The Chemistry of Nitroso-compounds. Part X.[1] Acid Catalysed Nitrosation of Azulene and 1-Nitroazulene

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Rates of nitrosation in dilute aqueous $HClO_4$ and HCl under various conditions are reported for azulene (to form the 1-nitroso-derivative) and 1-nitroazulene. Both reactions show a first-order dependence on substrate, nitrous acid, and solvent acid concentrations, and for azulene the reaction is further catalysed by chloride ion. A primary kinetic hydrogen isotope effect is observed for 1-nitroazulene (k_H/k_D 2.8) but not for azulene. These results are consistent with the expected A–S_E2 pathway characteristic of aromatic electrophilic substitution, where encounter of the reactants is rate limiting for azulene, and proton loss from the Wheland intermediate is rate limiting for 1-nitroazulene. Activation parameters for azulene ($\Delta H^{\ddagger}$ 33 ± 5 kJ mol^{-1}; $\Delta S^{\ddagger}$ 45 ± 7 J K^{-1} mol^{-1}) are consistent with an encounter-controlled rate. These findings confirm recent deductions from the nitrosation of indoles that highly reactive substrates ($pK_a \geqslant -3.5$) react on encounter with NOCl and H_2ONO^+, and suggest that the high reactivity of indoles is not a consequence of reaction at the heterocyclic nitrogen atom.

AROMATIC nitrosation generally proceeds by an A–S_E2 pathway in which proton loss from the Wheland intermediate is rate limiting.[2] Recently, however, two exceptions have been noted.[3,4] The first concerns phenolic compounds where reaction proceeds *via* a neutral dienone intermediate whose formation is slow in mildly acidic buffer solutions (pH 2—5).[3] The second is found for basic indole substrates ($pK_a \geqslant -3.5$) which appear to be sufficiently reactive towards both nitrosyl chloride (NOCl) and the nitrous acidium ion (H_2ONO^+) in aqueous solution to allow diffusion of the reactants to become rate limiting.[4] Although this second finding seems remarkable in view of the relatively low electrophilic reactivity of nitrosating reagents (NO^+, for example, is 10^{14} times less reactive than NO_2^+),[2] a precedent is known from the diazotisation of primary aromatic amines.[5] Here, too, both NOCl and H_2ONO^+ appear to react at a diffusion-controlled rate, but only with aromatic amines that are considerably more basic (and presumably more reactive) than the indole compounds referred to above. Thus the question concerning their high reactivity remains.

One plausible explanation is that nitrosation of indoles proceeds on encounter initially at the heterocyclic nitrogen atom (thereby reflecting their secondary amino-properties) with subsequent rapid rearrangement to the 3-nitroso-product. Formation of the required N-nitroso-intermediates could not be detected experimentally,[4] but the argument is consistent with the high 'kinetic basicity' of the nitrogen atom evident from the enhanced exchange rate of isotopic hydrogen at this site relative to the 3-position.[6]

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[1] Part IX, B. C. Challis and S. P. Jones, *J.C.S. Perkin II*, 1975, 153.

[2] B. C. Challis, R. J. Higgins, and A. J. Lawson, *J.C.S. Perkin II*, 1972, 1831.

[3] B. C. Challis and R. J. Higgins, *J.C.S. Perkin II*, 1973, 1597.

[4] B. C. Challis and A. J. Lawson, *J.C.S. Perkin II*, 1973, 918.

[5] See J. H. Ridd, *Quart. Rev.*, 1961, **15**, 418; B. C. Challis and A. R. Butler, 'Chemistry of the Amino Group,' ed. S. Patai, Wiley, London, 1968, p. 277.

[6] B. C. Challis and E. M. Millar, *J.C.S. Perkin II*, 1972, 1116; M. Koizumi, *Bull. Chem. Soc. Japan*, 1939, **14**, 453, 491.

To test this explanation further, we have now examined the nitrosation of two aromatic hydrocarbons, azulene and 1-nitroazulene, whose basicities are similar to those of the indole substrates. For the hydrocarbons, of course, there is no possibility of a similar intramolecular rearrangement of the kinetic to the thermodynamically stable product. Azulene is reported [7] to give the 1-nitroso-derivative on reaction with nitrous acid, but 1-nitroazulene has not previously been examined in this context. A preliminary account of some of our findings has been published.[8]

EXPERIMENTAL

Substrates and Reagents.—Reagent grade azulene was recrystallised from ethanol and then vacuum-dried over P_2O_5, m.p. 99 °C (lit.,[9] 98.5—99 °C). 1-Nitroazulene was prepared by the method of Anderson *et al.*,[10] recrystallised from methylene chloride–light petroleum and then vacuum dried over P_2O_5, m.p. 107 °C (lit.,[10] 106—107 °C). [3-$^2H_1$]-1-nitroazulene and [1,3-$^2H_2$]azulene were both prepared by stirring homogeneous mixtures of unlabelled substrates (*ca.* 0.5 g), 98% D_2SO_4 (10 ml), D_2O (10 ml), and ether (10 ml; Na-dried) for 24 h at room temperature. After neutralisation the labelled substrates were extracted with ether and purified as for the unlabelled substrates above. Mass spectral analysis showed *ca.* 100% deuteriation of the 3- and 1,3-positions, respectively.

AnalaR $HClO_4$, HCl, $NaNO_2$, and NaCl were used without further purification other than vacuum drying where appropriate. D_2O (Koch–Light; 99.7% D) was redistilled from alkaline $KMnO_4$. D_2SO_4 was prepared by distilling freshly prepared SO_3 into 99.7% D_2O.

Products.—The nitrosation of azulene at the 1-position has been reported [7] and 1-hydroxyiminoazulenium perchlorate is the exclusive product obtained from reaction with nitrosonium perchlorate. The free base (*i.e.* 1-nitrosoazulene) is apparently too unstable to be purified [7] and, indeed, our attempts to isolate this compound were unsuccessful. With the low substrate concentrations employed for the kinetic studies (*ca.* 10^{-5}M), the conjugate acid product was quite stable and the reaction gave a good isosbestic point at λ 290 nm. Assuming quantitative reaction, the u.v. absorption of 1-hydroxyiminoazulenium perchlorate based on the initial azulene concentration gave, in 10^{-3}M-$HClO_4$ at 18 °C, $\lambda_{max.}$ 280 nm (log ε 4.08), 307 (4.23), 350sh (4.02), and 400 nm (3.66).

For 1-nitroazulene, the product from reaction in dilute acid with excess of substrate could not be isolated; t.l.c. analysis of an ether extract, showed a single, yellow highly polar product which darkened to an intractable tar on removal from the plate. From reaction in 1M-$HClO_4$ with excess of HNO_2, however, 1,3-dinitroazulene was obtained. It was therefore assumed that the initial product is 1-nitro-3-nitrosoazulene which is oxidised by either $HClO_4$ or excess of HNO_2. Similar behaviour has been found for the nitrosation of benzene and toluene. Also, nitration of 1-nitroazulene yields 1,3-dinitroazulene exclusively.[10]

Kinetics.—Both reactions were followed by the change of u.v. absorption of the reaction solution contained in a temperature-controlled cell of a Unicam SP 700 spectrophotometer. The reactions were initiated by adding the appropriate amount of aqueous $NaNO_2$ to a temperature-adjusted solution of the azulene and other components in a volumetric flask. After rapid mixing and volume adjustment, a portion of this solution was placed in the spectrophotometer cell. For azulene, the reaction solution was usually monitored at λ 307 nm [log ε (azulene) 3.40; log ε (1-hydroxyiminoazulenium perchlorate) 4.23].

For 1-nitroazulene, $\lambda_{max.}$ 424 nm was used with log ε (1-nitroazulene) 4.19 and log ε (product) 3.66. Absorption of HNO_2 at both wavelengths was negligible (log ε *ca.* 1.5).

1-Hydroxyiminoazulenium perchlorate is stable under the experimental conditions and so the rate of nitrosation of azulene can easily be ascertained from the formation of this product. We noted quantitative reactions and very stable infinity readings.

Further oxidation of the product from the nitrosation of 1-nitroazulene could lead to complications and so we employed conditions where this oxidation was rapid and complete. Errors were further minimised by following the decrease in reactant absorption and by using 100-fold excess of HNO_2: thus even if HNO_2 is consumed in the oxidation, this extra consumption is not kinetically significant. Further details have been given elsewhere [11] and the typical reaction for [3-$^2H_1$]-1-nitroazulene in 1.02M-$HClO_4$ at 25 °C cited in Table 1 shows that the pseudo-first-order rate coefficient (Rate = k_1 [Substrate]) was constant over three half-lives.

TABLE 1

Nitrosation of [3-$^2H_1$]-1-nitroazulene in 1.02M-$HClO_4$ at 25 °C: initial [Substrate] 6 × 10^{-5}M; [$NaNO_2$] 2.90 × 10^{-3}M

t/min	O.D.$_{424}$	% Reaction	10^4k_1/s^{-1}
5	0.889	6.7	Taken as t_0
15	0.777	23.6	3.38
25	0.686	37.5	3.36
35	0.611	49.0	3.37
50	0.536	60.4	3.18
60	0.498	66.2	3.09
70	0.455	72.8	3.16
80	0.424	77.5	3.16
90	0.389	82.9	3.15
100	0.378	87.7	3.14
∞	0.276	100	

RESULTS

Azulene.—Rates of aromatic nitrosation in dilute acid carried out with low nitrite concentrations usually show a first order dependence on both substrate and HNO_2 concentrations [equation (1)]. Data given in Table 2 for two representative acidities confirm the validity of this expression for azulene. k_2 Values are independent of the initial

$$\text{Rate} = k_2\,[\text{Substrate}][\text{HNO}_2] \qquad (1)$$

reactant concentrations and, further, the integrated second-order plots from whence the k_2 values come [which are very sensitive to the validity of equation (1) when the ratio of initial reactant concentrations is *ca.* 2:1] are linear over more than three half-lives.

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[7] K. Hafner, A. Stephen, and C. Bernhard, *Annalen*, 1961, **650**, 42; T. Nozoe, P. W. Yang, H. Ogawa, and T. Toder, *Bull. Chem. Soc. Japan*, 1968, **41**, 2095.

[8] B. C. Challis, R. J. Higgins, and A. J. Lawson, *Chem. Comm.*, 1970, 1223.

[9] 'Dictionary of Organic Compounds,' eds. J. R. A. Pollock and R. Stevens, Eyre and Spottiswoode, London, 1955, 4th edn., vol. 4, p. 2660.

[10] A. G. Anderson, J. A. Nelson, and J. T. Tazuma, *J. Amer. Chem. Soc.*, 1953, **75**, 4980.

[11] R. J. Higgins, Ph.D. Thesis, London, 1972.

Previous experience [3,4] has shown that aromatic nitrosation is usually acid catalysed and azulene conforms in this respect, too. In $HClO_4$, k_2 has a linear dependence on acidity (Figure 1), so the complete kinetic expression here is given by equation (2). The slope of Figure 1 gives $k_3 = 3830$ l^2 mol^{-2} s^{-1} at 2 °C.

$$\text{Rate} = k_3\,[\text{Substrate}][HNO_2][H_3O^+] \qquad (2)$$

TABLE 2

Variation of k_2 with reactant concentrations for the nitrosation of azulene in $HClO_4$ at 2 °C

$10^3[HClO_4]$/M	10^5[Azulene]/M	$10^5[NaNO_2]$/M	k_2/l mol^{-1} s^{-1}
2.5	4.0	11.3	9.3
2.5	2.0	5.6	9.0
2.5	2.0	8.0	9.6
12.0	4.0	5.6	45.2
12.0	4.0	11.3	45.8
12.0	2.0	5.6	46.1

Nitrosation reactions are also prone to catalysis by nucleophilic species (such as Cl^-),[5] and for aromatic nitrosation such catalysis has important mechanistic implications.[4] Addition of NaCl to the reaction of azulene in 5×10^{-3}M-$HClO_4$ increases the rate significantly (Table 3), much more so than that expected for a salt effect. In fact, these data are well fitted to a two parameter rate expression [equation (3)], the first term of which is identical with that for $HClO_4$ [equation (2)] and the second shows a first-order dependence on $[Cl^-]$ as well as $[H_3O^+]$. Values obtained for the two rate coefficients are k_3 3 700 l^2 mol^{-2} s^{-1} and k_4 9.6×10^5 l^3 mol^{-3} s^{-1}. This matter was examined further by measurements in HCl. It is clear from equation (3) that the relationship between k_2, k_3, and k_4 is given by equation (4), and, by noting that $[H_3O^+] = [Cl^-]$ in dilute HCl, equation (5) follows for reaction under these conditions. The relevant plot of $k_2/[H_3O^+]$ *versus* $[H_3O^+]$ shown in Figure 2 has the expected linear form and leads to values of k_3 3 500 l^2 mol^{-2} s^{-1} and k_4 9.7×10^5 l^3 mol^{-3} s^{-1}. Both coefficients are in satisfactory agreement with those obtained from experiments in $HClO_4$ and in $HClO_4$ + NaCl (see earlier).

$$\text{Rate} = [\text{Substrate}][HNO_2]\{k_3[H_3O^+] + k_4[H_3O^+][Cl^-]\} \qquad (3)$$

$$k_2 = k_3\,[H_3O^+] + k_4\,[H_3O^+][Cl^-] \qquad (4)$$

$$k_2/[H_3O^+] = k_3 + k_4\,[H_3O^+] \qquad (5)$$

TABLE 3

Chloride ion catalysis of the nitrosation of azulene in 5.0×10^{-3}M-$HClO_4$ at 2 °C

10^2[NaCl]/M	k_2/l mol^{-1} s^{-1}
0.5	41.8
1.5	90.4
5.5	279
10.5	512

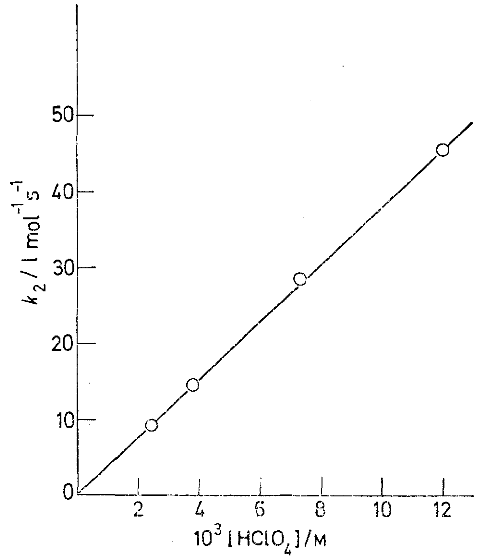

FIGURE 1 Variation of k_2 with $[HClO_4]$ for the nitrosation of azulene at 2 °C

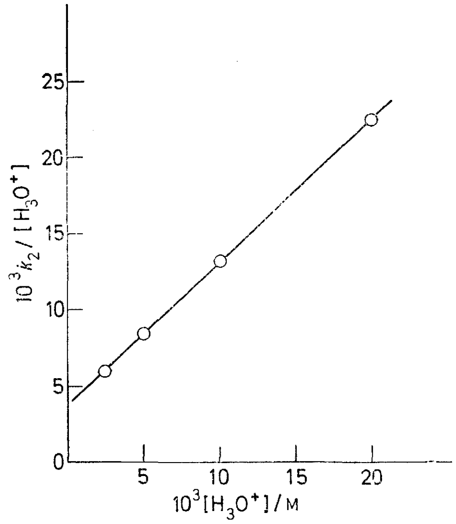

FIGURE 2 Plot of $k_2/[H_3O^+]$ *versus* $[H_3O^+]$ for the nitrosation of azulene in HCl at 25 °C

Deuterium isotope effects. Because hydrogen exchange of [1,3-$^2H_2$]azulene [12] is faster than nitrosation in dilute acid, deuterium isotope effects for nitrosation were obtained by comparison of reaction rates in similarly acidified H_2O and D_2O. These results are listed in Table 4 where it is evident that the experimental isotopic rate ratio (k_2^H/k_2^D) has a mean value of 0.71.

TABLE 4

Deuterium isotope effects for the nitrosation of azulene: $[HClO_4] = [DClO_4] = 8.0 \times 10^{-3}$M

T/°C	Solvent	k_2^L/l mol^{-1} s^{-1}	k_2^H/k_2^D
14.5	H_2O	38.7	0.68
14.5	D_2O	56.8	
25.8	H_2O	81.9	0.75
25.8	D_2O	109	
26.8	H_2O	77.7	0.69
26.8	D_2O	112	

Temperature dependence. Nitrosation rates of azulene were also measured over the temperature range 0—25.3 °C in both 4×10^{-3}M-$HClO_4$ and 1.0×10^{-3}M-$HClO_4$ containing 0.01M-NaCl. Values of k_4 (for the Cl^--catalysed pathway) were obtained from the latter results by subtracting interpolated values of k_3 (measured in $HClO_4$, alone) from the

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[12] J. Schulze and F. A. Long, *J. Amer. Chem. Soc.*, 1964, **86**, 331.

observed reaction rates. These results, including the derived values of k_3 and k_4, are summarised in Table 5.

TABLE 5

Temperature dependence of the rate of nitrosation of azulene in 4×10^{-3}M-$HClO_4$ and 1×10^{-3}M-$HClO_4$ containing 0.01M-NaCl

4×10^{-3} M-$HClO_4$

T/°C	k_2/l mol^{-1} s^{-1}	10^3k_3/l^2 mol^{-2} s^{-1}
25.3	92	23.0
19.6	59.7	14.9
14.5	43.2	10.8
9.0	25.1	6.3
3.9	15.2	3.8
2.0		3.6 [a]
0	11.9	3.0

4×10^{-3}M-$HClO_4$ + 0.01M-NaCl

T/°C	k_2/ l mol^{-1} s^{-1}	$k_3[H_3O^+]$ [b]/ l mol^{-1} s^{-1}	$10^{-6}k_4$/ l^3 mol^{-3} s^{-1}	K_{NOCl} [c]/ mol^2 l^{-2}	$10^{-9}k_{NOCl}$/ l mol^{-1} s^{-1}
21.1	88.5	25.1	6.34	848	5.48
20.2	56.5	16.3	4.02	990	4.27
13.8	36.8	9.44	2.74	1 180	3.16
8.8	26.1	6.84	1.93	1 360	2.63
2.0	13.6	3.60	1.01	1 680	1.70

[a] Mean value from Figure 1. [b] Interpolated from the data for $HClO_4$ alone. [c] Interpolated from Schmid's [17] data.

1-*Nitroazulene*.—At constant acidity, the nitrosation rate for 1-nitroazulene (see earlier) has a first-order dependence on [Substrate]. Also the kinetic dependence on [HNO_2] was briefly checked (Table 6) and, as expected, found to be first order. Thus, as for azulene, the nitrosation of the 1-nitro-derivative follows equation (1).

TABLE 6

Nitrosation of 1-nitroazulene in 1.02M-$HClO_4$ at 25 °C; initial [1-Nitroazulene] 6.0×10^{-5}M

$10^3[NaNO_2]$/M	10^4k_1/s^{-1}	k_2/l mol^{-1} s^{-1}
1.50	4.95	0.33
2.90	9.30	0.32
4.50	15.8	0.35
2.9	3.30	0.116 [a]
4.5	5.40	0.120 [a]

[a] For [3-$^2H_1$]-1-nitroazulene.

The main purpose in examining 1-nitroazulene was to measure the primary deuterium isotope effect for the nitrosation of a deactivated azulenium substrate. In this instance, the rate of hydrogen exchange ($t_{\frac{1}{2}}$ *ca.* 12 h in 1M-$HClO_4$) in dilute acid [12] is substantially less than that of nitrosation ($t_{\frac{1}{2}}$ *ca.* 20 min), so the relevant deuterium substrate could be examined in $HClO_4$, itself. These results are also given in Table 6, and they show that $k_2^H/k_2^D = 2.8 \pm 0.2$ in 1.02M-$HClO_4$ at 25 °C.

DISCUSSION

It is clear from equations (2) and (3) that either one or two pathways are available for the nitrosation of azulene in dilute acid depending on whether or not Cl^- is present in the reaction mixture. Similar kinetic expressions have been observed before with benzenoid [2] and heteroaromatic (indole) [4] substrates where the purely H_3O^+-catalysed pathway [equation (2)] was associated with a reaction of the nitrous acidium ion (H_2ONO^+) and the HCl-catalysed pathway with nitrosyl chloride (NOCl). It seems very reasonable to draw the same conclusions here with both reagents formed in a rapid pre-equilibrium reacting with the neutral substate. Neither azulene (pK_a −1.67)[13,14] nor 1-nitroazulene (pK_a $\leqslant$−4.76)[13] are significantly protonated under our conditions.

The fundamental questions to which our experiments were addressed concern both the rate limiting step for nitrosation and its dependence on the reactivity (basicity) of the azulenium substrate. The answers lie in the magnitude of the hydrogen isotope effects and the activation parameters.

Primary Hydrogen Isotope Effects.—As explained above, measurement of the isotopic rate ratio for azulene nitrosation necessitated the use of a deuteriated solvent. In this event, the experimental ratio (k_2^H/k_2^D *ca.* 0.71) comprises any primary isotope effect for nitrosation plus a solvent deuterium isotope effect for the pre-equilibrium protonation of HNO_2. (No corresponding allowance for the different concentrations of neutral azulene in H_2O and D_2O has to be made because protonation of the substrate is negligible.[13]) The protonation of HNO_2 has not been examined directly, but previous studies of acid catalysed diazotisation suggests that $[D_2ONO^+]/[H_2ONO^+] = 2.2$.[15] Thus, assuming that equation (2) refers to reaction between the nitrous acidium ion and neutral azulene (*i.e.* Rate = k^L[1-L_1-Azulene][L_2ONO^+]*), it can be shown readily that the relationship between k^L and k_2^L is given by equation (6) and that the isotopic rate ratio (*i.e.* the kinetic hydrogen isotope effect after correction for a solvent effect on HNO_2 protonation) is expressed by equation (7). On substituting the right hand side of equation (7) with the values

$$k^L = k_2^L\,[LNO_2]/[L_2ONO^+] \qquad (6)$$

cited above $k^H/k^D = 1.4 \pm 0.2$ for azulene in 0.008M-$HClO_4$ over 14.5—26.8 °C. This ratio, similar in magnitude to that previously observed for 1,2-dimethylindole

$$k^H/k^D = k_2^H\,[D_2ONO^+]/k_2^D[H_2ONO^+] \qquad (7)$$

(k^H/k^D 1.26 ± 0.2),[4] is unreasonably low for a primary hydrogen isotope effect associated with aromatic nitrosation.[2-4] It is consistent, however, with a diffusion controlled nitrosation reaction where the rate ratio arises from the different viscosity of H_2O and D_2O, a factor of *ca* 1.25 at 25 °C.[16]

The datum for 1-nitroazulene is clear cut with k_2^H/k_2^D 2.8 ± 0.2 indicative of slow proton transfer from the Wheland intermediate, as is normal for aromatic nitrosation.[2-4]

Activation Energies.—Direct evidence for a diffusion-controlled reaction with azulene comes from both the magnitudes of the molecular rate coefficients and

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* The symbol L throughout the text refers to isotopic hydrogen, *i.e.* L = D in D_2O and H in H_2O.

[13] F. A. Long and J. Schulze, *J. Amer. Chem. Soc.*, 1964, **86**, 327.

[14] M. T. Reagan, *J. Amer. Chem. Soc.*, 1969, **91**, 5506.

[15] B. C. Challis, L. F. Larkworthy, and J. H. Ridd, *J. Chem. Soc.*, 1962, 5203.

[16] R. Vaillard, 'Nouveau Traite de Chimie Minerale,' ed. P. Pascal, Masson, Paris, 1956, vol. 1, p. 818.

examination of the activation parameters from the data of Table 5. Assuming for the HCl-catalyst pathway (given by coefficient k_4) that NOCl is formed in a rapid pre-equilibrium [equation (8)], it follows that the molecular rate coefficient (k_{NOCl}) for reaction between NOCl and azulene is given by equation (9), where K_{NOCl} = [HNO_2][H_3O^+][Cl^-]/[NOCl].

$$\left.\begin{aligned} HNO_2 + HCl &\overset{K_{NOCl}}{\rightleftharpoons} NOCl + H_2O \\ NOCl + C_{10}H_8 &\xrightarrow{k_{NOCl}} C_{10}H_7NO + HCl \end{aligned}\right\} \quad (8)$$

From the temperature dependence of K_{NOCl} reported by Schmid,[17] it is possible

$$k_{NOCl} = k_4K_{NOCl} \quad (9)$$

to calculate k_{NOCl} at each of the experimental temperatures and these, along with interpolated values of K_{NOCl} from Schmid's [17] data, are also listed in Table 5.

The magnitudes of k_{NOCl} are large, of the order expected for the calculated encounter rate of two neutral species in aqueous solution (*e.g.* $k_{en} = 5 \times 10^9$ l mol^{-1} s^{-1} at 25 °C).[18] Moreover, the temperature dependence of k_{NOCl} (an increase of only *ca.* 3 in going from 2—26 °C) is low, as would be expected for a diffusion-controlled process where the change in solvent viscosity is the major contributor to the activation parameters.[18] The Arrhenius plot of log k_{NOCl}/T *versus* $1/T$ (Figure 3) is satisfactorily linear, and leads to values of $\Delta H^\ddagger$ 33 ± 5 kJ mol^{-1} and $\Delta S^\ddagger$ 45 ± 7 J K^{-1} mol^{-1} at 0 °C. These stand in satisfactory agreement with activation parameters at 0 °C for the diazotisation of three aromatic amines by NOCl (aniline,[19] $\Delta H^\ddagger$ 18.9, $\Delta S^\ddagger$ 0; *o*-chloroaniline,[19] $\Delta H^\ddagger$ 21.2, $\Delta S^\ddagger$ −2.1; *m*-chloroaniline,[20] $\Delta H^\ddagger$ 27.8 kJ mol^{-1}, $\Delta S^\ddagger$ 27.1 J K^{-1} mol^{-1}) all of which are also believed to be encounter-controlled reactions.

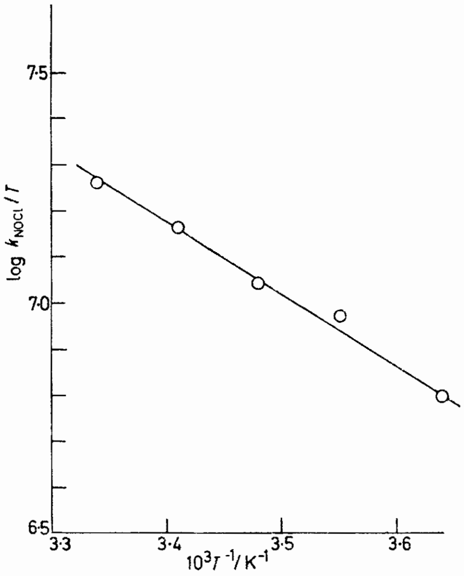
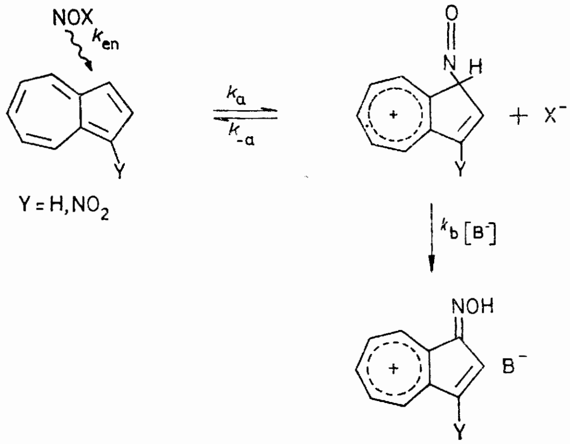


FIGURE 3 Plot of log k_{NOCl}/T *versus* $1/T$ for the chloride ion catalysed nitrosation of azulene

In principle a similar analysis for the purely H_3O^+-catalysed reaction (measured by k_3) could be effected, but here the temperature dependence for the pre-equilibrium formation of H_2ONO^+ is unknown. Values of k_3 do generate a satisfactorily linear Arrhenius plot, however, from which a value of $\Delta H^\ddagger$ 55.5 ± 5 kJ mol^{-1} is obtained.



SCHEME A–S_E2 Pathway for the nitrosation of azulene

A reasonable supposition is that H_2ONO^+ will also react on encounter with azulene, so, assuming that the activation energy is similar for both reagents, the enthalpy associated with the pre-equilibrium formation of H_2ONO^+ is *ca.* 22 kJ mol^{-1}.

Conclusions.—Our findings for azulene and 1-nitroazulene substantiate those reported previously [4] for indole substrates. Thus the significant primary deuterium isotope effect for 1-nitroazulene (k_2^H/k_2^D 2.8) implies that forward decomposition (Scheme, step k_b) of the Wheland intermediate is rate limiting for the A–S_E2 pathway with unreactive substrates. For the more reactive unsubstituted azulene, however, the low activation energy provides clear-cut evidence that diffusion of the reactants (k_{en}) is rate limiting for NOCl, and the diminutive deuterium isotope effect (k_H/k_D 1.4) suggests this to be true for H_2ONO^+ also.

TABLE 7

Values of k_3 and k_{NOCl} for the nitrosation of indoles and azulenes

Substrate	pK_a	T/°C	k_3/ l^2 mol^{-2} s^{-1}	10^8k_{NOCl}/ l mol^{-1} s^{-1}
1,2-Dimethylindole	0.30 [a]	3	530	9.9 [e]
2-Methylindole	−0.28 [a]	3	484	
Azulene	−1.67 [b]	2	3 700 (1 850)	17 (8.5)
2-Phenylindole	−1.85 [c]	3	650	7.7 [e]
2-Methyl-5-nitroindole	−3.58 [a]	0.5	250	3.2 [e]
1-Nitroazulene	−4.68 [d]	25	0.32	No Cl$^-$ catalysis
5-Cyanoindole	−6.0 [a]	0.5	21	
1-Methyl-5-nitroindole	−6.6 [c]	0.5	12	
5-Nitroindole	−7.4 [a]	0.5	4.5	

[a] From R. J. Hinman and J. Lang, *J. Amer. Chem. Soc.*, 1964, **86**, 3796. [b] From ref. 14. [c] From ref. 4. [d] From ref. 13. [e] Recalculated from ref. 4 using revised values of K_{NOCl} = 1 760 and 1 620 mol^2 l^{-2} at 0.5 and 3 °C, respectively.

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The high reaction rates for azulene seem to exclude any possibility that the diffusion-controlled rates for reactive indole substrates (pK_a $\geqslant -3.5$) arise from direct participation of the amino-nitrogen atom. In fact, mean values of k_3 and k_{NOCl} for both azulenes and indoles summarised in Table 7 show clearly that azulene is more reactive than any of the indole compounds studied earlier, particularly towards the H_2ONO^+ reagent. The reasons for this difference are not fully understood at present, but the spread of apparent diffusion rates is similar to those observed for other reactions such as nitration [21] or proton transfer.[22] One contributing factor may be the presence of two equivalent reactive sites (the 1- and 3-positions) in azulene, itself, and supporting evidence to this effect comes from the lower rate of proton transfer because of reduced symmetry for HS^- (three electron pairs) relative to F^- (four electron pairs).[23] Dividing the azulene data by a ' statistical ' factor of 2 gives the parenthesized rate coefficients in Table 7: the datum for NOCl then agrees satisfactorily with those for the indole substrates but that for H_2ONO^+ is still higher by a factor of *ca.* 3.5.

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