Reactions of 1-X-2,4,6-Trinitrobenzenes and 1-X-2,4-Dinitrobenzenes with Hydroxide Ions. Comparison of the Relative Rates of Nucleophilic Attack at Substituted and Unsubstituted Ring-Positions

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Kinetic and equilibrium measurements are reported for the reactions with hydroxide ions of 1-X-2,4,6-trinitrobenzenes (X = H, F, Cl, Br, I) in water and of 1-X-2,4-dinitrobenzenes in dimethyl sulphoxide–water (80:20, v/v). Attack at unsubstituted ring-positions results in the formation of σ-adducts while attack at halogen-substituted positions leads to 2,4,6-trinitro- or 2,4-dinitro-phenolate ions by nucleophilic substitution; the rate constants for these processes are compared. The results provide evidence for two types of steric effects: (i) increasing the size of the halogen atom results in disruption of the planarity of the nitro-groups, giving a general decrease in reactivity at both unsubstituted and halogen-substituted positions; (ii) unfavourable steric and electrostatic repulsion between entering and leaving groups slows the attack of hydroxide at carbon atoms carrying Cl, Br, or I. In water there is evidence for ionization of added hydroxy groups [Scheme 1; **(2)**$\rightleftharpoons$**(3)**] and for nucleophilic displacement of nitrite by hydroxide within the 3-hydroxy adducts **(2)** and **(3)**. Contrary to a recent report the reaction of hydroxide ions with nitro compounds to form hydroxy adducts is found to occur without the observation of spectrophotometrically detectable intermediates.

There have been several reports of the observation of σ-adducts[1] during nucleophilic substitutions of ring-activated chlorobenzenes.[2–4] However, spectroscopic and kinetic studies of these reactions have shown that the observed adducts result from nucleophilic attack at unsubstituted ring positions rather than at the chloro-substituted position.[5–9] The intermediates on the substitution pathway are not observed owing to their ready loss of chloride. More generally, attack at unsubstituted ring-positions in aromatics is found to be faster than at similarly activated but substituted positions.[10] This can have important mechanistic and synthetic consequences. For example, reaction of chloronitrobenzenes with carbanions may result in the 'vicarious' substitution of hydrogen in preference to substitution of chloride,[11] and substitutions in heterocyclic systems may occur *via* ring-opened intermediates.[12]

Varying the nature of the halogen displaced can be an important strategy in synthesis. Here we report a kinetic study by stopped-flow spectrophotometry of the reactions with hydroxide ions of a series of 1-X-2,4,6-trinitrobenzenes and 1-X-2,4-dinitrobenzenes (X = H, I, Br, Cl, F). The results allow an examination of the effects of the halogen on the relative rates of nucleophilic attack at both substituted and unsubstituted ring positions, and also a comparison of these effects in the picryl series with those in the less sterically demanding 2,4-dinitrobenzene series.

There is a growing awareness that single electron transfer may be the initial step in a wide range of chemical reactions.[13–15] The ability of aromatic compounds carrying electron-withdrawing groups to act as electron acceptors in basic solutions was established by Russell,[16] and radical anions are accepted to be intermediates in $S_{RN}1$ substitutions[17] and in reductions of such compounds.[18] However, as the number of electron-withdrawing groups in the ring is increased, the formation of anionic σ-adducts becomes increasingly favoured at equilibrium relative to the formation of radical anions.[1,16] An important part of the present paper is an examination of a recent claim[19] that charge-transfer and radical-pair species are observable intermediates during the σ-adduct forming reactions of trinitro-substituted aromatics with hydroxide ions in water.

Table 1. Kinetic data for reaction of *sym*-trinitrobenzene (**1**; X = H) with hydroxide ions in water at 25 °C.

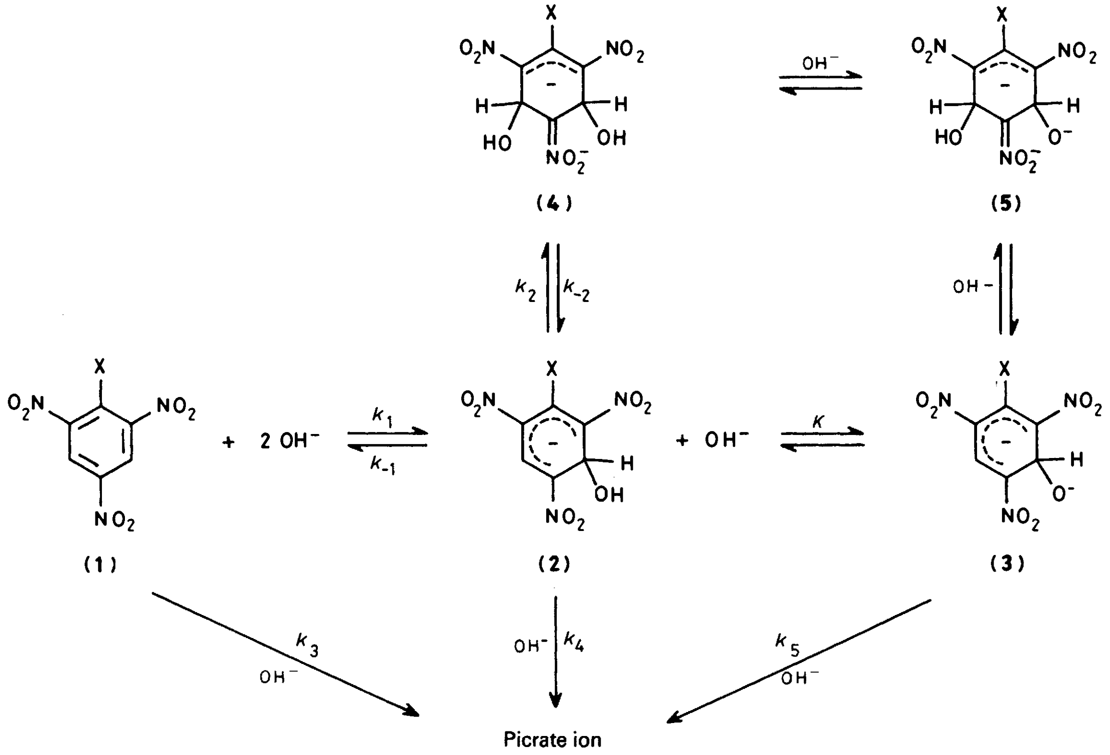
[NaOH][a]/ mol dm^{-3}	k^{b}_{fast}/s^{-1}	$k^{c}_{\text{calc.}}$	k^{b}_{slow}/s^{-1}
0.01	12.7 ± 0.5	12.7	
0.02	12.2	12.2	
0.05	11.7	11.3	0.065
0.10	11.6	11.4	0.065
0.20	13.8	13.7	0.072
0.40	20	21	0.071
0.60	29	29	0.076
0.80	38	38	0.082
1.00	49	47	0.086

[a] I = 2 mol dm^{-3} with NaCl. [b] Measured by stopped-flow in region 400–480 nm. [c] Calculated from equation (1) with k_1 46 dm^3 mol^{-1} s^{-1}, k_{-1} 13.5 s^{-1} and K 10 dm^3 mol^{-1}.

Results and Discussion

Reactions of 1-X-2,4,6-*Trinitrobenzenes with Hydroxide Ions.*—Kinetic measurements were made in water with the sodium hydroxide concentration, (0.01–1 mol dm^{-3}) in large excess of the substrate concentration (1 × 10^{-5} to 1 × 10^{-4} mol dm^{-3}). Ionic strength was maintained at I = 2 mol dm^{-3} using sodium chloride. The results provide evidence for the processes shown in Scheme 1.

sym-Trinitrobenzene (**1**; X = H) has no good nucleofuge at the 1-position so that formation of picrate was not observed. The two rate processes observed by stopped-flow in the visible region are attributed[1,20] to formation of the 3-hydroxy adduct (**2**; X = H) and the 3,5-dihydroxy adduct (**4**; X = H), respectively. This system has been previously studied by Bernasconi and Bergstrom.[20] Our results differ from theirs in that we have made measurements at lower hydroxide concentrations and the dependence of k_{fast} on base concentration (Table 1) is seen to show a minimum at *ca.* 0.1 mol dm^{-3} sodium hydroxide. This behaviour can be understood in terms of



Scheme 1.

ionization of the added hydroxy group [(2) + HO⁻ $\rightleftharpoons$ (3) in Scheme 1] for which there is precedent[6,21–23] in related systems. Since this proton transfer will be rapid on the stopped-flow timescale we obtain equation (1) for the base dependence of

$$k_{\text{fast}} = k_1[\text{NaOH}] + \frac{k_{-1}}{1 + K[\text{NaOH}]} \qquad (1)$$

k_{fast}. Values calculated with k_1 46 dm^3 mol^{-1} s^{-1}, k_{-1} 13.5 s^{-1}, and K 10 dm^3 mol^{-1} give excellent agreement with experimental values. There is a very shallow dependence of k_{slow}, for which equation (2) is predicted, on base concentration. In fact because

$$k_{\text{slow}} = \frac{k_2K_1[\text{NaOH}]^2}{1 + K_1[\text{NaOH}]} + k_{-2} \qquad (2)$$

of the ionization of added hydroxy groups and the rapid equilibration of (2) with (3) and of (4) with (5), values of k_2 and k_{-2} will be weighted averages of values for, respectively, hydroxide attack on (2) and (3) and hydroxide loss from (4) and (5). We do not have sufficient information to determine all the rate coefficients involved. However, the invariance of k_{slow} with base concentration indicates a value for k_{-2} of *ca.* 0.07 s^{-1}.

It has been reported recently[19] that two intermediates may be observed during the formation of (**2**; X = H) from (**1**; X = H) and hydroxide ions. The first species, absorbing at 500 nm, was thought to be a π-complex and the second, absorbing at 258 nm, was thought to be a 'charge-transfer complex of a pair of radicals.' We looked particularly carefully at the absorbances over the complete wavelength during the 5 ms after mixing and were not able to substantiate this claim. In the region 400–500 nm we saw only a single colour-forming process attributable to direct formation of (**2**; X = H). At 258 nm, a wavelength close to the absorbance maximum of the parent, a single fading process was observed with a rate constant identical with that observed at longer wavelength. Cooling the solutions to 10 °C, where rate constants were considerably reduced, failed to provide evidence for the two additional species.

The reactions with base of picryl iodide (**1**; X = I) and picryl bromide (**1**; X = Br) were qualitatively similar to those reported previously[6] for picryl chloride (**1**; X = Cl). In each case initial fast reaction gave the 3-hydroxy adduct (**2**; X = I or Br) with absorption maxima at 420 nm and 480sh nm. Careful examination of the early stages of these reactions indicated direct formation of the adducts from the reactants without the incursion of spectrophotometrically observable intermediates.[19] The variations with base concentration of k_{fast} are shown in Figure 1 and accord with equation (1) indicating rapid equlibration of (**2**) with the ionized forms (**3**). For both (**1**; X = I and Br) a slower reaction, k_{slow}, was observed resulting in the formation of picrate ion ($\lambda_{\text{max.}}$ 350 nm). It is known from independent measurements[6] that the equilibration of picrate ion with its hydroxide adducts is rapid compared with k_{slow}, so that the rate-determining step in the slow reaction will be nucleophilic attack by hydroxide at the ring carbon carrying the halogen. If it is assumed that nucleophilic attack occurs only on the neutral parent then the variation of k_{slow} with base concentration is given by equation (3). However if we also allow

$$k_{\text{slow}} = \frac{k_3[\text{NaOH}]}{1 + K_1[\text{NaOH}] + KK_1[\text{NaOH}]^2} \qquad (3)$$

nucleophilic substitution by hydroxide attack at the 1-position of (**2**) and (**3**) we obtained equation (4). The very much better

$$k_{\text{slow}} = \frac{k_3[\text{NaOH}] + k_4K_1[\text{NaOH}]^2 + k_5KK_1[\text{NaOH}]^3}{1 + K_1[\text{NaOH}] + KK_1[\text{NaOH}]^2} \qquad (4)$$

agreement of the experimental data in Tables 2 and 3 with values calculated using equation (4) than with values calculated using equation (3) argues strongly for substitution by the pathways k_4 and k_5 in Scheme 1. These involve nucleophilic substitutions within 3-hydroxy adducts. Other instances

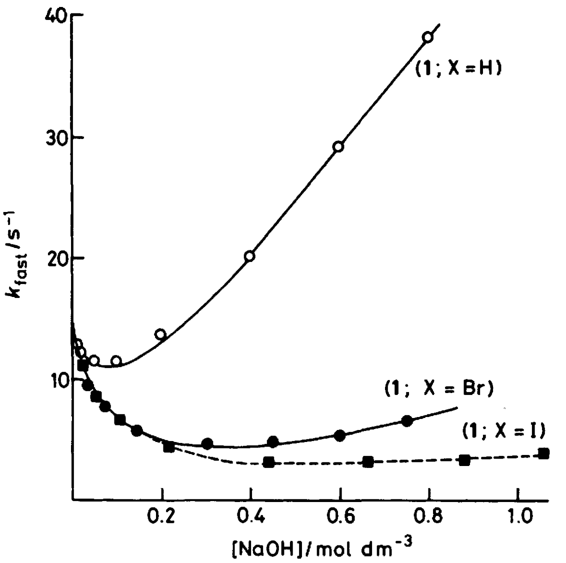


Figure 1. Variation with [NaOH] of k_{fast} for reactions of 1,3,5-trinitrobenzene (○), picryl bromide (●) and picryl iodide (■). All measurements are at 25 °C, and ionic strength 2 mol dm^{-3} using NaCl. The lines are calculated from equation (1) using the values for 1,3,5-trinitrobenzene: k_1 46 dm^3 mol^{-1} s^{-1}, k_{-1} 13.5 s^{-1}, K 10 dm^3 mol^{-1}; picryl bromide, k_1 6.2 dm^3 mol^{-1} s^{-1}, k_{-1} 14 s^{-1}, K 13 dm^3 mol^{-1}; picryl iodide, k_1 2.5 dm^3 mol^{-1} s^{-1}, k_{-1} 15 s^{-1}, K 13 dm^3 mol^{-1}.

Table 2. Rate data for the slow (picrate forming) reaction of picryl bromide (**1**; X = Br) with sodium hydroxide in water at 25 °C.

[NaOH][a]/ mol dm^{-3}	$10^2k^b_{slow}$/s^{-1}	$10^2k^c_{calc.}$	$10^2k^d_{calc.}$
0.022	0.51	0.52	0.52
0.055	1.29	1.27	1.27
0.075	1.75	1.70	1.70
0.11	2.29	2.36	2.5
0.15	3.0	3.0	3.1
0.30	4.5	4.3	4.7
0.45	5.2	4.6	5.4
0.60	5.8	4.3	5.6
0.75	5.4	3.9	5.4

[a] I = 2 mol dm^{-3} with NaCl. [b] Measured as a colour-forming reaction at 360 nm, or fading reaction at 480 nm. [c] Calculated from equation (3) with k_3 0.24 dm^3 mol^{-1} s^{-1}, K_1 0.44 dm^3 mol^{-1} and K 13 dm^3 mol^{-1}. [d] Calculated from equation (4) with k_3 0.24 dm^3 mol^{-1} s^{-1}, k_4 0.1 dm^3 mol^{-1} s^{-1}, k_5 0.02 dm^3 mol^{-1} s^{-1}, K_1 0.44 dm^3 mol^{-1} and K 13 dm^3 mol^{-1}.

Table 3. Rate data for the slow (picrate forming) reaction of picryl iodide (**1**, X = I) with sodium hydroxide in water at 25 °C.

[NaOH][a]/ mol dm^{-3}	$10^2k^b_{slow}$/s^{-1}	$10^2k^c_{calc.}$	$10^2k^d_{calc.}$
0.022	0.17	0.15	0.15
0.055	0.38	0.38	0.38
0.11	0.74	0.75	0.75
0.22	1.5	1.3	1.4
0.44	2.9	2.0	2.8
0.66	4.3	2.2	4.0
0.88	5.0	2.2	5.0
1.1	5.6	2.0	6.0

[a] I = 2 mol dm^{-3} with NaCl. [b] Measured as a colour-forming reaction at 360 nm, or fading reaction at 480 nm. [c] Calculated from equation (3) with k_3 0.07 dm^3 mol^{-1} s^{-1}, K_1 0.17 dm^3 mol^{-1}, K 13 dm^3 mol^{-1}. [d] Calculated from equation (4) with k_3 0.07 dm^3 mol^{-1} s^{-1}, k_4 0.05 dm^3 mol^{-1} s^{-1}, k_5 0.05 dm^3 mol^{-1} s^{-1}, K_1 0.17 dm^3 mol^{-1}, K 13 dm^3 mol^{-1}.

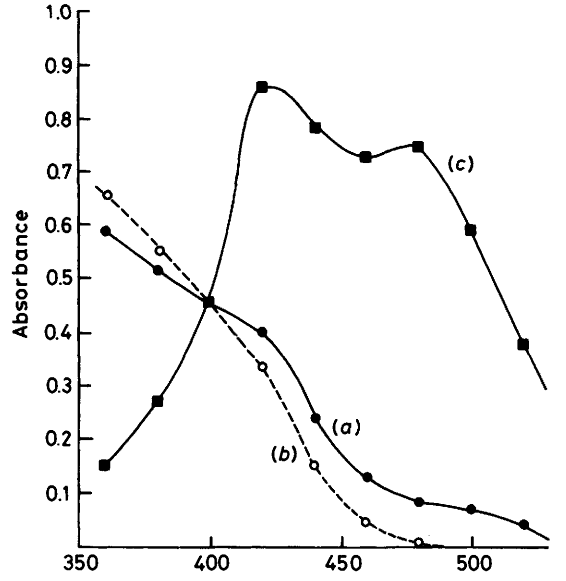


Figure 2. Visible spectra of picryl fluoride (**1**; X = F) (5 × 10^{-5} mol dm^{-3}) and sodium hydroxide (0.12 mol dm^{-3}) in water: (*a*) on completion of the fast reaction (●) corresponding to a mixture of picrate and adduct (**2**) $\rightleftharpoons$ (**3**); (*b*) on completion of the slow reaction (○), corresponding to picrate; (*c*) spectrum calculated for the adduct (**2**) $\rightleftharpoons$ (**3**) (■).

involving substitutions by attack on σ-adducts have been reported.[6,24]

Our results for the picryl halides indicate that the two major reactions involve formation of the 3-hydroxy adducts and nucleophilic substitution of halide ions. We have no direct evidence for formation of the 1,2-dihydroxy adducts (**4**) and (**5**) (X = Br, I). This is probably a consequence of the low values of equilibrium constants for formation of (**4**) and (**5**) from (**2**) and (**3**). Since these latter reactions are equilibria while nucleophilic substitution involves an essentially irreversible attack of hydroxide at the 1-position it does not follow that values of rate constants, k_2, are necessarily lower than values of k_4 and k_5. However, we were able to discern at the highest base concentrations used a third very slow reaction giving rise to a small increase in absorbance at 360 nm. This process might be attributable to the slow conversion into picrate of small concentrations of (**4**) and/or (**5**) formed in these systems.

The reaction of picryl fluoride (**1**; X = F) with hydroxide was, interestingly, different to those of the other picryl halides in that in an initial fast process the parent was partitioned between the 3-hydroxy adducts (**2**) and (**3**) (X = F) and picrate ion. A second, much slower process, results in conversion of the adduct into picrate. Visible spectra are shown in Figure 2. Treatment by standard methods[25] gives equations (5) and (6) respectively for the base dependences of these processes. Data

$$k_{fast} = (k_3 + k_1)[\mathrm{NaOH}] + \frac{k_{-1}}{1 + K[\mathrm{NaOH}]} \quad (5)$$

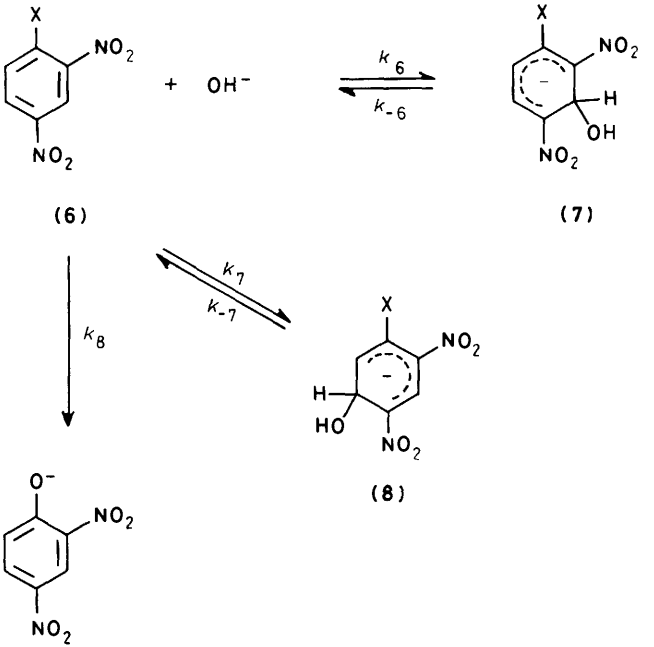
$$k_{slow} = \frac{k_{-1}}{(1 + K[\mathrm{NaOH}])} \cdot \frac{k_3}{(k_3 + k_1)} \quad (6)$$

are in Table 4. A plot, not shown, of k_{fast} *versus* base concentration was linear with a small intercept. This indicates that the first term in equation (5) dominates the rate expression and gives a value for $k_1 + k_3$ of 850 dm^3 mol^{-1} s^{-1}. In order to split this sum we used the initial absorbance at 480 nm, where

Table 4. Rate data for reaction of picryl fluoride (**1**; X = F) with sodium hydroxide in water at 25 °C.

$[NaOH]^a$/ mol dm^{-3}	k^b_{fast}/s^{-1}	k^c_{slow}/s^{-1}	$k^d_{calc.}$
0.011	11	1.83	1.83
0.027	24	1.71	1.71
0.055	46	1.54	1.53
0.072	61	1.44	1.42
0.096	84	1.33	1.31
0.11	93	1.21	1.25
0.22	185	0.95	0.92

[a] I = 2 mol dm^{-3} with NaCl. [b] Measured as a colour-forming reaction at 400 nm. [c] Fading reaction at 480 nm. [d] Calculated from equation (6) with k_{-1} 2.2 s^{-1}, K 5 dm^3 mol^{-1} and $k_3/(k_1 + k_3)$ with value 0.88.



Scheme 2.

picrate does not absorb, and an extinction coefficient, ε = 1.5 × 10^4 dm^3 mol^{-1} cm^{-1}, typical of hydroxy adducts[1] to calculate the fraction of adduct produced in the initial reaction. The value of 0.12 ± 0.02 obtained for this fraction leads to values for k_3 750 and k_1 100 dm^3 mol^{-1} s^{-1}. The data for the slower reaction, k_{slow} are consistent with equation (6) with values k_{-1} 2.2 s^{-1}, K 5 dm^3 mol^{-1} and the ratio $k_3/(k_3 + k_1)$ = 0.88.

Reactions of 2,4-*Dinitrophenyl Halides with Hydroxide Ions.*—Measurements were made in dimethyl sulphoxide (DMSO)–water (80:20, v/v) where there was evidence for the processes shown in Scheme 2. The 3-hydroxy adducts (**7**) have absorption maxima at longer wavelength, $\lambda_{max.}$ 560—580 nm, than the 5-hydroxy adducts (**8**), $\lambda_{max.}$ 505–510 nm, where addition occurs *para* to a strongly electron-withdrawing group.[1] There is eventually complete conversion into the 2,4-dinitrophenolate ion with $\lambda_{max.}$ 360, 420 nm. There is strong evidence[1,10,26] that DMSO has good ability to solvate delocalized negative charges but is much inferior to water in the solvation of localized negative charges; we found no evidence here for ionization of the added hydroxy groups in (**7**) and (**8**) to form dianionic species.

With (**6**; X = I, Br, Cl) two major processes were observable on the stopped-flow timescale. The fast, k_{fast}, involved equilibration of (**6**) with the 5-hydroxy adduct (**8**) and the slower, k_{slow}, conversion into dinitrophenolate ion. Since these processes were well separated in time their dependences on base concentrations are given by equations (7) and (8), respectively.

$$k_{fast} = k_7[OH^-] + k_{-7} \tag{7}$$

$$k_{slow} = \frac{k_8[OH^-]}{1 + K_7[OH^-]} \tag{8}$$

Data allowing the determination of values of rate and equilibrium constants are given in Tables 5–7. At the base concentrations used, formation of the 3-hydroxy adducts (**7**), although faster than the two measured processes, was a minor reaction accounting for < 10% of the substrate.

2,4-Dinitrophenyl fluoride was considerably more reactive than the related 2,4-dinitrophenyl halides and the analysis of kinetic data was more complicated. We first determined the value 500 ± 20 dm^3 mol^{-1} s^{-1} for k_8 in DMSO–water (80:20) by linear extrapolation (plot of log k_8 *versus* mole fraction of DMSO[1,10,25,27,28]) of data obtained in media containing 50, 60, and 70% DMSO where formation of the dinitrophenolate ion was the only major reaction. In DMSO–water (80:20) with base (0.001—0.01 mol dm^{-3}) formation of dinitrophenolate with $\lambda_{max.}$ 420 nm was again the major reaction; however, rapid reactions involving formation of the 3-hydroxy and 5-hydroxy adducts were observable. Equilibration of the parent and (**7**; X = F) was observed as a rapid process with low amplitude at 560—580 nm. Extrapolation to zero base concentration of rate constants measured at 570 nm gave a value for k_{-6} of 9 ± 2 s^{-1}, and using the initial absorbances at 570 nm together with an extinction coefficient, ε = 2 × 10^4 dm^3 mol^{-1} cm^{-1} typical for such adducts, we obtained a value for K_6 of 6 ± 1 dm^3 mol^{-1}. Hence k_6 ($=K_6k_{-6}$) has the value 50 ± 20 cm^3 mol^{-1} s^{-1}. Nevertheless, in the stated range of base concentrations the 3-hydroxy adduct accounted for <10% of the parent. At 510 nm, the absorption maximum of the 5-hydroxy adduct, two reactions were observed, a fast colour-forming process, k_{fast}, and a slower fading reaction, k_{slow}. Since these latter reactions are strongly coupled it can be shown using standard methods[25] that equations (9) and (10) will apply. Linear plots not shown

$$k_f + k_s = (k_7 + k_8)[OH^-] + k_{-7} \tag{9}$$

$$k_fk_s = k_8k_{-7}[OH^-] \tag{10}$$

gave values for k_{-7} of 1.1 ± 0.1 s^{-1} and $k_7 + k_8$ of 700 ± 50 dm^3 mol^{-1} s^{-1}. Since k_8 has been determined to be 500 dm^3 mol^{-1} s^{-1}, we obtain, by difference, a value of 200 ± 50 dm^3 mol^{-1} s^{-1} for k_7. Thus K_7 ($=k_7/k_{-7}$) has the value 180 dm^3 mol^{-1}.

Comparison of Rate and Equilibrium Constants.—Data are summarized in Tables 9 and 10. It must be noted that we have applied statistical corrections to experimental data so that rate and equilibrium constants apply to reaction at single ring positions of the substrates. Also, values for the 2,4-dinitro series were obtained in DMSO–water (80:20, v/v) and are thus not directly comparable with those for the 2,4,6-trinitro series which relate to water as the solvent. It is expected[1,10,26–28] that values for rate coefficients for forward reactions and for equilibrium constants will increase with increasing proportion of DMSO while values for reverse coefficients will decrease.

Values of K_1 in Table 9 refer to hydroxide addition at unsubstituted ring-positions of the trinitro-activated compounds. Values for the 1-halogeno compounds are compared with *sym*-trinitrobenzene by the ratios $K_1(X)/(K_1(H)$. The polar effect at the 3-position of the *meta*-halogen substituents should

Table 5. Kinetic and equilibrium data for reaction of 2,4-dinitrophenyl iodide[a] with hydroxide in DMSO–water (80:20, v/v) at 25 °C.

[NMe$_4$OH]/ mol dm^{-3}	k^b_{fast}/ s^{-1}	Absorbance[c] 510 nm	K^d_7/dm^3 mol^{-1}	k_{slow}/s^{-1}	$k^e_{calc.}$
0.010	0.76	0.0034	8.4	—	—
0.020	0.88	0.0052	6.7	0.0070	0.0060
0.035	0.94	0.0084	6.8	0.0104	0.0096
0.050	1.00	0.0116	7.2	0.0126	0.0125
0.075	1.15	0.016	7.6	0.015	0.016
0.10	1.36	0.019	7.6	0.017	0.019

[a] Concentration is 1 × 10^{-5} mol dm^{-3}. [b] Measured at 510 nm by stopped-flow spectrophotometry. Values of k_7 6 dm^3 mol^{-1} s^{-1} and k_{-7} 0.7 s^{-1} obtained using equation (7). [c] On completion of the fast reaction, measured with 2 mm pathlength cell. [d] Calculated as absorbance/(0.044 − absorbance)[NMe$_4$OH]. [e] Calculated from equation (8) with k_8 0.35 dm^3 mol^{-1} s^{-1} and K_7 8 dm^3 mol^{-1}.

Table 6. Kinetic and equilibrium data for the reaction of 2,4-dinitrophenyl bromide[a] with hydroxide in DMSO–water (80:20, v/v) at 25 °C.

[NMe$_4$OH]/ mol dm^{-3}	k^b_{fast}/ s^{-1}	Absorbance[c] 510 nm	K^d_7/dm^3 mol^{-1}	k_{slow}/s^{-1}	$k^e_{calc.}$
0.010	0.76	0.015	16	0.0032	0.0034
0.020	0.91	0.026	15	0.0066	0.0064
0.040	1.10	0.042	15	0.0083	0.0097
0.060	1.38	0.047	13	0.010	0.012
0.080	1.62	0.061	16	0.013	0.014
0.10	1.75	0.070	17	0.015	0.015

[a] Concentration is 2.5 × 10^{-5} mol dm^{-3}. [b] Measured by stopped-flow spectrophotometry at 510 nm. Values of k_7 11.2 dm^3 mol^{-1} s^{-1} and k_{-7} 0.7 s^{-1} obtained using equation (7). [c] On completion of the rapid reaction, with 2 mm pathlength cell. [d] Calculated as absorbance 510/(0.11 − absorbance 510)[NMe$_4$OH]. [e] Calculated from equation (8) with k_8 0.4 dm^3 mol^{-1} s^{-1}, K_7 16 dm^3 mol^{-1}.

Table 7. Kinetic and equilibrium data for reaction of 2,4-dinitrophenyl chloride[a] with hydroxide in DMSO–water (80:20, v/v) at 25 °C.

[NMe$_4$OH]/ mol dm^{-3}	k^b_{fast}/s^{-1}	Absorbance[c] 510 nm	K^d_7/dm^3 mol^{-1}	k_{slow}/s^{-1}	$k^e_{calc.}$
0.01	0.88	0.0067	18	—	
0.02	1.12	0.013	21	0.013	0.013
0.035	1.34	0.017	18	0.018	0.019
0.05	1.65	0.023	22	0.023	0.023
0.075	1.80	0.028	23	0.028	0.027
0.10	2.16	0.032	26	0.030	0.029

[a] Concentration is 1 × 10^{-5} mol dm^{-3}. [b] Measured at 510 nm by stopped-flow spectrophotometry. Values of k_7 17 dm^3 mol^{-1} s^{-1} and k_{-7} 0.7 s^{-1} obtained using equation (7). [c] On completion of the fast reaction, measured with cell of 2 mm pathlength. [d] Calculated as absorbance/(0.044 − absorbance)[NMe$_4$OH]. [e] Calculated from equation (8) with k_8 (1 dm^3 mol^{-1} s^{-1}, K_7 24 dm^3 mol^{-1}.

Table 8. Kinetic data for reaction of 2,4-dinitrophenyl fluoride[a] with hydroxide in DMSO–water (80:20, v/v) at 25 °C.

[NMe$_4$OH]/ mol dm^{-3}	k^b_{fast}/s^{-1}	k^c_{slow}/s^{-1}
0.002	1.8	0.38
0.004	3.2	0.67
0.006	4.3	0.74
0.008	6.4	0.78
0.010	7.6	0.81
0.012	8.2	0.84

[a] Concentration is 5 × 10^{-5} mol dm^{-3}. [b] Colour forming at 510 nm. [c] Fading at 510 nm.

be similar since σ_M values are in the narrow range 0.34–0.39 for the four halogens.[29] The observed decrease in the values of $K_1(X)/K_1(H)$ in the order F > H > Cl > Br > I indicates that steric effects play a dominant role here. The presence of three groups at the 2-, 1-, and 6-positions will result in severe steric crowding[1] so that nitro groups are rotated from the ring-plane and the ring will show decreased reactivity towards nucleophiles.[30] The lower values of K_1 and of k_1 for (**1**; X = Cl, Br, I) relative to (**1**; X = H) indicate the importance of this effect. In (**1**; X = F) the smaller size of fluorine will allow a return to coplanarity, or near coplanarity, of the substituents so that the expected electron-withdrawing effect at the 3-position of the fluorine substituent is observed. It is significant that data in Table 10 for the 2,4-dinitro series, where steric disruption around the 1-position will be reduced, show that values of the ratio $K_7(X)/K_7(H)$ are all greater than unity and decrease in the order F > Cl > Br > I > H. The higher value (130) of $K_7(F)/K_7(H)$ in the 2,4-dinitro series compared with the value (21) of $K_1(F)/K_1(K)$ in the 2,4,6-trinitro series may indicate that some steric disruption remains in (**1**; X = F) or may be a manifestation of the resonance saturation effect,[31] *i.e.* the decreasing relative efficiency of electron-withdrawing substituents to stabilise negative charge as the number of such groups in a molecule increases. In both series values of the reverse rate coefficients, k_{-1} and k_{-7}, are relatively insensitive to that nature of the 1-substituent and the major changes are in the values of k_1 and of k_7. This may indicate that the transition states for hydroxide attack are relatively advanced and resemble the hydroxy adducts.

Nucleophilic substitution of halogen results in the formation of 2,4,6-trinitrophenolate or 2,4-dinitrophenolate ions. In the solvents used here, in which halide ions will be well solvated, hydroxide attack was found to be rate-limiting and intermediates on the substitution pathway were not observed. In both series the reactivity order was F $\gg$ Cl > Br > I, with the fluoro substituents being replaced very much faster than the other halogens.[32] Interestingly, the enhancement of reactivity of the fluoro derivative was greater in the 2,4,6-trinitro series than in the 2,4-dinitro series. For example, $k_3(F)/k_3(I)$ = 11 000 while $k_8(F)/k_8(I)$ = 1 400. Increasing the size of the halogen results, as referred to earlier, in a general decrease in reactivity at all ring positions owing to steric disruption. Moreover, because of the larger steric effects in the trinitro series the relative decrease in the reactivity (F > Cl > Br > I) will be greater than in the dinitro series. It is also of interest to compare rate constants for nucleophilic attack at the 1-position with those for attack at an unsubstituted position *in the same molecule*. This comparison is given in the final columns of Tables 9 and 10. The slower attack, by a factor of *ca.* 20, of hydroxide at ring carbon atoms carrying Cl, Br, or I substituents than at similarly activated ring carbons carrying hydrogen can be attributed to the steric and electrostatic repulsion between the entering and leaving groups.[33] The generally similar values obtained in the 2,4,6-trinitro and 2,4-dinitro series indicate that this repulsion depends mainly on the groups at the reaction centre and not on the *ortho* substituents. Surprisingly, values do not vary much in the series Cl, Br, and I and this may indicate that increasing steric repulsion in the series is balanced by decreasing electrostatic repulsion. The faster attack of hydroxide at the fluoro-substituted positions than an unsubstituted positions in the same molecule can be attributed to the high electronegativity of fluorine, resulting in high positive charge at the reaction centre, coupled with its small size.

To summarize, our results provide evidence for two types of steric effects in these reactions. (*i*) The presence of bulky groups

Table 9. Comparison of statistically corrected[a] values for rate and equilibrium constants for hydroxide attack at the 3- and 1-positions of 1-X-2,4,6-trinitrobenzenes in water at 25 °C.

X	k_1/dm^3 mol^{-1} s^{-1}	k_{-1}/s^{-1}	K_1/dm^3 mol^{-1}	K/dm^3 mol^{-1}	k_3/dm^3 mol^{-1} s^{-1}	K_1(X)/K_1(H)	k_3/k_1
I	1.25	15	0.083	13	0.07	0.075	0.056
Br	3.1	14	0.22	13	0.24	0.20	0.077
Cl[b]	6	14	0.43	15	0.40	0.39	0.067
F	50	2.2	23	5	750	21	15
H	15	13.5	1.1	10	15	2	1

[a] Experimental values of k_1 and K_1 were divided by 2 for (**1**; X = I, Br, Cl, and F). Values of k_1 and K_1 for 1,3,5-trinitrobenzene were divided by 3. [b] Values from ref. 6.

Table 10. Comparison of statistically corrected[a] values for rate and equilibrium constants for hydroxide attack at the 5- and 1-positions of 1-X-2,4-dinitrobenzenes in DMSO–water (80:20, v/v) at 25 °C.

X	k_7/dm^3 mol^{-1} s^{-1}	k_{-7}/s^{-1}	K_7/dm^3 mol^{-1}	k_8/dm^3 mol^{-1} s^{-1}	K_7(X)/K_7(H)	k_8/k_7
I	6	0.7	8	0.35	5.7	0.058
Br	11.2	0.7	16	0.40	11	0.036
Cl	17	0.7	24	1.0	17	0.059
F	200	1.1	180	500	130	2.5
H[b]	3.5	2.5	1.4	3.5	1	1

[a] Values of k_7 and K_7 for (**6**; X = H) have been divided by 2. [b] Values from ref. 10.

at adjacent ring-positions results in the twisting of nitro-groups from the ring plane so that there is a general decrease in reactivity at both the unsubstituted and the halogeno-substituted ring-positions. This effect decreases in the order I > Br > Cl > F > H and is more pronounced in the 2,4,6-trinitro system than in the 2,4-dinitro system. (*ii*) Unfavourable steric and electrostatic repulsion between entering and leaving groups slows the attack of hydroxide at carbon atoms carrying Cl, Br, and I substituents.

Our results for the reactions of 1-X-2,4,6-trinitrobenzenes with hydroxide in water provide further evidence[6,21–23] for the ionization of added hydroxy groups [Scheme 1, (**2**) $\rightleftharpoons$ (**3**)]. The values obtained for the equilibrium constant, K, show little variation with the nature of the halogeno-substituent. This is not unexpected since there is no direct pathway for delocalization of the resultant negative charge. The results also show that nucleophilic displacement of nitrite by hydroxide[6,24] may occur by attack on the 3-hydroxy adducts [(**2**) and (**3**)]. The values of rate constants k_4 and k_5 are lower than k_3 for a given substrate but nevertheless a considerable part of the substitution may occur by these pathways at high base concentrations where the hydroxy adducts are the dominant forms.

π-Complex and Radical Intermediates.—In a recent investigation[19] by stopped-flow spectrophotometry of the reactions of some 2,4,6-trinitrophenyl halides with hydroxide ions in aqueous media, it was reported that two intermediates were observable between the reactants and σ-complex. The intermediates were postulated to be π-complexes, absorbing at *ca.* 500 nm, and radical-pairs, absorbing at *ca.* 260 nm. This was an unexpected result in that in more than one hundred previous investigations[1] of related systems in several laboratories using both stopped-flow and relaxation methods such intermediates had not been detected. We therefore looked very carefully at the initial stages of these reactions. We did not detect the proposed intermediates, our results showing direct conversion of the parent nitro-compounds ($\lambda_{max.}$ *ca.* 260 nm) into the σ-adducts, (**2**), absorbing in the region 400–550 nm.

We do not doubt that reactions of aromatic nitro-compounds with bases in non-polar solvents may yield π-complexes,[34] or that in less activated systems radicals may be observed.[16] However in the systems we have studied we found no evidence for spectrophotometrically observable intermediates on the pathway to σ-complex formation.

Experimental

2,4-Dinitrophenyl halides, 1,3,5-trinitrobenzene, and 2,4,6-trinitrophenyl chloride were available commercially. 2,4,6-Trinitrophenyl fluoride, m.p. 133 °C (lit.,[35,36] 130 °C) was prepared[35] by reaction of 2,4,6-trinitrophenyl chloride with anhydrous potassium fluoride for 5 h at 185 °C and crystallized from benzene. 2,4,6-Trinitrophenyl bromide, m.p. 123 °C (lit.,[37] 123 °C) was prepared by nitration of 2,4-dinitrophenyl bromide and crystallized from benzene–ethanol. 2,4,6-Trinitrophenyl iodide, m.p. 163 °C (lit.,[28] 163 °C) was prepared[38] by reaction of 2,4,6-trinitrophenyl chloride with sodium iodide in acetone and crystallized from ethanol. DMSO was refluxed with calcium hydride and fractionated under reduced pressure. The distilled water used was boiled to remove carbon dioxide and subsequently protected from the atmosphere. Tetramethyl ammonium hydroxide was a commercial sample supplied as a concentrated (2.8 mol dm^{-3}) solution in water; due account of the water content of the base was taken when making dilute solutions in mixed solvents. Stock solutions of 2,4,6-trinitrophenyl halides were freshly prepared in dioxane; after dilution the solvent contained <1% of the organic component. Solutions of 2,4,6-trinitrophenyl fluoride were particularly unstable due to hydrolysis and were used within five minutes of preparation. Stock solutions of 2,4-dinitrophenyl halides were prepared in DMSO.

Kinetic and equilibrium measurements were made with Pye-Unicam Lambda 3 or SP8-100 instruments or with a Hi-Tech SF3L stopped-flow spectrophotometer, the mixing time of which was determined to be less than 2 ms. Rate coefficients at 25 °C were measured under first-order conditions with base in large excess of the nitro compound. Quoted values are the mean of at least five separate determinations and are precise to within ±5%.

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References

1 For reviews of σ-adduct formation see: M. R. Crampton, *Adv. Phys. Org. Chem.*, 1969, **7**, 211; M. J. Strauss, *Chem. Rev.*, 1970, **70**, 667; F. Terrier, *ibid.*, 1982, **82**, 77; G. A. Arkamkina, M. P. Egorov, and I. P. Beletskaya, *ibid.*, 1982, **82**, 427; E. Buncel, M. R. Crampton, M. J. Strauss, and F. Terrier, 'Electron Deficient Aromatic- and Heteroaromatic-Base Interactions,' Elsevier, Amsterdam, 1984.

2 R. Gaboriaud and R. Schaal, *Bull. Soc. Chim. France*, 1969, 2683.

3 M. Gisler and H. Zollinger, *Angew. Chem., Int. Ed. Engl.*, 1981, **20**, 203.

4 Y. Hasegawa and T. Abe, *Chem. Lett.*, 1972, 985; *Bull. Chem. Soc. Jpn.*, 1973, **46**, 2756; Y. Hasegawa, *ibid.*, 1974, **47**, 2186.

5 M. R. Crampton, M. A. ElGhariani, and H. A. Khan, *Tetrahedron*, 1972, **28**, 3299.

6 M. R. Crampton and B. Gibson, *J. Chem. Soc., Perkin Trans. 2*, 1979, 648.

7 K. Bowden and R. S. Cook, *J. Chem. Soc. B*, 1971, 1771.

8 K. Bowden and N. S. Nadri, *J. Chem. Soc., Perkin Trans. 2*, 1987, 189.

9 J. F. Bunnett, M. Gisler, and H. Zollinger, *Helv. Chim. Acta*, 1982, **65**, 63.

10 M. R. Crampton and C. Greenhalgh, *J. Chem. Soc., Perkin Trans. 2*, 1985, 599; *ibid.*, 1986, 187, 873.

11 M. Makosza and T. Glinka, *J. Org. Chem.*, 1983, **48**, 3860.

12 D. A. de Bie, B. Geurtsen, and H. C. van der Plas, *J. Org. Chem.*, 1985, **50**, 484.

13 A. Pross, *Acc. Chem. Res.*, 1985, **18**, 212.

14 F. G. Bordwell, A. H. Clemens, P. E. Smith, and J. Begemann, *J. Org. Chem.*, 1985, **50**, 1151; F. G. Bordwell and M. J. Bausch, *J. Am. Chem. Soc.*, 1986, **108**, 1985.

15 L. Eberson and F. Radner, *Acc. Chem. Res.*, 1987, **20**, 53.

16 G. A. Russell and E. G. Janzen, *J. Am. Chem. Soc.*, 1962, **84**, 4153; G. A. Russell, E. G. Janzen, and E. T. Strom, *J. Am. Chem. Soc.*, 1964, **86**, 1807.

17 J. F. Bunnett, *Acc. Chem. Res.*, 1978, **11**, 413.

18 C. Mariani, G. Modena, G. P. Pizzo, and L. Kistenbrügger, *J. Chem. Soc., Perkin Trans. 2*, 1979, 1187; A. Bassaini, M. Prato, P. Rampazzo, U. Quintily, and G. Scorrano, *J. Org. Chem.*, 1980, **45**, 2263; M. Maggini, C. Paradisi, G. Scorrano, S. Daniele, and F. Magno, *J. Chem. Soc., Perkin Trans. 2*, 1986, 267.

19 R. Bacaloglu, C. A. Bunton, and G. Cerichelli, *J. Am. Chem. Soc.*, 1987, **109**, 621.

20 C. F. Bernasconi and R. G. Bergstrom, *J. Am. Chem. Soc.*, 1974, **96**, 2397.

21 M. R. Crampton, *J. Chem. Soc., Perkin Trans. 2*, 1978, 343.

22 F. Terrier, F. Millot, and W. P. Norris, *J. Am. Chem. Soc.*, 1976, **98**, 5883.

23 V. Gold and C. A. Rochester, *J. Chem. Soc.*, 1964, 1727.

24 E. B. de Vargas, R. H. de Rossi, and A. V. Veglia, *J. Org. Chem.*, 1986, **51**, 1976.

25 C. F. Bernasconi, 'Relaxation Kinetics,' Academic Press, New York, 1976.

26 A. J. Parker, *Q. Rev.*, 1962, **16**, 163.

27 W. L. Hinze, L.-J. Liu, and J. H. Fendler, *J. Chem. Soc., Perkin Trans. 2*, 1975, 1751.

28 P. Fogel, P. G. Farrell, J. Lelievre, A. P. Chatrousse, and F. Terrier, *J. Chem. Soc., Perkin Trans. 2*, 1985, 711.

29 G. B. Barlin and D. D. Perrin, *Q. Rev. (London)*, 1966, **20**, 75.

30 P. Pollitzer, P. Lane, K. Jayasuriya, and L. N. Domelsmith, *J. Am. Chem. Soc.*, 1987, **109**, 1899.

31 F. G. Bordwell, J. E. Bares, H. E. Bartmess, G. J. McCollum, M. Van Der Puy, M. R. Vanier, and W. S. Matthews, *J. Org. Chem.*, 1977, **42**, 321.

32 J. Miller, 'Aromatic Nucleophilic Substitution,' Elsevier, New York, 1968.

33 G. Bartoli and P. E. Todesco, *Acc. Chem. Res.*, 1977, **10**, 125.

34 J. Hayami, S. Otani, F. Yamaguchi, and Y. Nishikawa, *Chem. Lett.*, 1987, 739; R. I. Cattana, J. O. Singh, J. D. Anunziata, and J. J. Silber, *J. Chem. Soc., Perkin Trans. 2*, 1987, 79.

35 N. N. Vorozhtsov and G. G. Yakobson, *Zh. Obshch. Khim.*, 1961, **31**, 3705.

36 S. J. Kuhn and G. A. Olah, *J. Am. Chem. Soc.*, 1961, **83**, 4564.

37 E. Hertel and G. H. Romer, *Z. Phys. Chem. (Leipzig), Abt. B.*, 1933, **22**, 267.

38 A. H. Blatt and E. W. Tristram, *J. Am. Chem. Soc.*, 1952, **74**, 6273; A. H. Blatt and N. Cross, *J. Org. Chem.*, 1957, **22**, 1046.

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