3680 *J. Org. Chem.* 1986, *51*, 3680–3686

Rate-Limiting Proton Transfer in σ-Complex Formation between 1,3,5-Trinitrobenzene and *N*-Methylaniline in Dimethyl Sulfoxide. The Differing Reactivities of Aromatic and Aliphatic Amines in σ-Complex Formation and in S_NAr Processes

Erwin Buncel* and Cristobal Innis

Department of Chemistry, Queen's University, Kingston, Canada K7L 3N6

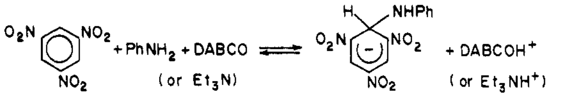
Ikenna Onyido

Department of Chemistry, University of Ibadan, Ibadan, Nigeria

Received March 13, 1986

σ-Complex formation between 1,3,5-trinitrobenzene (TNB) and *N*-methylaniline (NMA) in the presence of 1,4-diazabicyclo[2.2.2]octane (DABCO) has been studied in dimethyl sulfoxide (Me_2SO) solution. The reaction is catalyzed solely by DABCO in a linear fashion, indicating that deprotonation of the zwitterionic intermediate (PH) formed along the reaction coordinate is rate-limiting. Rate and equilibrium constants for the constituent steps have been evaluated. The rate constant for reversion of PH to reactants, k_{-1}, is substantially higher for aromatic amines than for aliphatic amines of comparable basicity. It is suggested that this is a result of stabilization of the transition state for the reactions of aromatic amines through charge delocalization. With NMA as the nucleophile, k_{-1} is an order of magnitude higher than in the case of aniline, reflecting the effect of release of steric compression in PH on reversion to reactants in the former case. The effect of addition of tetraethylammonium chloride on rates and equilibria in the title reaction was also determined. The overall equilibrium constant for the reaction, *K*, increases ca. 13-fold as the Et_4NCl concentration is increased from 0.03 to 0.30 M. This effect is shown to arise mainly from a decrease in the reverse second order rate constant, k_r^2. Evidence is presented for the effect of heteroconjugation of the type $DABCOH^+ + Cl^- \rightleftharpoons DABCOH^+\cdots Cl^-$ in these processes. The observation of rate-limiting proton transfer in σ-complex formation in this and other systems strengthens the idea that proton transfer can be rate-limiting in nucleophilic aromatic substitution (S_NAr) reactions. The present work sheds further light on the apparent dichotomy regarding the differing reactivities of aromatic vs. aliphatic amines as nucleophiles in σ-complex formation. Our results also provide a rationale for the observation that under certain conditions for S_NAr reactions involving aromatic and aliphatic amines of the same basicity, the reaction involving the aromatic amine is base catalyzed, while the aliphatic one is not.

Studies of rates and equilibria of σ-complex formation have played a significant role in the elucidation of the mechanism of nucleophilic aromatic substitution (S_NAr) and related reactions,[1] since these species have been postulated as intermediates in such processes. An interesting observation has been that whereas both aliphatic and aromatic amines can participate in facile S_NAr reactions,[2] the interactions of aromatic amines with nitroaromatics such as 1,3,5-trinitrobenzene (TNB) give rise only to charge transfer type complexes.[3] We showed, however, that the σ-complexes between TNB and arylamines can be formed indirectly via reaction of the $TNB{\cdot}OMe^-$ σ-complex with various arylamines in Me_2SO.[4] Subsequently we were able to demonstrate[5] that the $TNB{\cdot}NHPh^-$ σ-complex can be formed directly by the reaction of TNB with aniline in the presence of a strongly basic tertiary amine like 1,4-diazabicyclo[2.2.2]octane (DABCO) or triethylamine, eq 1. A kinetic and equilibrium study of this reaction revealed[6] that the difference in behavior of aromatic and aliphatic amines in their reaction with TNB has its origin primarily in the unfavorable thermodynamic factor associated with formation of the initial zwitterionic adduct (vide infra) when an aromatic amine acts as the nucleophile.



(1)

We have now extended the study to the system involving a secondary aromatic amine, *N*-methylaniline (NMA), in part because this would enable us to compare with other data available in the literature for systems involving a variety of nucleophiles. Hitherto, such comparisons have involved only aniline on the one hand and strongly basic aliphatic amines on the other. As well, there is some controversy regarding the mechanism of S_NAr reactions involving NMA as the nucleophile,[7-10] since it is found that certain S_NAr reactions of aniline are subject to base ca-

---

(1) (a) Artamkina, G. A.; Egorov, M. P.; Beletskaya, I. P. *Chem. Rev.* **1982**, *82*, 427. (b) Terrier, F. *Chem. Rev.* **1982**, *82*, 125. (c) Buncel, E. In *The Chemistry of Amino, Nitro and Nitroso Compounds*; Patai, S., Ed.; Wiley: London, 1982; Supplement F. (d) Buncel, E.; Crampton, M. R.; Strauss, M. J.; Terrier, F. *Electron Deficient Aromatic- and Heteroaromatic-Base Interactions. The Chemistry of Anionic σ-Complexes*; Elsevier: Amsterdam, 1984. (e) Fendler, J. H.; Hinze, W. L.; Liu, L. J. *J. Chem. Soc., Perkin Trans. 2* **1975**, 1768. (f) Strauss, M. J. *Chem. Rev.* **1970**, *70*, 667. (g) Crampton, M. R. *Adv. Phys. Org. Chem.* **1969**, *7*, 211.

(2) (a) Bunnett, J. F.; Cartano, A. V. *J. Am. Chem. Soc.* **1981**, *103*, 4861. (b) Miller, J. *Aromatic Nucleophilic Substitution*; Elsevier: Amsterdam, 1968. (c) Pietra, F. *Q. Rev.* **1969**, *23*, 504. (d) Bernasconi, C. F. *MTP Int. Rev. Sci. Org. Chem. Ser. 1* **1973**, *3*, 33.

(3) (a) Ross, D. S.; Labes, M. M. *J. Am. Chem. Soc.* **1957**, *79*, 76. (b) Foster, R.; Morris, J. W. *J. Chem. Soc. B* **1970**, 703.

(4) (a) Buncel, E.; Webb, J. G. K. *Can. J. Chem.* **1974**, *52*, 630. (b) Buncel, E.; Jarell, H.; Leung, H. W.; Webb, J. G. K. *J. Org. Chem.* **1974**, *39*, 372. (c) Buncel, E.; Webb, J. G. K. *Tetrahedron Lett.* **1976**, 4417. (d) Buncel, E.; Webb, J. G. K.; Wiltshire, J. F. *J. Am. Chem. Soc.* **1977**, *99*, 4429.

(5) Buncel, E.; Leung, H. W. *J. Chem. Soc., Chem. Commun.* **1975**, 19.

(6) (a) Buncel, E.; Eggimann, W. *J. Am. Chem. Soc.* **1977**, *99*, 5958. (b) Buncel, E.; Leung, H. W.; Eggimann, W. *J. Chem. Soc., Chem. Commun.* **1977**, *55*. (c) Buncel, E.; Eggimann, W. *J. Chem. Soc., Perkin Trans. 2* **1978**, 673.

(7) (a) Bamkole, T. O.; Hirst, J.; Onyido, I. *J. Chem. Soc., Perkin Trans. 2* **1981**, 1201. (b) Bamkole, T. O.; Hirst, J.; Onyido, I. *Ibid.* **1979**, 1317.

(8) Bunnett, J. F.; Randall, J. J. *J. Am. Chem. Soc.* **1958**, *80*, 6020.

(9) Kavalek, J.; Kubias, J.; Sterba, V. *Collect Czech. Chem. Commun.* **1972**, *37*, 4041.

(10) Bamkole, T. O.; Hirst, J.; Hussain, G. *J. Chem. Soc., Perkin Trans. 2* **1984**, 681.

0022-3263/86/1951-3680$01.50/0 © 1986 American Chemical Society

Table I. Rate and Equilibrium Data for the Reaction of TNB[a] with NMA[b] in the Presence of DABCO at Three Different Electrolyte Concentrations in Me_2SO at 25 °C

$[Et_4NCl]$, M	10^2[DABCO], M	% convn	K, M^{-1}	$10^5k_f^1$, s^{-1}	$10^2k_f^2$, $M^{-1}\,s^{-1}$	k_f^3, $M^{-2}\,s^{-1}$	k_r^2, $M^{-1}\,s^{-1}$
0.029	4.00	33.8	0.085	9.97	1.96	0.49	5.94
	7.06	39.3	0.072	18.1	3.55	0.50	6.97
	15.0	54.0	0.084	34.8	6.84	0.46	5.43
	25.1	61.9	0.080	53.4	10.5	0.42	5.23
	35.1	68.1	0.082	72.7	14.3	0.41	4.96
	50.1	72.1	0.074	105	20.5	0.41	5.54
0.101	0.22	18.3	0.37	1.55	0.31	1.37	3.71
	1.11	34.3	0.32	3.83	0.75	0.68	2.14
	4.00	48.5	0.23	11.8	2.31	0.58	2.51
	7.12	58.3	0.23	23.4	4.59	0.65	2.80
	10.0	71.3	0.35	35.4	6.94	0.69	1.98
	14.9	78.5	0.38	50.9	9.99	0.67	1.76
	20.0	81.6	0.36	81.4	16.0	0.80	2.22
	25.1	84.6	0.23	98.0	19.3	0.77	3.33
0.303	1.11	53.5	1.11	5.62	1.10	0.99	0.90
	4.00	74.4	1.08	12.0	2.36	0.59	0.55
	7.06	75.3	0.65	18.7	3.67	0.52	0.80
	9.98	78.2	0.56	31.3	6.14	0.62	1.10
	15.0	85.7	0.69	44.0	8.64	0.58	0.83
	20.0	87.6	0.62	61.3	12.0	0.60	0.97

[a] $[TNB]_0 = 1.001 \times 10^{-4}$ M. [b] $[NMA]_0 = 5.093 \times 10^{-3}$ M.

talysis, while corresponding reactions of NMA are not. It appeared probable that a study of σ-complex formation involving NMA as the nucleophile and the consequent evaluation of rate constants for the individual steps would lead to a better understanding of the results of analogous S_NAr reactions. These are the objectives pursued in the present paper.

Results

The addition of a solution of TNB in Me_2SO to NMA and DABCO in Me_2SO gave rise to a red-colored solution with the characteristic twin absorbance maxima of Meisenheimer complexes[1] at 442 and 524 nm, the lower wavelength absorbance having the higher intensity. The value of the extinction coefficient at 442 nm, obtained by reacting TNB with a very large excess of NMA and DABCO in the presence of 0.1 M tetraethylammonium chloride, was 3.04×10^4 M^{-1} cm^{-1}, similar to the value obtained for aniline.[6] Equilibrium constants were calculated from eq 2, where A_e is the equilibrium absorbance value of the

$$K = \frac{[\text{TNB·NMePh}^-]_e[\text{DABCOH}^+]_e}{[\text{TNB}]_e[\text{PhNHMe}]_e[\text{DABCO}]_e} = (A_e/\epsilon l)^2/\{([\text{TNB}]_0 - A_e/\epsilon l)([\text{PhNHMe}]_0 - A_e/\epsilon l)([\text{DABCO}]_0 - A_e/\epsilon l)\} \quad (2)$$

TNB·NMePh⁻ complex at 442 nm and ϵ is the molar extinction coefficient. As it has been shown that ionic strength effects could be important in these systems where charged products are obtained from uncharged reactants,[6] all measurements were done at constant electrolyte concentration by addition of Et_4NCl.

The rates of formation of the products were followed spectrophotometrically under pseudo-first-order conditions with NMA and DABCO in large excess over TNB. Under these conditions the system reduces to eq 3, i.e., a mixed

$$\text{TNB} \underset{k_r^2}{\overset{k_f^1}{\rightleftharpoons}} \text{TNB·NMePh}^- + \text{DABCOH}^+ \quad (3)$$

first-order (forward) and second-order (reverse) equilibrium process, to which the differential rate eq 4 applies.

$$\text{rate} = \frac{d[\text{TNB·NMePh}^-]}{dt} = k_f^1[\text{TNB}] - k_r^2[\text{TNB·NMePh}^-]^2 \quad (4)$$

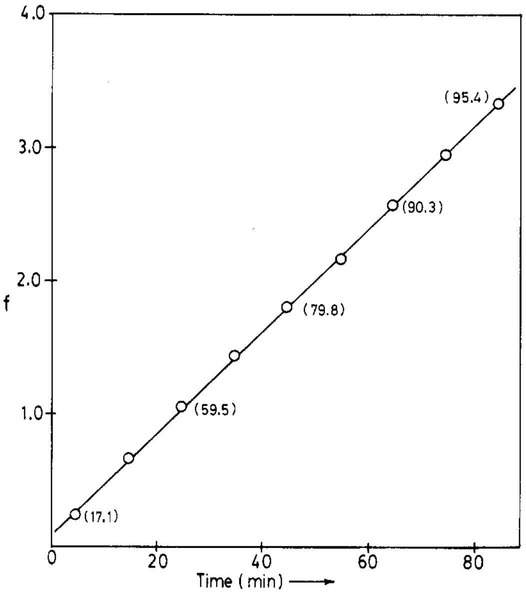


Figure 1. Illustrative plot for a kinetic run, in which the function *f* represents the left-hand side of eq 5. The numerical data adjacent to the points refer to percent conversion with respect to the equilibrium position.

The integrated rate eq 5[11] yielded the pseudo-first-order forward rate constant, k_f^1, by plotting the left-hand side against time after substituting $[\text{TNB·NMePh}^-]_e = A_e/\epsilon l$ and $[\text{TNB·NMePh}^-]_t = A_t/\epsilon l$, where A_t and A_e are the absorbances at time t and at equilibrium, respectively. A

$$\ln \{[\text{TNB·NMePh}^-]_t([\text{TNB}]_0 - [\text{TNB·NMePh}^-]_e) + [\text{TNB}]_0[\text{TNB·NMePh}^-]_e\}/\{[\text{TNB}]_0([\text{TNB·NMePh}^-]_e - [\text{TNB·NMePh}^-]_t)\} = \frac{2[\text{TNB}]_0 - [\text{TNB·NMePh}^-]_e}{[\text{TNB·NMePh}^-]_e}k_f^1t \quad (5)$$

linear plot is expected with slope = $k_f^1(2[\text{TNB}]_0 - [\text{TNB·NMePh}^-]_e)/[\text{TNB·NMePh}^-]_e$. All such plots were in fact linear over 90% conversion as shown in Figure 1 for an illustrative case. The reaction rates and equilibria

---

(11) Moore, J. W.; Pearson, R. G. *Kinetics and Mechanism*; Wiley: New York, 1981; p 305.

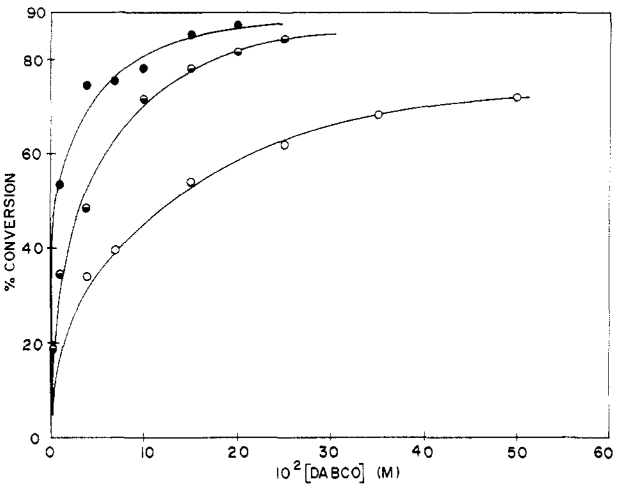


Figure 2. Dependence of the extent of conversion in the reaction of TNB (1.00×10^{-4} M), NMA (5.09×10^{-3} M), and DABCO in Me_2SO at 25 °C to the *N*-methylanilide complex (eq 9) on the concentration of DABCO at constant tetraethylammonium chloride concentration: (○) [Et_4NCl] = 0.029 M; (◒) [Et_4NCl] = 0.101 M; (●) [Et_4NCl] = 0.303 M.

were determined at three different Et_4NCl concentrations and the results are assembled in Table I. The additional quantities given in Table I are defined in eq 6–8.

$$k_f^2 = k_f^1/[\text{PhNHMe}] \qquad (6)$$

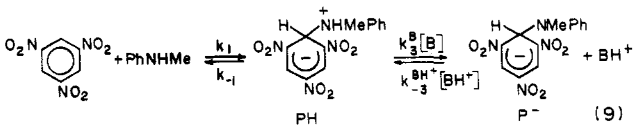
$$k_f^3 = k_f^1/[\text{PhNHMe}][\text{DABCO}] \qquad (7)$$

$$k_r^2 = k_f^3/K \qquad (8)$$

The extent of conversion at constant Et_4NCl concentration increased with DABCO concentration in a nonlinear fashion as shown in Figure 2. At constant DABCO concentration, it is seen that higher percent conversions were obtained as the Et_4NCl concentration was increased. As pointed out before,[6a] a greater uncertainty is associated with the value of K as the percent conversion increases. In all cases plots of k_f^2 vs. DABCO concentration are linear, passing through the origin, as shown in Figure 3.

Discussion

Mechanistic Schemes and Kinetic Form. The kinetic form of reactions involving primary and secondary amines and nitroaromatic substrates can provide information regarding the relative importance of the different elementary steps in the mechanism postulated for the reaction. The absence of an intercept in the linear plots of k_f^2 vs. [DABCO] (Figure 3) indicates that the forward reaction is catalyzed solely by DABCO; i.e., catalysis by both PhNHMe and the solvent Me_2SO is not significant. We previously concluded that the zwitterionic intermediate complex mechanism of eq 9 applies to the analogous reaction with aniline,[6] and the following discussion is predicated on this mechanism which has been established for the TNB/aliphatic amine[12] and TNB/spiro[13a,b] systems as well.



(9)

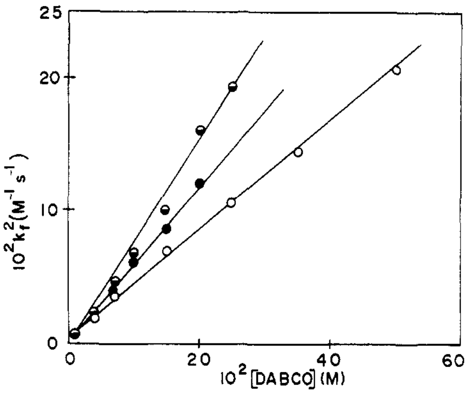


Figure 3. Plots showing the dependence of the second-order forward rate constant k_f^2 on the concentration of DABCO in the reaction of TNB (1.00×10^{-4} M) with NMA (5.09×10^{-3} M) in Me_2SO at 25 °C at constant tetraethylammonium chloride concentration: (○) [Et_4NCl] = 0.029 M; (◒) [Et_4NCl] = 0.101 M; (●) [Et_4NCl] = 0.303 M.

On the assumption that PH can be treated as a steady-state intermediate, eq 10 and 11 can be derived for the second-order forward and the reverse rate constant, respectively. Three cases can be considered. (a) If $k_{-1} \ll$

$$k_f^2 = \frac{k_1 k_3^B[B]}{k_{-1} + k_3^B[B]} \qquad (10)$$

$$k_r^2 = \frac{k_{-1} k_{-3}^{BH^+}}{k_{-1} + k_3^B[B]} \qquad (11)$$

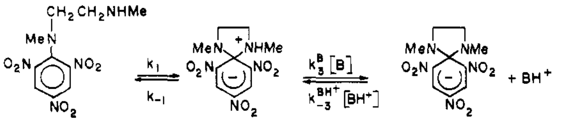
$k_3^B[B]$, then $k_f^2 = k_f^1$, and the measured forward second order rate constant is the rate of formation of PH; i.e., formation of PH is rate-limiting in the forward direction. k_r^2 is therefore a composite quantity; i.e., $k_r^2 = k_{-1}k_{-3}^{BH^+}/k_3^B[B]$. (b) If $k_{-1} \gg k_3^B[B]$, then eq 12 and 13 apply. A linear dependence of k_f^2 on [DABCO] results,

$$k_f^2 = \frac{k_1 k_3^B[B]}{k_{-1}} \qquad (12)$$

$$k_r^2 = k_{-3}^{BH^+} \qquad (13)$$

deprotonation of PH is rate-limiting and k_r^2 is identified as being equal to $k_{-3}^{BH^+}$. (c) If $k_{-1} \approx k_3^B[B]$, then a curvilinear dependence on [DABCO] results. At low [B], base catalysis is observed since in this region $k_{-1} > k_3^B[B]$. As [B] increases, the quantity $k_3^B[B]$ approaches the value of k_{-1} which leads to curvature in the plots.

Our results clearly fall into category b above. Thus the linear plots obtained in Figure 3 indicate that transfer of the labile proton in the zwitterionic intermediate PH to the catalyzing base constitutes the rate-determining step of the reaction. Hence, in terms of the energetics of the reaction, the energy barrier for the proton transfer step is larger than that for reversion of PH to reactants as was the case with aniline as the nucleophile.[6a] The situation in which the energy barriers for both steps are of comparable magnitude has been shown to exist for σ-complex formation in the spiro system given in eq 14.[13a,b]



(14)

Derivation of Specific Rate and Equilibrium Constants. It is desirable to obtain estimates of the various rate and equilibrium constants for the mechanism depicted in eq 9 in order to enable a comparison of the present

---

[12] Crampton, M. R.; Gold, V. *J. Chem. Soc. B* **1967**, 23.

[13] (a) Bernasconi, C. F.; Gehriger, C. L. *J. Am. Chem. Soc.* **1974**, *96*, 1092. (b) Bernasconi, C. F.; Terrier, F. *J. Am. Chem. Soc.* **1975**, *97*, 7458. (c) Bernasconi, C. F.; Muller, M. C.; Schmid, P. *J. Org. Chem.* **1979**, *44*, 3189. (d) Bernasconi, C. F.; Muller, M. C. *J. Am. Chem. Soc.* **1978**, *100*, 5530.

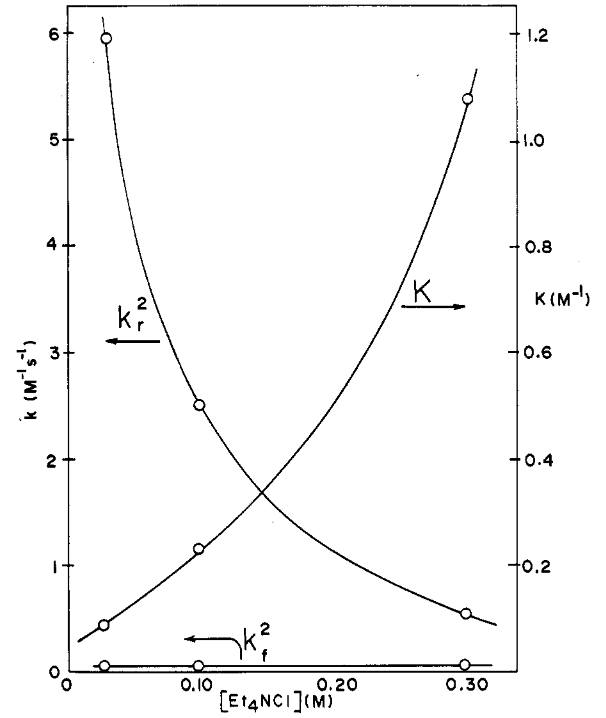


Figure 4. Dependence of rate and equilibrium parameters for reaction in eq 9 on Et_4NCl concentration. Left-hand scale refers to k_f^2 and k_r^2, while right-hand scale refers to K only.

results with data in the literature. As the values of these quantities for the earlier study with aniline as nucleophile[6a] were given at ionic strength of 0.1 M, the values derived below are for our data at $[Et_4NCl] = 0.1$ M.

One can evaluate K_1 in the present system from the relationship $K = K_1K_3 = K_1k_3^{B}/k_{-3}^{BH^+}$ since $k_{-3}^{BH^+} = k_r^2$ and making the usual assumption[1b] that $k_3^{B} \approx 10^7$. Insertion of the experimental values of k_r^2 give $K_1 = 7.5 \times 10^{-8}$ M^{-1} for *N*-methylaniline while Buncel and Eggimann's[6a] results give K_1 for aniline as 1.7×10^{-6} M^{-1}. Hence the ratio $K_1^{A}/K_1^{NMA} \approx 23$ is obtained where the superscripts A and NMA denote aniline and *N*-methylaniline, respectively. Alternative methods of obtaining this ratio are given below.

As it has been shown that the present system falls under category b above, i.e., eq 12 is obeyed, it is then not possible to obtain a value of k_1 (via appropriate plots involving eq 10). However, by utilizing the data of Buncel and Eggiman,[6a] values of the ratio K_1^{A}/K_1^{NMA} can be obtained in two different ways. From eq 12, the slopes of the plots (S) in Figure 3 are given by $S = k_1k_3^{B}/k_{-1}$. If the assumption is made[1b] that k_3^{B}(aniline) $\approx k_3^{B}$(*N*-methylaniline) $\approx 10^7$, and since $S^{A} = 26.7$ and $S^{NMA} = 0.78$, one obtains

$$\frac{S^{A}}{S^{NMA}} = \frac{k_1^{A}}{k_{-1}^{A}} \cdot \frac{k_{-1}^{NMA}}{k_1^{NMA}} = 34$$

The overall equilibrium constant K is known for both nucleophiles, and since $K = K_1K_a^{PH}/K_a^{DABCOH^+}$ where $K_a^{DABCOH^+}$ is the dissociation constant of the conjugate acid of DABCO, it follows that

$$\frac{K^{A}}{K^{NMA}} = \frac{K_1^{A}}{K_1^{NMA}} \cdot \frac{(K_a^{PH})^{A}}{(K_a^{PH})^{NMA}}$$

Bernasconi[13] has shown that for σ-complex formation between R_2NH and TNB, $K_a^{PH}/K_a^{R_2NH_2^+} \approx 500$ where $K_a^{R_2NH_2^+}$ is the dissociation constant of the conjugate acid of the nucleophile forming the complex. If it is then assumed that the small difference in basicity between aniline (pK_a 4.60) and *N*-methylaniline (pK_a 4.84) in water is maintained in dimethyl sulfoxide, then there is little error in assuming that $(K_a^{PH})^{A} \approx (K_a^{PH})^{NMA}$, whence $K^{A}/K^{NMA} = K_1^{A}/K_1^{NMA} = 6$. Thus the three methods of calculation, one based on kinetics, one based on equilibrium constants, and one employing both kinetics and equilibria, give values of the K^{A}/K^{NMA} ratio within a factor of six and show the internal consistency of the method and assumptions employed.

Table II. Relative Values of Kinetic and Equilibrium Parameters for the Reactions of Aniline (A) and *N*-Methylaniline (NMA) with 1,3,5-Trinitrobenzene in Dimethyl Sulfoxide at 25 °C

k_1^{A}/k_1^{NMA}	K_1^{A}/K_1^{NMA}	k_{-1}^{A}/k_{-1}^{NMA}
1.4	23	0.06
1.4	34	0.04
1.4	6	0.23

One can estimate the ratio k_{-1}^{A}/k_{-1}^{NMA} from the relationship $K_1 = k_1/k_{-1}$ if k_1^{A}/k_1^{NMA} is known. For the reaction of 1-chloro-2,4-dinitrobenzene with these nucleophiles in acetonitrile at 30 °C, Bamkole, Hirst, and Hussain[10] give a value of 1.4 for the ratio of the rate constants, while Kavalek et al.[9] for the same system at 20 °C state that *N*-methylaniline reacts two times more slowly than aniline. Assuming a value of 1.4 in the present case, one obtains the values of k_{-1}^{A}/k_{-1}^{NMA} given in Table II. Other relevant kinetic and equilibrium parameters pertaining to these and related systems are assembled in Table III.

Comparison with Other Systems. It is evident from Table III that wherever relevant data are available, PH is a stronger acid than the conjugate acid of the reactant amine (i.e., $K_a^{PH} > K_a^{R_2NH_2^+}$ or $K_a^{ArNH_3^+}$); hence proton transfer from PH to the amine is in the thermodynamically favored direction.

The reactions of *n*-butylamine, benzylamine, and isopropylamine with TNB show a curvilinear dependence of k_f^2 on amine concentration,[14] i.e., at high amine concentrations $k_{-1} < k_3^{B} + k_s$ where k_s is the rate constant for proton abstraction by solvent molecules. The reactions with TFE were carried out at higher amine concentrations than the others and no base catalysis was observed; consequently, no experimental value of k_{-1} is available for this nucleophile. As for a given type of leaving group (e.g., substituted phenoxy)[13d] there is a direct relationship between nucleofugality from PH and the pK_a of the conjugate acid of the leaving group, then in the series of primary aliphatic amines k_{-1} for TFE would be expected to be greater than for *n*-butylamine, i.e., $k_{-1} > 2.3 \times 10^4$ s^{-1}.

In aqueous solution there is only a 10-fold difference between the basicities of aniline, pK_a 4.60,[15] and TFE, pK_a 5.59,[15] and less than a 10-fold difference between the basicities of NMA, pK_a 4.84,[15] and TFE, and if the assumption is made that these differences do not change drastically with change of solvent, then the fact that the reactions of aniline and *N*-methylaniline are base catalyzed while that of TFE is not shows that k_{-1} for the aromatic amines is much greater than that for the aliphatic amine, despite the fact that these amines have approximately equal basicity.

We suggest that the much larger value of k_{-1} for aromatic amines relative to aliphatic amines of similar basicity is due to stabilization of the transition state for decomposition of adduct PH to reactants for aromatic amines, by

---

(14) Crampton, M. R.; Gibson, B. *J. Chem. Soc., Perkin Trans. 2* 1981, 533.

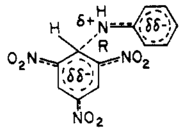
(15) Perrin, D. D. *Dissociation Constants of Organic Bases in Aqueous Solutions*; Butterworths: London, (a) 1965, (b) 1972; (b) Supplement.

Table III. Comparison of Rate and Equilibrium Data for the TNB/NMA/DABCO (in Me_2SO at 25 °C with $[Et_4NCl] = 0.1$ M) and Related Systems

	TNB/NMA/DABCO	TNB/$PhNH_2$/DABCO[b,c]		TNB/TFE[d]	TNB/n-$BuNH_2$[e]	TNB/$PhCH_2NH_2$[e]	TNB/i-$PrNH_2$[e]	TNB/Pip[e]	spiro system[f]
k_1, $M^{-1}\ s^{-1}$	a	a		4×10^{-2}	4.5×10^{4}	1.3×10^{4}	8×10^{3}	$>6 \times 10^{4}$	1.2×10^{3}
k_{-1}, s^{-1}	a	a		$>2.3 \times 10^{4}$	2.3×10^{4} [g]	6×10^{4} [g]	2×10^{4} [g]	$>7 \times 10^{3}$ [g]	1.9×10^{5}
$K_1 = k_1/k_{-1}$, M^{-1}	7.5×10^{-8}	1.7×10^{-6}	$\sim 3 \times 10^{-6}$ [c]	$<1.7 \times 10^{-6}$	2[g]	0.2[g]	0.4[g]	9[g]	6.2×10^{-3}
k_3^B, $M^{-1}\ s^{-1}$	$\sim 10^{7}$ (DABCO)	$\sim 10^{7}$ (DABCO)	$\sim 10^{7}$ (DABCO)	$\sim 10^{7}$	3×10^{7}	7.5×10^{6}	7.5×10^{6}	5×10^{4}	5.2×10^{9} (OH^-) 1.4×10^{4} (H_2O)
$k_{-3}^{BH^+}$, $M^{-1}\ s^{-1}$	2.6 ($DABCOH^+$)	~ 10 ($DABCOH^+$)[b]	~ 375[c] ($DABCOH^+$)		6×10^{4}	1.5×10^{4}	1.5×10^{4}	100	445 (H_2O), 5.9×10^{10} (H_3^+O)
$K_3 = k_3^B/k_{-3}^{BH^+}$	4.2×10^{6}	$\sim 10^{6}$ [b]	2.7×10^{4} [c]		500	500	500	500	
K_a^{PH}, M	1.05×10^{-2}	2×10^{-3} [b]	$\sim 1.10^{-8}$ [c]						4.6×10^{-7}
$K_a^{R_2NH_2^+}$ or $K_a^{ArNH_3^+}$, M	$\sim 2.5 \times 10^{-4}$ ($ArNH_3^+$)	2.5×10^{-4} ($ArNH_3^+$)[b]	2.5×10^{-11} ($ArNH_3^+$)[c]	$\sim 2.5 \times 10^{-4}$	7.9×10^{-12} [h]	4×10^{-10} [i]	2.5×10^{-11} [i]	2.5×10^{-11} [i]	2.8×10^{-9}
$K_a^{PH}/K_a^{R_2NH_3^+}$	~ 42	~ 10	400[c]	500[g]	500[g]	500[g]	500[g]	500[g]	200
K, M^{-1}	0.31	1.7[b]	0.08[c]	0.77	10^{3}	105	200	4.5×10^{3}	

[a] See Table II for k_1/k_{-1} values. [b] Reference 6a; Me_2SO, 25 °C. [c] Reference 7a; MeCN, 30 °C. [d] Reference 7a; Me_2SO, 30 °C. [e] Reference 14; Me_2SO, 25 °C. [f] Reference 13a; aqueous medium, 25 °C. In this case k_1 has units of s^{-1} and K_1 is dimensionless. [g] Values estimated by assuming $K_a^{PH}/K_a^{R_2NH_2^+} = 500$; see ref 13. [h] See ref 17. [i] Value in water.

interaction of the partially liberated lone pair of electrons on the nitrogen atom with the aromatic ring of the amine as shown in 1. Such stabilization is not possible for aliphatic amines. Hirst and co-workers[7] have suggested this effect as a possible explanation for the observed reactivity differences between these two classes of amines in some S_NAr reactions.



1

The reaction between TNB and TFE in acetonitrile (MeCN) is subject to base catalysis, whereas in Me_2SO catalysis is not observed even in the presence of the much stronger base, DABCO.[7] When the solvent is Me_2SO and the substrate is TNB, reactions with strongly basic aliphatic amines show base catalysis.[12] Hence in these systems there is a change of mechanism from deprotonation of PH being the rate-limiting step to its formation constituting the rate-limiting step of the reaction, induced by change of solvent or change of nucleophile. In terms of the mechanism of eq 9, these changes are equivalent to a change from the kinetic condition $k_{-1} \gg k_3^B[B]$ to $k_{-1} \ll k_3^B[B]$. The $k_3^B[B]$ term is actually the sum of all the catalytic rate constants for the deprotonation of PH by the basic species present in solution, i.e., $\sum k_3^B[B]$, considering all basic species that deprotonate PH, including the solvent.

The results outlined above can be understood if in Me_2SO the catalyzed pathway when TFE is the nucleophile involves deprotonation of PH by solvent molecules. This pathway would not be favored either in the poorly basic solvent MeCN, as there is ca. 10^7-fold difference in the basicities of Me_2SO and MeCN,[17] or when the nucleophile (and consequently the catalyst base) is changed to more strongly basic amines.

We have earlier[6] identified the unfavorable thermodynamic factor associated with formation of PH in the case of aromatic amines as being responsible for the inability of these amines to form σ-complexes in the absence of strong but nonnucleophilic amines such as DABCO or Et_3N. Table III provides a quantitative assessment of this effect in Me_2SO for cases where relevant data are available. Thus K_1 values for the aliphatic amines n-butylamine, piperidine, isopropylamine, and benzylamine in Me_2SO are substantially greater than for aromatic amines. For the spiro system data are available in aqueous medium, and there is at least a 600-fold difference between K_1 for this system and those involving aromatic amines. For aniline as the nucleophile, using our earlier assumption that $k_3^B \approx 10^7$ and the experimental value of $k_{-3}^{BH^+} \approx 10$, one obtains $K_3 \approx 10^6$. Also from the expression $K_3 = K_a^{PH}/K_a^{DABCOH^+}$ and the value[18] $K_a^{DABCO} = 2.5 \times 10^{-9}$, $K_a^{PH} = 2.5 \times 10^{-3}$ is obtained, which on using $K_a^{PhNH_2} = 2.4 \times 10^{-4}$ gives $K_a^{PH}/K_a^{ArNH_3^+} = 10$. Thus for the hypothetical reaction between TNB and aniline in Me_2SO where the proton abstraction from the zwitterionic intermediate PH is by aniline, the overall equilibrium constant $K = K_1K_a^{PH}/K_a^{PhNH_3^+} = 1.7 \times 10^{-6} \times 10 = 1.7 \times 10^{-5}$. Hence a much stronger base such as DABCO, for which $K_a^{PH}/K_a^{DABCOH^+} = 10^6$, is needed to displace the equilibrium in the direction of the products.

This requirement for a stronger base can be rationalized in terms of the equilibria in eq 15–17. The equilibrium

$$TNB{\cdot}NH_2Ph^{\pm} + PhNH_2 \rightleftarrows TNB{\cdot}NHPh^- + PhNH_3^+ \quad (15)$$

$$TNB{\cdot}NH_2Ph^{\pm} + RNH_2 \rightleftarrows TNB{\cdot}NHPh^- + RNH_3^+ \quad (16)$$

$$TNB{\cdot}NH_2R^{\pm} + RNH_2 \rightleftarrows TNB{\cdot}NHR^- + RNH_3^+ \quad (17)$$

process for eq 15 is disfavored relative to eq 16 and 17 due to loss in resonance of the aromatic amine in formation of the conjugate acid. Consistent with this explanation is the observed very much smaller value of $k_{-3}^{BH^+}$ (≈ 10) for protonation of $TNB{\cdot}NHPh^-$ by RNH_3^+ compared to protonation of $TNB{\cdot}NHR^-$ ($\approx 10^4$). In the former case, aromaticity of the bound aniline moiety is destroyed in formation of the conjugate acid (PH). It is reasonable that this kinetic effect should be smaller than the equilibrium effect discussed above.

It is noted in this context that from Table III, in the system TNB/$PhNH_2$/DABCO, $K_1 = 1.7 \times 10^{-6}$, whereas for the TNB/TFE system $K_1 < 1.7 \times 10^{-6}$. An apparent anomaly in these relative K_1 values is that the aliphatic

Table IV. Data for the TNB[a]/NMA[b]/DABCO[c] System at Different Et_4NCl Concentrations in Me_2SO at 25 °C

$[Et_4NCl]$, M	% convn	K, M^{-1}	$10^5 k_f^1$, s^{-1}	$10^2 k_f^2$, $M^{-1}\ s^{-1}$	k_f^3, $M^{-2}\ s^{-1}$	k_r^2, $M^{-1}\ s^{-1}$
0.029	33.8	0.085	9.97	1.96	0.49	5.94
0.101	48.5	0.23	11.8	2.31	0.58	2.51
0.303	74.4	1.08	12.0	2.36	0.59	0.55

[a] $[TNB]_o = 1.001 \times 10^{-4}$ M. [b] $[NMA]_o = 5.093 \times 10^{-3}$ M. [c] $[DABCO]_o = 4.00 \times 10^{-2}$ M.

amine spontaneously forms a σ-complex whereas the aromatic amine requires the presence of a stronger base. However, this can also be rationalized in terms of eq 15 and 17 inasmuch that the TFE system does not involve loss in resonance in formation of the conjugate acid.

The variation in K_1 for aliphatic amines follows a trend similar to the basicities of these amines. In water, the order of basicity of the aliphatic amines in Table III as given by their pK_a values is piperidine > *n*-butylamine, isopropylamine > benzylamine > TFE.[15] It has been suggested[14] that the depression of K_1 for isopropylamine reflects unfavorable steric interactions in PH.

It is noted in the present system that although the two amines have approximately the same basicity in water, it is found that $K_1^{NMA} < K_1^{A}$, which again indicates the operation of a steric effect. The greater value of k_{-1} for *N*-methylaniline as compared to aniline (Table II) reflects the effect of release of steric strain in PH as it reverts to reactants.

Kavalek and co-workers[9] have reported that the reaction of NMA with 1-fluoro-2,4-dinitrobenzene in acetonitrile is not catalyzed by NMA, whereas the corresponding reaction of aniline exhibits catalysis by aniline. Moreover, on the basis of the observed order of halogen mobility (Cl > F) for the reaction of NMA, these workers concluded that decomposition of the zwitterionic intermediate to products constitutes the rate-limiting step of the reaction. Hirst and co-workers[7,10] have reported that the same reaction is mildly catalyzed by NMA and strongly catalyzed by DABCO, that when the nucleophile is changed to aniline the corresponding reaction is catalyzed by aniline, and that the uncatalyzed pathway is negligible. Analysis of our rate data as above shows that in the analogous σ-complex-forming reaction, k_{-1} is larger for NMA than for aniline, and hence reactions of NMA should show greater susceptibility to base catalysis than those of aniline. The above results in S_NAr processes can be reconciled on the basis that NMA is ineffective in abstracting the proton from PH because of its greater steric requirement relative to aniline; under such circumstances decomposition of PH would occur largely by an uncatalyzed pathway. Inhibition of the base-catalyzed step due to steric effects has been found before,[2d,16] and it is interesting to note that when the added base is the stronger and sterically less hindered amine, DABCO, the *N*-methylanilinodefluorination reaction becomes base-catalyzed,[10] in agreement with this interpretation.

Salt Effects on the Reaction of TNB with NMA. Our earlier studies with the TNB/aniline/DABCO system[6a,c] have shown that the reaction is subject to significant salt effects. Consequently we have studied rates and equilibria in the present system at three different Et_4NCl concentrations. The results are given in Table IV.

It is found that on increasing $[Et_4NCl]$ the extent of conversion of the reactants to the σ-complex is also increased. The overall equilibrium constant, K, increases 13-fold as $[Et_4NCl]$ is increased from 0.03 to 0.3 M. There is a very modest (ca. 20%) increase in the second-order forward rate constant, k_f^2, which is more than offset by a corresponding 11-fold decrease in k_r^2. The plots given in Figure 4 reveal a behavior which is similar to the effect observed for the TNB/aniline/DABCO system.[6c]

The modest increase in k_f^2 with increasing $[Et_4NCl]$ in this and the TNB/aniline/DABCO system is explicable in terms of stabilization of the transition state for formation of ionic products from neutral species. The direction and magnitude of the salt effect on k_r^2 is the same in both systems. The large decrease in k_r^2 caused by addition of Et_4NCl was earlier explained[6c] as due to the association of Cl^- with protonated DABCO to yield the $DABCOH^+\cdots Cl^-$ heteroconjugate complex. This stabilization of the ground state by heteroconjugation leads to decreased catalytic activity towards the anionic σ-complex P^-, resulting in a decrease in $k_{-3}^{BH^+}$. Since analysis of our kinetic data shows that $k_r^2 = k_{-3}^{BH^+}$ (eq 13), the 11-fold decrease in the value of k_r^2 in Table IV is in line with this hypothesis. It is interesting to note that similar effects have been observed recently by Crampton and co-workers[14,19] in σ-complex forming reactions involving TNB and other nitroaromatic substrates with several primary and secondary aliphatic amines in Me_2SO, and these effects have been rationalized in like terms. This phenomenon therefore appears to be a general one in these reactions.

Conclusions. The present results show that proton transfer between PH and the catalyzing base DABCO constitutes the rate-limiting step over the entire range of DABCO concentrations studied. This observation adds to the growing body of evidence that proton transfers between electronegative atoms could be rate-determining in such processes.[6,7,13,14,19,20] The importance of this observation in the context of S_NAr reactions is that it reinforces the possibility that the proton transfer step could be rate-determining under appropriate conditions.

The present work sheds further light on the differing reactivities of aromatic and aliphatic amines, both in S_NAr processes and in σ-complex formation, where this is accentuated to the extent that the overall equilibrium is highly unfavorable and σ-complex formation does not occur in the absence of a much stronger base (e.g., DABCO). For the first stage, leading to the formation of the zwitterionic intermediate PH, it has been found that k_{-1} for reversion from PH is greater for aromatic than for aliphatic amines of comparable basicities, as a consequence of stabilization of the transition state for reversion of PH

---

[16] (a) Pietra, F.; Fava, A. *Tetrahedron Lett.* **1963**, 1535. (b) Bernasconi, C. F.; Zollinger, H. *Helv. Chim. Acta* **1966**, *49*, 103. (c) Bernasconi, C. F.; Zollinger, H. *Tetrahedron Lett.* **1965**, 1083.

[17] Kolthoff, I. M.; Chantooni, M. K.; Bhowmik, S. *J. Am. Chem. Soc.* **1968**, *90*, 23.

[18] The K_a value for $DABCOH^+$ refers to water as medium, and it is assumed that any deviation due to a differential medium effect, on going to Me_2SO as the medium, would not seriously affect the present discussion. Thus the pK_a of aniline changes from 4.6 in water to 3.6 in Me_2SO,[17] and a corresponding change for DABCO would have little effect on our conclusions.

[19] (a) Crampton, M. R.; Routledge, P.; Golding P. *J. Chem. Soc., Perkin Trans. 2* **1984**, 329. (b) Crampton, M. R.; Routledge, P. *Ibid.* **1984**, 573.

[20] (a) Kresge, A. J. *Pure Appl. Chem.* **1981**, *53*, 189. (b) Barnett, R.; Jencks, W. P. *J. Am. Chem. Soc.* **1968**, *90*, 4199. (c) Kresge, A. J.; Tang, Y. C. *J. Chem. Soc., Chem. Commun.* **1980**, 309. (d) Hibbert, F. *J. Chem. Soc., Chem. Commun.* **1973**, 463. (e) Hibbert, F. *J. Chem. Soc., Perkin Trans. 2* 1974, 1862. (f) Buncel, E.; Wilson, H. *Adv. Phys. Org. Chem.* **1977**, *14*, 133. (g) Hasegawa, Y. *J. Chem. Soc., Perkin Trans. 2* **1985**, 87.

to the reactants for the aromatic amine systems by charge delocalization. In comparison of aniline with NMA, the higher value of k_{-1} for the latter is due to the relief of steric compression in PH on reversion to the reactants. In the second stage, deprotonation of PH by an aromatic amine is strongly disfavored compared to an aliphatic amine due to the loss in resonance stabilization in the resulting conjugate acid.

For aliphatic amine systems in Me_2SO, a change in mechanism results, from formation of PH being rate-determining to its deprotonation being rate-limiting, by a change in the basicity of the reacting amine, from less to more strongly basic; for the weaker bases the solvent-catalyzed reaction becomes the more favorable pathway.

For a weakly basic nucleophile such as TFE a change in mechanism also occurs on switching from Me_2SO to the much less basic acetonitrile, from an uncatalyzed pathway (formation of PH rate-limiting) to a catalyzed pathway (deprotonation of PH rate-limiting).

Experimental Section

Materials. TNB was recrystallized from ethanol and dried in vacuo, mp 123 °C. NMA was purified via the *N*-nitroso derivative,[21] and the resulting amine was fractionated three times under reduced pressure and stored under nitrogen in the dark. A solution of DABCO in benzene was refluxed over potassium hydroxide pellets, the solvent was distilled off, and the DABCO was recrystallized twice from a mixture of benzene–hexane (1:1 v/v) and dried in vacuo. The resulting material was sublimed to yield white crystals, mp 157 °C. Et_4NCl was recrystallized twice from a mixture of benzene–acetonitrile (1:1 v/v) and dried in vacuo. Me_2SO (Fisher Certified Reagent) was distilled from barium oxide under nitrogen and stored in the dark under nitrogen. All solutions were made up in a drybox and protected from light.

Kinetic Measurements. The reactions were followed spectrophotometrically by monitoring the increase in absorbance due to the product, $TNB{\cdot}NMePh^-$, as a function of time on a Beckman Acta IV spectrophotometer at 442 nm, the λ_{max} of the σ-complex. Solutions of DABCO in Me_2SO at a given electrolyte concentration were introduced into a 1-cm cuvette placed in the cell compartment of the spectrophotometer thermostated at 25.0 ± 0.2 °C. Reaction was initiated by injecting 5 μL of a stock solution of TNB in Me_2SO (6.01×10^{-2} M) into 3 mL of the DABCO solution, and the cuvette was shaken to ensure homogeneity. Data were collected at 442 nm. The pseudo-first-order rate constants were calculated by application of eq 5. The plot for a typical run in which $[TNB]_0 = 1.00 \times 10^{-4}$ M, $[NMA]_0 = 5.09 \times 10^{-3}$ M, $[DABCO] = 0.100$ M, and $[Et_4NCl] = 0.101$ M is given in Figure 1.

The molar extinction coefficient for the $TNB{\cdot}NMePh^-$ complex was obtained by increasing the concentrations of NMA and DABCO until conversion of TNB to the σ-complex was complete. The value $\epsilon = 3.04 \times 10^4\ M^{-1}\ cm^{-1}$ at λ_{max} 442 nm obtained in this study is in good agreement with a previously reported value.[4a]

Acknowledgment. We thank the Natural Sciences and Engineering Research Council of Canada for a grant in aid of this research (E.B.) and for a CIDA/NSERC Fellowship (I.O.). Discussions with Prof. J. Hirst are also acknowledged.

Registry No. TNB, 99-35-4; NMA, 100-61-8; DABCO, 280-57-9.

---

[21] Vogel, A. I. *A Textbook of Practical Organic Chemistry*; 4th ed.; Longman: London, 1979; p 671.

Products and Mechanism of the Oxidation of 9-Methylanthracene by Peroxydisulfate. Proton Loss and Nucleophile Addition Reactions of the 9-Methylanthracene Radical Cation[1]

Larrie A. Deardurff,[†] Mikhail S. Alnajjar,[†] and Donald M. Camaioni*

Battelle, Pacific Northwest Laboratories, Richland, Washington 99352

Received March 25, 1986

The Cu(II)–$S_2O_8^{2-}$ oxidation of 9-methylanthracene (**1**) was studied in refluxing CH_3CN/acetic acid and aqueous CH_3CN. Side-chain and nuclear oxidation products and the dimeric compound lepidopterene (**7**) were produced. The lepidopterene was determined to be formed by the reaction of intermediate anthracenylmethyl cation with **1**. In CH_3CN/H_2O nuclear oxidation products, 10-hydroxy-10-methyl-9-anthrone (**2**) and 10-methylene-9-anthrone (**3**) and dimer **7** were produced, with the nuclear products predominating. In CH_3CN/HOAc the dimer and side-chain substitution products, 1–OAc (**5a**) and 1–NHAc (**5c**), were predominant over the nuclear products, which consisted mainly of **3** and 10-acetoxy-9-methylanthracene (**4a**). A mechanism is proposed where the initially formed radical cation undergoes competing proton loss and reversible nucleophile addition reactions to form respectively the anthracenylmethyl radical and nucleophile adduct radicals. Oxidation of the radicals by Cu(II) or $S_2O_8^{2-}$ yield the corresponding cations that react to form the products **4**, **5**, and **7**. Compounds **2** and **3** form by subsequent oxidation of the nuclear oxidation product, 10-methyl-9-anthrol. The results suggest that nucleophile addition is faster than proton loss and that it is more reversible in CH_3CN/HOAc than in CH_3CN/H_2O.

Radical cations have come under intense study due to a growing realization that they are intermediates in many organic reactions.[2-4] Since the early 1970s the oxidations of aromatic substrates by peroxydisulfate have been understood to occur via radical-cation intermediates,[5-8] and the oxidations have proven useful for studying the reactions of aromatic radical cations in solution.[9-13] A large number of functionally substituted alkylbenzene com-

---

[†] University of Washington—Northwest College and University Association for Science (NORCUS) Postdoctoral Research Associates.

(1) This work supported by the Gas Research Institute, Basic Coal Science Program, Contracts 5081-260-0536 and 5084-260-1087.

(2) Pross, A. *Acc. Chem. Res.* **1985**, *18*, 212. Eberson L. *Adv. Phys. Org. Chem.* **1982**, *18*, 79–186. Davidson, R. S. *Adv. Phys. Org. Chem.* **1983**, *19*, 1–130.

(3) (a) Hammerich, O.; Parker, V. D. *Adv. Phys. Org. Chem.* **1984**, *20*, 55–189. (b) Bard, A. J.; Ledwith, A.; Shine, H. J. *Adv. Phys. Org. Chem.* **1976**, *13*, 155–278.

0022-3263/86/1951-3686$01.50/0