J. Org. Chem. **1992**, *57*, 4169–4173

Nucleophilic Reactivity: Nucleophilic Aromatic Substitution Reactions of 2,4-Dinitrochlorobenzene and Picryl Chloride in Aqueous and Methanol Solutions

Joseph R. Gandler,* Irianto U. Setiarahardjo, Chrisanthus Tufon, and Chinpan Chen

Department of Chemistry, California State University, Fresno, California 93740-0070

Received January 24, 1992

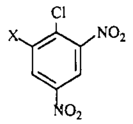
Rate constants for nucleophilic aromatic substitution reactions of picryl chloride, **I**, with acetate ion and a series of amine nucleophiles, including primary, secondary, tertiary (quinuclidines), and amines which show the α-effect, in aqueous and methanol solutions have been measured. Rate constants have also been measured, in water, for the reactions of 2,4-dinitrochlorobenzene, **II**, with trifluoroethylamine and semicarbazide. Reactions of picryl chloride with 3-quinuclidinol and DABCO yield picrate ion via general base catalyzed hydrolysis. On the other hand, reaction with quinuclidine proceeds at least in part via a mechanism in which *N*-picrylquinuclidinium ion is formed and then converted into a *N*-picrylpiperidine derivative. When the kinetic data are combined with data previously reported in the literature, the slopes of plots of log of the second-order rate constants against Ritchie's N+ parameter are 0.95 ± 0.13 and 0.79 ± 0.11 for the reactions of 2,4-dinitrochlorobenzene and picryl chloride, respectively (the reported error limits are the 95% confidence intervals). Steric effects may be important in these reactions, but these effects do not significantly change the slopes of the N+ correlation lines. The slope smaller than one for the reactions of picryl chloride is consistent with decreased selectivity towards nucleophilic attack, and with the modified form of Ritchie's equation, log k = S^+N+ + log k_0, in which relative nucleophilic reactivities are substrate dependent.

The reaction between a nucleophile and an electrophile is one of the most fundamental of all processes in chemistry. One approach to better understanding these reactions has been studies aimed at systematizing and understanding the factors controlling nucleophilic reactivity. Equations such as the Swain–Scott,[1] Edwards,[2] and Brönsted-type[3] equations have been very helpful in this regard.

Ritchie's N+ equation,[4] log k = N+ + log k_0, further complements these useful relationships. This equation has been applied to a variety of reactions in which nucleophilic addition to, or combination with, an electrophilic center is rate-limiting. The N+ equation has successfully correlated data for reactions with stabilized carbocations,[4] such as triarylmethyl, diazonium, and tropylium ions, and reactions at sulfur,[5] aromatic,[6] carbonyl,[7] and π-hydrocarbons, coordinated to a transition metal,[8] centers. However, unlike the Swain–Scott and Edwards equations, which are two- and four-parameter equations, respectively, the N+ equation correlates data using only one parameter (N+) that is characteristic of the nucleophile (and the solvent that the reaction is carried out in), but independent of the electrophile (i.e., in these systems, plots of log k against the N+ parameter are linear with slopes equal to 1).

Several types of deviations from the N+ equation have been identified. For example, deviations due to steric effects are sometimes observed,[9,10] and the reactivities of azide and thiolate ions appear to depend on the character of the electrophile: azide shows an enhanced reactivity toward cationic compared to neutral electrophiles, whereas thiolate ions are relatively more reactive toward "soft" electrophiles than "hard" ones.[6,11] Other "deviations" from the equation include reactions for which plots of log k for nucleophilic addition or combination against N+, although linear, show relative nucleophilic reactivities that are substrate dependent (slopes that are greater or less than 1.0). For example, slopes of 0.47, 0.39, 1.20, and 0.81 have been reported for nucleophilic addition reactions of acetyl chloride,[12] triphenylmethyl carbocation,[13] 9-(dinitromethylene)fluorene,[14] and trianisylmethyl carbocation,[15] respectively, although in the last example the slope equals 1 if the point for the reaction with water is omitted from the correlation line.[9] To accommodate these latter results, a more general form of the equation has been proposed,[14,15] log k = S^+N+ + log k_0, in which S^+ is electrophile dependent.[16]

Because of these reports, we were interested in knowing whether the previously reported correlations with the N+ equation for nucleophilic aromatic substitution reactions of 2,4-dinitrohalobenzenes[6] could be extended to include the more reactive substrate, picryl chloride (**I**). Picryl chloride is ca. 10^3 to 10^4 times more reactive than 2,4-dinitrochlorobenzene in these reactions. We therefore report



I X = NO_2
II X = H

---

[1] Swain, C. G.; Scott, C. B. *J. Am. Chem. Soc.* **1953**, *75*, 141.
[2] Edwards, J. O. *J. Am. Chem. Soc.* **1954**, *76*, 1540.
[3] Brönsted, J. N.; Pederson, K. J. *Z. Phys. Chem., Stoechiom. Verwandschaftsl.* **1924**, *108*, 185.
[4] Ritchie, C. D. *Acc. Chem. Res.*, **1972**, *5*, 348.
[5] Kice, J. L.; Mullan, L. F. *J. Am. Chem. Soc.* **1976**, *98*, 4259.
[6] Ritchie, C. D.; Sawada, M. *J. Am. Chem. Soc.* **1977**, *99*, 3754.
[7] Ritchie, C. D. *J. Am. Chem. Soc.* **1975**, *97*, 1170.
[8] Alavosus, T. J.; Sweigart, D. A. *J. Am. Chem. Soc.* **1985**, *107*, 985.
[9] Bunton, C. A.; Carrasco, N.; Davoudzadeh, F.; Watts, W. E. *J. Chem. Soc., Perkin Trans. 2* **1980**, 1520.
[10] Ritchie, C. D.; Kubisty, C.; Ting, G. Y. *J. Am. Chem. Soc.*, **1983**, *105*, 279 and references cited therein.
[11] Ritchie, C. D.; Gandler, J. R. *J. Am. Chem. Soc.* **1979**, *101*, 7318.
[12] Palling, D. J.; Jencks, W. P. *J. Am. Chem. Soc.* **1984**, *106*, 4869.
[13] McClelland, R. A.; Banait, N.; Steenken, S. *J. Am. Chem. Soc.* **1986**, *108*, 7023.
[14] Hoz, S.; Speizman, D. *Tetrahedron Lett.* **1978**, 1775.
[15] Hillier, K.; Scott, J. M. W.; Barnes, D. J.; Steele, F. J. P. *Can. J. Chem.* **1976**, 54, 3312.
[16] (a) Selectivities also decrease with increasing carbocation reactivities for the reactions of alkyl alcohols toward 1-phenylethyl carbocations,[16b] halide ions toward 2-aryl-1,1,1,3,3,3-hexafluoropropyl carbocations,[16c] and oxyanions toward 1-aryl-2,2,2-trifluoroethyl carbocations.[16d] (b) Richard, J. P.; Jencks, W. P. *J. Am. Chem. Soc.* **1984**, *106*, 1373. (c) Richard, J. P. *J. Am. Chem. Soc.* **1991**, *113*, 4588. (d) Richard, J. P.; Amyes, T.; Vontor, T. *J. Am. Chem. Soc.*, in press.

0022-3263/92/1957-4169$03.00/0

a study of these reactions using acetate ion and a series of amine nucleophiles, including primary, secondary, tertiary (quinuclidines), and amines which show the α-effect, in aqueous and methanol solutions. We have also measured rate constants in water for the reactions of 2,4-dinitrochlorobenzene (**II**) with trifluoroethylamine and semicarbazide—these reactions have not previously been reported in the literature.

The results of this study, when combined with data previously reported in the literature, show that rates of nucleophilic aromatic substitution reactions correlate well with the N+ parameter, but with the slope of a plot of log of the second-order rate constants for nucleophilic substitution against the N+ parameter that is significantly smaller than one for the reactions of picryl chloride. The slopes of the plots of log *k* for nucleophilic attack against the N+ parameter are 0.79 ± 0.11 and 0.95 ± 0.13 for the reactions of picryl chloride (**I**) and 2,4-dinitrochlorobenzene (**II**), respectively. The slope smaller than one observed for the reactions of picryl chloride is consistent with decreased selectivity toward nucleophilic attack and with the modified form of Ritchie's equation in which relative nucleophilic reactivities are substrate dependent.

Experimental Section

All melting points were measured on a Thomas Hoover or Melt-Temp melting point apparatus and are uncorrected. Kinetic experiments and UV–vis spectra were run on a Perkin-Elmer Lamba 6 or Cary 17D UV–vis spectrophotometer.

Materials. Reagent-grade NaCl was used without further purification. Commercially available picryl chloride, 2,4-dinitrochlorobenzene, and amine hydrochlorides were recrystallized prior to use. All free amines were refluxed over clean Na metal for several hours and then distilled. Quinuclidines and their hydrochloride salts were purified by recrystallization or sublimation (quinuclidine) before use.

Preparations of *N*-(2,4-dinitrophenyl)semicarbazide (mp 204–206 °C (lit.[17] mp 207 °C)), *N*-(2,4,6-trinitrophenyl)semicarbazide (mp 218 °C (lit.[17] mp 220 °C)), *N*-(2,4,6-trinitrophenyl)morpholine (mp 160 °C (lit.[18] mp 161 °C), *N*-(2,4,6-trinitrophenyl)trifluoroethylamine (mp 115 °C (lit.[18] mp 115–16 °C)), *N*-(2,4,6-trinitrophenyl)piperidine (mp 106 °C (lit.[19] mp 106 °C)), and *N*-(2,4-dinitrophenyl)trifluoroethylamine (mp 115 °C (lit.[19] mp 115–116 °C)) were carried out according to previously reported procedures.

Kinetics. Kinetic experiments were carried out by following spectrophotometrically the appearance of the substitution product at 358 (the absorbance maximum of picrate ion) or at the absorbance maximum of the substitution product—between 327 and 382 nm. Reactions were studied under pseudo-first-order conditions with the nucleophile in excess over the substrate. The concentration of picryl chloride in these experiments varied from 2.14×10^{-4} to 5.33×10^{-5} M. The reactions of picryl chloride were followed to completion, and plots of log $(A_{inf} - A)$ against time obeyed good pseudo-first-order kinetics. A minimum of 50 data points were analyzed for no less than 2 to 3 half-lives of reaction. For the slower reactions of picryl chloride in DABCO and 3-quinuclidinone buffer solutions, and for the reactions of 2,4-dinitrochlorobenzene with trifluoroethylamine and semicarbazide, rates of reaction were obtained by the method of initial rates in which $k_{obsd} = (\Delta A/\Delta t)/[S]_o(\epsilon_p - \epsilon_s)$ where ΔA is the initial change in absorbance, $[S]_o$, the initial substrate concentration, and ϵ_p and ϵ_s are the molar absorptivities of the product of the reaction and the substrate, respectively.

Measurements of pH were made on a Beckman Altrex 71 pH Meter with a Beckman 39505 combination electrode.

Product Analysis. The products of the reactions of picryl chloride with nucleophiles were characterized by comparing the UV–vis spectrum of the products at the end of kinetic runs with the UV–vis spectrum of authentic samples of the expected substitution products. For the slower reactions of 2,4-dinitrochlorobenzene the products follow from the adherence of the rate constants to the N+ and Brönsted correlation lines that are based on reactions established by kinetic and product studies here and in previous work[6] to involve rate-limiting nucleophilic attack and overall substitution.

Table I. Second-Order Rate Constants for Nucleophilic Aromatic Substitution Reactions of 2,4-Dinitrochlorobenzene and Picryl Chloride[a]

	Nucleophile (N+)[b]	log *k* M^{-1} s^{-1} PC[c]	DNCB[d]
1	$NH_2CH_2CH_2NH_2$ (5.37)	0.412	
2	$NH_2CH_2CH_2NH_3^+$ (3.91)	−0.821	
3	$CF_3CH_2NH_2$ (2.89)	−1.91	−5.58
4	$NH_2NHCONH_2$ (3.17)	−1.10	−5.15
5	morpholine (5.25)	0.23	−2.48[e]
6	piperidine (6.11)	1.05	−1.39
7	HO^- (4.75)	−0.155[f]	−3.91[e]
8	morpholine[g] (5.8)[k]	0.131	−2.59[e]
9	piperidine[g] (6.6)[k]	1.06	−2.00[e]
10	CH_3ONH_2 (3.88)	−1.06	−5.35[e]
11	phenoxide (5.6)		−3.00[e]
12	HOO^- (8.08)		−0.64[e]
13	$^-SCH_2CO_2^-$ (8.7)[l]	3.00[h]	0.57[e]
14	CH_3O^- (7.68)		−1.50[e]
15	thiophenoxide[g] (10.51)		1.30[e]
16	$NH_2CH_2CONHCH_2CO_2^-$ (4.48)	−0.194[i]	−4.20[e]
17	$NH_2CH_2CO_2^-$ (5.22)		−3.40[e]
18	NH_2NH_2 (5.66)	0.959[i]	−2.80[e]
19	quinuclidine (5.50)	−1.31	
20	3-quinuclidinol	−3.22	
21	DABCO (5.30)	−4.01[j]	
21	3-quinuclidine	−4.96	
22	CH_3COO^- (>2.95)	−4.41	
23	H_2O (0)	−7.19[f,m]	
24	CO_3^{2-}	−2.62[f]	
25	HCO_3^-	−3.84[f]	
26	PO_4^{3-}	−2.06[f]	
27	borate	−4.70[f]	

[a] At 25.0 °C in aqueous solution. [b] From ref 7 unless noted otherwise. [c] PC is picryl chloride. [d] DNCB is 2,4-dinitrochlorobenzene. [e] Data from ref 6. [f] Ref 25. [g] In methanol at 25 °C. [h] Data from ref 23. [i] Data from ref 29. [j] log *k* = −4.01 from work reported in ref 25. [k] Ref 30. [l] Based on data from ref 6. [m] In units of s^{-1}.

Results

The reactions of picryl chloride and 2,4-dinitrochlorobenzene with the hydroxide ion, primary, secondary, tertiary, and amines which show the α-effect in aqueous and methanol solutions at 25 °C and a constant ionic strength of 1.0 M, maintained with NaCl, follow the rate law of eq 1, in which k_A and k_{OH} are the second-order rate constants for reactions with amines and hydroxide ion, respectively.

$$k_{obsd} = k_{OH}[OH^-] + k_A[\text{amine}] \tag{1}$$

Reactions in the presence of amine bases were carried out in a buffer of the amine and its conjugate acid, at a constant buffer ratio, in order to maintain constant pH. From the slopes of plots of k_{obsd} against amine or hydroxide ion concentration, second-order rate constants for the reactions of these nucleophiles with picryl chloride and 2,4-dinitrochlorobenzene were calculated; these second-order rate constants are summarized in Table I along with some other data previously reported in the literature.

Figure 1 shows a plot of log of the second-order rate constants for the reactions of 2,4-dinitrochlorobenzene and picryl chloride against the N+ parameter. The slopes of these plots are 0.95 ± 0.13 and 0.79 ± 0.11, respectively—correlation coefficients = 0.97 and 0.98, respectively. The reported error limits in these slopes and

---

(17) Kapil, R. S.; Joshi, S. S. *J. Ind. Chem. Soc.* **1959**, *36*, 505.
(18) Hexet, R. A.; Denk, W. M. *J. Am. Chem. Soc.* **1950**, *72*, 2806.
(19) Biggi, G.; Pietra, F. *J. Chem. Soc. B* **1971**, 44.

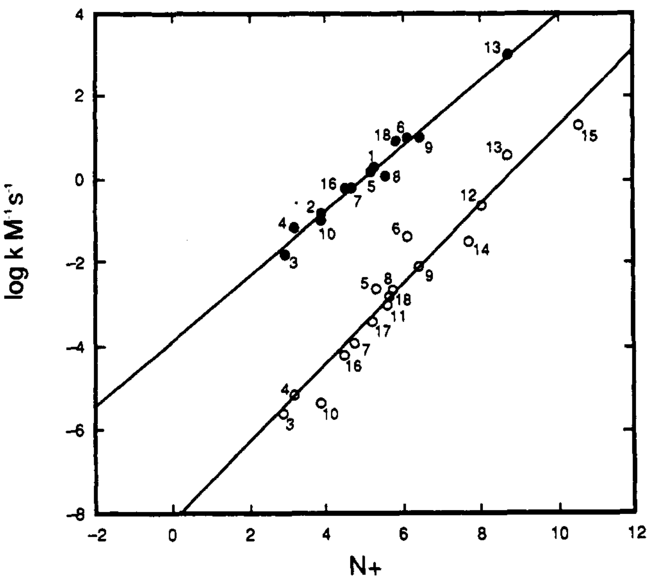
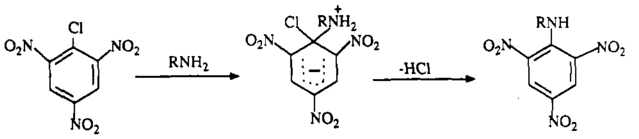


Figure 1. Plot of log *k* for the reactions of nucleophiles with 2,4-dinitrochlorobenzene and picryl chloride against the N+ parameter. In aqueous or methanol solutions at 25 °C.

Scheme I



in all slopes reported in this paper are the 95% confidence limits. Points for sulfur nucleophiles are included in these correlations, because the slopes do not change significantly if they are omitted: the slopes are 0.98 ± 0.19 and 0.77 ± 0.16 for plots in which thiolate ion nucleophiles are excluded.

A plot (not shown) of log *k* for the reactions of picryl chloride against log *k* for the reactions of 2,4-dinitrochlorobenzene, using a common set of 11 nucleophiles (nucleophiles 3–10, 13, 16, and 18) yields a slope of 0.68 ± 0.14 (correlation coefficient 0.96).

Discussion

Reaction Mechanism. The mechanism of nucleophilic aromatic substitution reactions by amines is well established[20] (Scheme I). The mechanism proceeds first by addition of the amine to the aromatic ring to form a Meisenheimer-type complex followed by proton transfer and expulsion of the leaving group (proton transfer and leaving-group expulsion can occur sequentially or concertedly).

Depending on the pK_a of the amine, the nature of the leaving group, and the solvent, the rate-limiting step in these reactions can either be addition of the nucleophile, leaving-group expulsion, or proton transfer.[20] With chloride as the leaving group, rate-limiting addition of the nucleophile is expected.[6,20,21] This is supported by the rate law (eq 1) that is second order—first order in amine and first order in substrate—the good correlations with the N+ parameter (Figure 1), a parameter derived from reactions in which nucleophilic attack is rate-limiting, and a value of β_{nuc} = 0.52, consistent with partial bond formation of the amine nucleophile in the rate-limiting transition state (β_{nuc} is the slope of a plot of log *k* against the pK_a values of the nucleophiles). The β_{nuc} value of 0.52 reported here, for the reactions of **I**, are derived using data from Table I for a series of four primary and two secondary amines (Figure 2a). The secondary amines, piperidine and morpholine, fall on or near the correlation line based on the primary amines (secondary amines are normally more nucleophilic than primary ones). This may be the result of a steric effect that slows the reactions of these secondary amines with picryl chloride. See **Correlations with the N+ Equation**, below, for evidence consistent with steric effects in these reactions. Similar arguments, including halogen leaving group effects (the element effect), have been made to establish rate-limiting nucleophilic attack for the reactions of 2,4-dinitrochlorobenzene, **II**.[6,21]

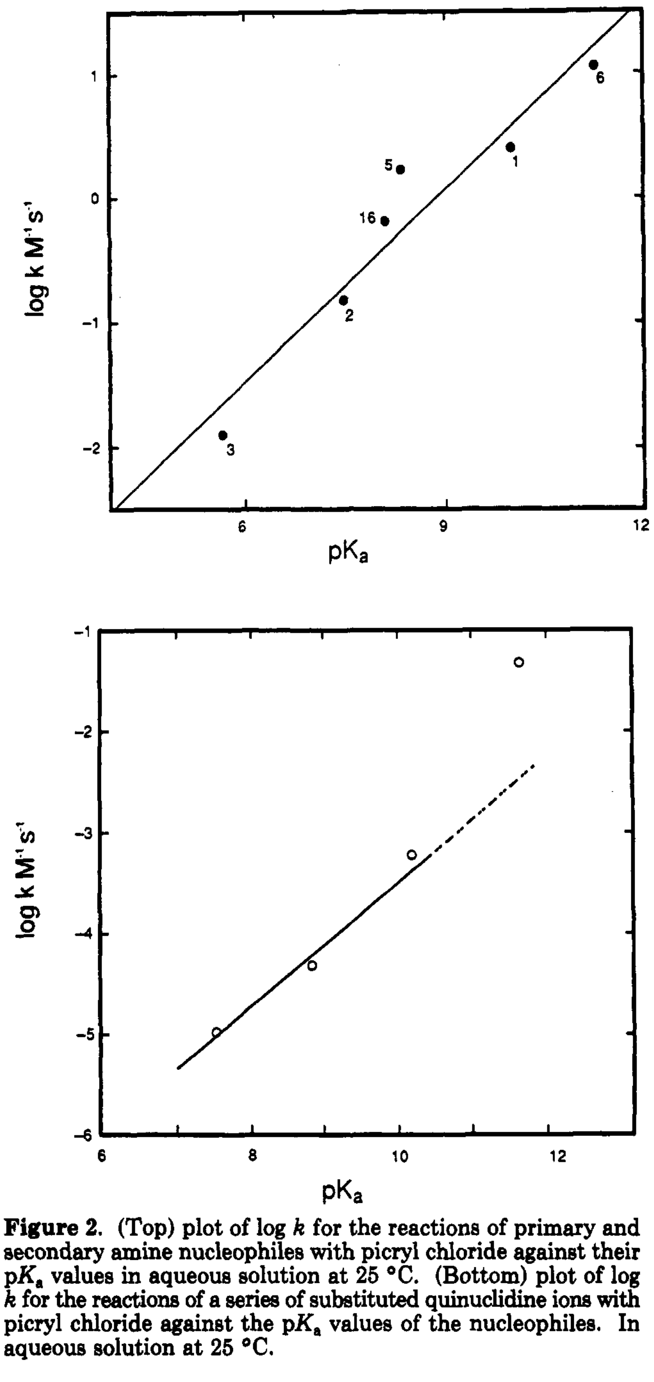


Figure 2. (Top) plot of log *k* for the reactions of primary and secondary amine nucleophiles with picryl chloride against their pK_a values in aqueous solution at 25 °C. (Bottom) plot of log *k* for the reactions of a series of substituted quinuclidine ions with picryl chloride against the pK_a values of the nucleophiles. In aqueous solution at 25 °C.

We considered the possibility that Scheme I is incomplete because it does not take into account nucleophilic addition to the 3-position of the ring. It is known that for a variety of nucleophiles addition is faster to the 3-position

---

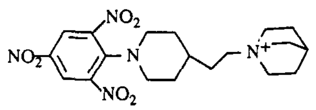
[20] Bernasconi, C. F.; Rossi, R. H.; Schmid, P. *J. Am. Chem. Soc.* **1977**, *99*, 4090.

[21] (a) Miller, J. *Aromatic Nucleophilic Substitution*; Elsevier: Amsterdam, 1968. (b) Bunnett, J. F.; Kato, T.; Nudelman, N. S. *J. Org. Chem.* **1969**, *34*, 785.

than to the 1-position.[22] However, at the concentrations of nucleophiles used in this work, addition to the 3-position does not appear to be a significant side reaction. Plots of k_{obsd} against nucleophile concentration are all linear. If significant amounts of the substrate were converted into the 3-adduct in a fast equilibrium step, then plots of k_{obsd} against nucleophile concentration would show downward curvature, because with increasing nucleophile concentration, increasingly more of the substrate would be in the form of the 3-adduct and formation of this adduct is a side reaction that does not result in product formation. For the hydroxide ion reaction, based on an equilibrium constant of 0.85 l mol^{-1} reported by Crampton[23] for addition of hydroxide ion to the 3-position of picryl chloride, even at the highest concentration of hydroxide ion used in this work (0.05 M), less than 5% of the substrate would be in the form of the 3-addition complex.

A plot of log k against the pK_a values of all the nucleophiles (plot not shown) is badly scattered. Differences of up to 10^8 are observed for bases with similar pK_a values. Part of this scatter is due to deviations that result because different families of nucleophiles (with different nucleophilic atoms) give rise to different Brönsted correlation lines. Brönsted plots for the reactions of picryl chloride illustrate this latter fact. Good correlations are observed for a family of oxyanions (β = 0.38, plot not shown), primary and secondary amines (Figure 2a, β = 0.52), and quinuclidines (Figure 2b, β = 0.66).

The point for quinuclidine appears to show a 12-fold positive deviation from the Brönsted line in Figure 2b, based on the reactions of the other substituted quinuclidines. This positive deviation is consistent with a change in mechanism: from general base to nucleophilic catalysis. Futher support for this interpretation are solvent isotope effects, $k_A(H_2O)/k_A(D_2O)$, that show a break from 1.31 to 1.52 to 1.37 for the reactions promoted by quinuclidinone, DABCO, quinuclidinol, to 0.66 for the reaction promoted by quinuclidine. The UV–vis spectra of the products in these reactions provide further support for a change in mechanism. Whereas for the DABCO and quinuclidinol promoted reactions the product is picrate ion (the products in these reactions gave A_{inf} values that were ca. 5% smaller than expected), for the reaction with quinuclidine (and to a small extent in quinuclidinol buffer solutions at high quinuclidinol concentrations), another product is evident with a maximum near 400 nm that is characteristic of the absorption of *N*-(2,4,6-trinitrophenyl)amines. For example, the UV–vis spectrum of *N*-(2,4,6-trinitrophenyl)piperidine is identical to the spectrum of the product of the quinuclidine promoted reaction, at high quinuclidine concentrations, but with a somewhat smaller molar absorptivity constant—1.15 × 10^4 and 1.37 × 10^4, respectively. These results are consistent with nucleophilic displacement of chlorine by quinuclidine to give *N*-picrylquinuclidinium ion, followed by nucleophilic substitution on the quinuclidine ring to give **III**. Ross[24] showed by product analyses that 4-nitrochlorobenzene and 2,4-dinitrochlorobenzene react in this way with DABCO in acetonitrile solution. The intermediate *N*-picrylquinuclidinium ion may also react with hydroxide ion or chloride ion[24] to give a picramide similar to **III** or, possibly, picrate ion via the S_NAr mechanism.



III

General Base Catalysis. Whereas for the reactions of the primary and secondary amines the reactions are nucleophilic substitutions according to Scheme I, for the reactions catalyzed by oxyanion bases, such as borate, CO_3^{2-}, HCO_3^-, and PO_4^{2-}, and for the DABCO-promoted reaction, a general base catalyzed mechanism has been suggested[25] (general base catalyzed hydrolysis). The small water–DABCO rate constant ratio, 6.6 × 10^{-4} M^{-1}, also supports a general base catalyzed mechanism for the reaction with DABCO. Larger ratios (0.06–0.20) have been suggested for reactions in which DABCO acts as a nucleophile.[26] If these assignments are correct, then the acetate-promoted reaction is also general base catalyzed, because the rate constant for the acetate-promoted reaction obeys the Brönsted correlation line defined by the other oxyanions bases.

The hydroxide ion may also follow a general base catalyzed mechanism because the rate constant for its reaction is correlated by the same Brönsted line. Hydroxide ion also falls near the Brönsted correlation line for the addition of water to triarylmethyl carbocations;[27] it was suggested that a general base catalyzed mechanism applied there, because direct nucleophilic attack was disfavored due to loss of the hydroxide ion's solvation shell as it approaches the electrophilic center in this mechanism. This loss of solvation energy may be sufficiently large so that the normally unfavorable general base catalyzed mechanism is observed. Since picryl chloride also has a reaction site that is hindered, the Brönsted behavior of the hydroxide ion in this reaction may be a manifestation of this same effect.

A mechanism involving single electron transfer with the formation of a charge-transfer complex that collapses to a Meisenheimer complex has been proposed for the hydroxide-promoted reaction of **I**[28a] (but not **II**[28b]) and several other nitro-activated arenes. If the formation of picrate ion from the reactions of **I** with oxyanions proceeds via a general base catalyzed mechanism, then the single electron transfer mechanism is unlikely because this mechanism is not expected to show general base catalysis.

Correlations with the N+ Equation. The correlation with the N+ parameter shown in Figure 1 for the reaction of picryl chloride is a good one, with a slope of 0.79 ± 0.11. The rate constants in this correlation span a range of almost 10^5 in reactivities. The rate constant for the reaction of picryl chloride with water[25] (k = 6.5 × 10^{-8} s^{-1}) shows a 1.5 × 10^3 negative deviation from the correlation line and was not included in the correlation. Deviations of water

---

[22] Buncel, E.; Crampton, M. R.; Strauss, M. J.; Terrier, F. *Electron Deficient Aromatic- and Heteroaromatic-base Interactions*; Elsevier: Amsterdam, 1984.

[23] Crampton, M. R.; Stevens, J. A. *J. Chem. Soc., Perkin Trans. 2* **1990**, 1097.

[24] Ross, S. D.; Bruno, J. J.; Peterson, R. C. *J. Am. Chem. Soc.* **1963**, *85*, 3999.

[25] Rossi, R. H.; Vargas, E. B. *J. Org. Chem.* **1979**, *44*, 4100.

[26] Ritchie, C. D.; Wright, D. J.; Huang, K. S.; Kamego, A. A. *J. Am. Chem. Soc.* **1975**, *97*, 1163.

[27] Gandler, J. R. *J. Am. Chem. Soc.* **1985**, *107*, 8218.

[28] (a) Bacaloglu, R.; Bunton, C. A.; Ortega, F. *J. Am. Chem. Soc.* **1988**, *110*, 3503. (b) Bacaloglu, R.; Blasko, A.; Bunton, C. A.; Dorwin, E.; Ortega, F.; Zucco, C. *J. Am. Chem. Soc.* **1991**, *113*, 238.

[29] Dixon, J. E.; Bruice, T. C. *J. Am. Chem. Soc.* **1972**, 94, 2052. Rate constants corrected from 30 to 25 °C using the Arrhenius equation, assuming an activation energy of 10 kcal/mol.

[30] Values of N+ for morpholine and piperidine in methanol solution were obtained by taking the average value of N+ determined by fitting the rate constants for the reactions of these nucleophiles with 2,4-dinitrofluorobenzene, 2,4-dinitrochlorobenzene, 2,4-dinitrobromobenzene, and 2,4-dinitroiodobenzene to plots of log k against N+ (using the data reported in ref 6). Data for the reactions of these substrates with azide ion were excluded from the correlation lines for the purpose of calculating these N+ values.

from the N+ equation are common and have been attributed to a different mechanism[4] for the addition of water than for the addition of other nucleophiles: general-base catalyzed addition, rather than direct nucleophilic attack (the point for water falls on the Brönsted correlation line based on the other oxyanion catalysts which appear to react via a general-base catalyzed mechanism).

Ritchie reported a slope near 1 when rate constants for the reactions of nucleophiles with 2,4-dinitrochlorobenzene and other 2,4-dinitrohalobenzenes were plotted against the nucleophile's N+ values.[6] We get a slope of 0.95 ± 0.13 (Figure 1), in which data from Ritchie's work[6] and from this study are included in the correlation (rate constants for the reactions promoted by azide ions (in water and methanol) are excluded—see above and ref 6). For the reactions of 2,4-dinitrochlorobenzene, the correlation spans a reactivity range of almost 10^7.

Despite these overall good correlations, there are significant changes in relative nucleophilic reactivities. For example, the piperidine–hydroxide ion rate constant ratio varies from 331 for 2,4-dinitrochlorobenzene to 16 for picryl chloride, and the piperidine–trifluoroethylamine ratio varies from 912 for picryl chloride to 3801 for 2,4-dinitrochlorobenzene. Some of these changes in relative nucleophilic reactivities may be a result of steric effects.[9,10] For example, secondary amines such as piperidine and morpholine are relatively more reactive than less hindered primary amines in reactions with 2,4-dinitrochlorobenzene (e.g., for the reactions of picryl chloride and 2,4-dinitrochlorobenzene the morpholine–semicarbazide and morpholine–methoxylamine ratios are 17 and 363 and 16 and 575, respectively). These effects can not, however, account for the slope of less than one observed for the reactions of picryl chloride, because the slope is not significantly different (0.82 ± 0.11) when the points for the more hindered secondary amines are omitted from the plot.

The slopes less than one observed here for the reactions of picryl chloride (Figure 1) mean that picryl chloride shows a lower selectivity toward nucleophilic attack than does 2,4-dinitrochlorobenzene, in accordance with the reactivity–selectivity principle and with relative nucleophilic reactivities that are substrate dependent.

Cyclodextrin Complexation of the Tetracyanoquinodimethane Anion Radical: The Chemical Consequences of Cavity Size and Alkyl Derivatization

Jackie L. Beckett, Cynthia J. Hartzell, Nathan L. Eastman,† Theodore Blake, and Michael P. Eastman*

Department of Chemistry, Northern Arizona University, Flagstaff, Arizona 86011

Received February 7, 1992

Optical spectroscopy shows that in aqueous solution the tetracyanoquinodimethane anion radical (TCNQ$^-$) exists in equilibrium with its π–π dimer (Boyd and Phillips). A study of the effect of various cyclodextrins on this equilibrium shows strikingly different results depending on cavity size and on alkyl derivatization. The equilibrium is unaffected by the presence of α-cyclodextrin. In contrast, γ-cyclodextrin complexes and stabilizes the π–π dimer. EPR and optical spectroscopy show that the anion radical is included and stabilized by heptakis(2,6-di-*o*-methyl)-β-cyclodextrin and a 2-hydroxypropyl derivative of β-cyclodextrin. Of great interest is the observation that the complex formed by TCNQ$^-$ and β-cyclodextrin rapidly reacts to form a diamagnetic product. Aqueous solutions of this diamagnetic product give evidence of appreciable concentrations of TCNQ$^-$ when heated or when low dielectric solvents like methanol are added. NMR indicates that the diamagnetic product is a dianion formed by the σ bonding of two β-cyclodextrin complexed anion radicals. σ-Bonded dimers of TCNQ$^-$ have been previously observed only in the solid phase (Vu Dong et al., Harms et al.). The tetrafluorotetracyanoquinodimethane anion radical exhibits the same general cyclodextrin chemistry as TCNQ$^-$.

Introduction

Here we describe the interesting aqueous chemistry of the tetracyanoquinodimethane anion radical (TCNQ$^-$) in the presence of cyclodextrins, in particular the formation of a dimer upon inclusion in β-cyclodextrin. Cyclodextrins (CDs) are α-1,4-linked cyclic oligomers of D-glucopyranose that form inclusion complexes with a variety of small molecules. The ability of the cyclodextrins to form complexes with nitroxide radicals in aqueous solution is well-known and has been investigated by EPR, NMR, and electrochemistry.[1-5] Other free radicals, such as the radical intermediate of the nitrophenolate anion and the benzosemiquinone radical anion, which are stable in aqueous solution, also form cyclodextrin complexes.[6,7] The aqueous chemistry of TCNQ$^-$ alone was studied by Boyd and Phillips who reported the reversible dimerization of TCNQ$^-$ in water and used optical spectroscopy to determine the equilibrium constant (2.5×10^3 at 298 K) and the enthalpy of dimerization (−10.4 kcal/mol) associated with the reaction[8]

$$2\mathrm{TCNQ}^- \rightleftharpoons (\mathrm{TCNQ})_2^{2-} \qquad (1)$$

---

† American Chemical Society—Petroleum Research Fund Scholar.

(1) Martinie, J.; Michon, J.; Rassat, A. *J. Am. Chem. Soc.* **1975**, *97*, 1818.
(2) Okazaki, M.; Kuwata, K. *J. Phys. Chem.* **1985**, *89*, 4437.
(3) Eastman, M. P.; Freiha, B.; Hsu, C. C.; Chang, C. A. *J. Phys. Chem.* **1988**, *92*, 1682.
(4) Eastman, M. P.; Brainard, J. R.; Stewart, D.; Anderson, G.; Lloyd, W. D. *Macromolecules* **1989**, *22*, 3888.
(5) Saint-Aman, E.; Serve, D. *New J. Chem.* **1989**, *13*, 121.
(6) Kubozono, Y.; Ata, M.; Aoyagi, M.; Gondo, Y. *Chem. Phys. Lett.* **1987**, *137*, 467.
(7) Kano, K.; Mori, K.; Uno, B.; Kubota, T. *J. Electroanal. Chem.* **1990**, *283*, 187.

0022-3263/92/1957-4173$03.00/0