–1204.

transfer involving 1,8-bis(dimethylamino)-2,7-dimethoxynaphthalene and 1,8-bis(diethylamino)-2,7-dimethoxynaphthalene in 60% Me_2SO-H_2O (v/v) is mostly due to a difference in entropies of activation. The value of the equilibrium constant for pre-equilibrium formation of the non-hydrogen-bonded intermediate from protonated 1,8-bis(diethylamino)-2,7-dimethoxynaphthalene ($K^* = $ ca. 2.0×10^{-5}) corresponds to an unfavorable free energy term of $\Delta G^{\circ}_{\mathrm{HB}} = 27$ kJ mol^{-1}. Hence according to the mechanism in eq 7 the overall free energy of activation for proton transfer to hydroxide ion from protonated 1,8-bis(diethylamino)-2,7-dimethoxynaphthalene in 70% Me_2SO-H_2O (v/v), $\Delta G^{\ddagger} = 67$ kJ mol^{-1}, is composed of the term $\Delta G^{\circ}_{\mathrm{HB}} = 27$ kJ mol^{-1} and the free energy of activation for the proton-transfer step ($\Delta G^{\ddagger}_{\mathrm{PT}} = 40$ kJ mol^{-1}). The proton-transfer step involves thermodynamically favorable proton removal by hydroxide ion from an ammonium ion and normally would be expected to occur at the diffusion limited rate. We have attributed the reduced rate to a steric effect. Therefore the large free energy of activation for this step ($\Delta G^{\ddagger}_{\mathrm{PT}} = 40$ kJ mol^{-1}) may be the result of a small enthalpy term, $\Delta H^{\ddagger}_{\mathrm{PT}} = $ ca. 16 kJ mol^{-1}, which is roughly the value expected for a diffusion-controlled reaction, and a large entropy contribution $T\Delta S^{\ddagger}_{\mathrm{PT}} = $ ca. -24 kJ mol^{-1}. It follows that the enthalpy of activation for the overall reaction consists of two terms, $\Delta H^{\circ}_{\mathrm{HB}} = $ ca. 19 kJ mol^{-1} and $\Delta H^{\ddagger}_{\mathrm{PT}} = $ ca. 16 kJ mol^{-1}, and the corresponding entropy terms are $T\Delta S^{\circ}_{\mathrm{HB}} = $ ca. -8 kJ mol^{-1} and $T\Delta S^{\ddagger}_{\mathrm{PT}} = $ ca. -24 kJ mol^{-1}. These results show that the mechanism in eq 7 provides a reasonable explanation of the observed activation parameters.

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Registry No. 1,8-Bis(diethylamino)-2,7-dimethoxynaphthalene, 67116-12-5; 1,8-bis(dimethylamino)-2,7-dimethylnaphthalene, 67116-11-4.

Kinetic Isotope Effects in the Menschutkin-Type Reaction of Benzyl Benzenesulfonates with *N*,*N*-Dimethylanilines. Variation in the Transition-State Structure[1]

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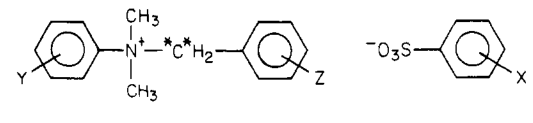
Abstract: Primary carbon-14 and secondary α-tritium isotope effects were measured for the Menschutkin-type reaction of *m*-bromobenzyl-*methylene*-^{14}C X-substituted benzenesulfonates with Y-substituted *N*,*N*-dimethylanilines in acetone at 35 °C (eq 1; Z = *m*-Br). The large carbon-14 ($^{12}k/^{14}k = 1.117$–1.151) and small α-tritium ($^{H}k/^{T}k = 1.026$–1.041) isotope effects were consistent with the S_N2 mechanism of the reaction. A monotonous trend was observed when the carbon isotope effects were plotted against the relative rates for varied Xs and a fixed Y (*p*-CH_3), while a bell shape was observed for varied Ys and a fixed X (*p*-Cl). Comparison of the results with those obtained for the unsubstituted benzyl esters indicated that the substitution on the benzyl moiety with the electron-withdrawing *m*-Br group made the transition state more product-like. Smaller α-tritium isotope effects for the *m*-Br series than those for the unsubstituted series verified tighter transition states for the former. The variation in the three-centered S_N2 transition states caused by the substituents on the leaving group, the nucleophile as well as the benzyl moiety, is discussed in terms of Thornton's rules and described on a potential energy map.

The concept of variable transition states in S_N2 reactions has been studied extensively in recent years.[2-12] Among a variety of techniques so far employed for these studies, kinetic isotope effects are of great importance since they give us most direct information concerning the structure of a transition state. However, the majority of the isotope effect studies have been concerned only with secondary α-deuterium effects, except for a few cases in which heavy atom isotope effects were measured.[3,12-17] Although secondary α-deuterium effects are generally accepted as a sensitive probe for detecting subtle changes in a transition-state structure, it is not safe to rely much on the results obtained from only one probe.



(1)

In previous papers from our laboratory, we have reported the usefulness of carbon-14 isotope effects in the study of variable S_N2 transition states.[1a,b] In the Menschutkin-type reaction of benzyl benzenesulfonates (**1**) with *N*,*N*-dimethylanilines (**2**) (eq 1; X, Y = variable; Z = H)[18] carbon-14 isotope effects at the reaction center (*C) have been found to vary to a great extent. This variation has been discussed in connection with the symmetry

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(1) Part of this work appeared in communication form: (a) Yamataka, H.; Ando, T. *Tetrahedron Lett.* **1975**, 1059–1062. (b) *J. Am. Chem. Soc.* **1979**, *101*, 266–267. (c) *Tetrahedron Lett.* **1982**, *23*, 4805–4808.

(2) Albery, W. J.; Kreevoy, M. M. *Prog. Phys. Org. Chem.* **1978**, *13*, 87–157.

(3) Westaway, K. C.; Ali, S. F. *Can. J. Chem.* **1979**, *57*, 1354–1367.

(4) Young, P. R.; Jencks, W. P. *J. Am. Chem. Soc.* **1979**, *101*, 3288–3294.

(5) Harris, J. M.; Shafer, S. G.; Moffatt, J. R.; Becker, A. R. *J. Am. Chem. Soc.* **1979**, *101*, 3295–3300.

(6) Ahsan, M.; Robertson, R. E.; Blandamer, M. J.; Scott, J. M. W. *Can. J. Chem.* **1980**, *58*, 2142–2145.

0002-7863/84/1506-2084$01.50/0