

## Electrophilic Aromatic Substitution. Part 36.<sup>1</sup> Kinetics of Aromatic Nitrations in Solutions of Dinitrogen Pentaoxide and of Nitronium Salts in Nitric Acid

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Kinetics of nitration of some aromatic substrates in nitric acid solutions containing dinitrogen pentaoxide or nitronium salt have been compared. Nitronium trifluoromethanesulphonate was the salt preferred for reasons of stability and solubility. In most cases rate coefficients for nitration in dinitrogen pentaoxide solutions were similar to those in nitronium salt solutions of the same estimated nitronium ion concentration; normal nitronium ion nitration is indicated. Previously recognised rate enhancements at high concentrations are largely medium effects. With 1,2,4-trichloro-5-nitrobenzene there is evidence for the intrusion of an extra mechanism for reaction in highly concentrated solutions of dinitrogen pentaoxide. Other substrates studied were 1,2-dichloro-4-nitrobenzene, 1,3-dimethyl-4,6-dinitrobenzene, 2-nitrobenzoic acid, 3-nitrobenzoic acid, 2-chloro-3-nitrobenzoic acid, and 4-chloro-3-nitrobenzoic acid. Relative reactivities among the benzoic acids are discussed.

We reported previously<sup>2</sup> that for several substrates investigated, rate coefficients for reaction in solutions containing high concentrations of dinitrogen pentaoxide in nitric acid increase with increasing concentration of dinitrogen pentaoxide more quickly than does the concentration of the nitronium ion. The question of whether this should be attributed to a medium effect or the incursion of another mechanism in highly concentrated solutions of dinitrogen pentaoxide was left unresolved though at that stage we tentatively favoured the former interpretation.

The present study in which nitration with dinitrogen pentaoxide in nitric acid is compared with nitration in nitric acid solutions of nitronium salts, gives more information about the medium effect. The intrusion of another mechanism is recognised in at least one case.

We report studies of several more aromatic substrates chosen because their reactivities come within the range suitable for kinetic study, *i.e.* roughly between that of nitrobenzene (which is nitrated much too quickly) and 1,3-dinitrobenzene (which is so unreactive that little nitration occurs before the dinitrogen pentaoxide has decomposed). We also avoided substrates which were readily oxidisable. In this paper we report on the kinetics of nitration of 1,3-dimethyl-4,6-dinitrobenzene, 1,2-dichloro-4-nitrobenzene, 1,2,4-trichloro-5-nitrobenzene, 2-nitrobenzoic acid, 3-nitrobenzoic acid, 2-chloro-3-nitrobenzoic acid, and 4-chloro-3-nitrobenzoic acid. Individual results for nitration of 2,4-dinitrotoluene and 1,3-dinitrobenzene with nitronium salt solutions are also described.

### Results

**Choice of Nitronium Salt.**—Initial tests showed that for our purposes nitronium hexafluorophosphate was insufficiently stable, and nitronium hexafluoroantimonate insufficiently soluble, in nitric acid. Nitronium tetrafluoroborate was found to be stable in solution in nitric acid even at elevated temperatures and its solubility at 30 °C is about 3 mol dm<sup>-3</sup>. The most satisfactory salt for our purposes was found to be nitronium trifluoromethanesulphonate (nitronium triflate). This salt, readily prepared by the addition of trifluoromethanesulphonic acid to an excess of dinitrogen pentaoxide in dichloromethane followed by removal of volatile materials under reduced pressure, has been used previously for nitration<sup>3</sup> but not as a

solution in nitric acid. Its solubility in nitric acid at 30 °C exceeds 5 mol dm<sup>-3</sup>. Such solutions were found to be stable for long periods.

**Kinetics of Reactions in Solutions of Nitronium Triflate in Nitric Acid.**—For all the substrates studied, reactions were found to be kinetically first order. To investigate the dependence of the first-order rate coefficients, *k* on the salt concentrations, *S*, concentrations, *M* of nitronium ion were first deduced as follows. Let *M*<sub>0</sub> be the concentration of nitronium ion in pure nitric acid arising from self ionisation [equation (1)].<sup>4</sup> Considering equilibrium (1) and ignoring changes in



the concentration of nitric acid and medium effects, equation (2) follows. Values of *M*<sub>0</sub> at the appropriate temperature were deduced from literature data<sup>4</sup> and then *M* was obtained using equation (2).

$$M_0^3 = M(M - S)^2 \quad (2)$$

Values of *M* (see Table 1) are only slightly greater than *S*; the additional concentration of nitronium ion arising from solvent self-ionisation is relatively small which justifies the approximate nature of the calculation.

Plots of ln(*k*/s<sup>-1</sup>) against ln(*M*/mol dm<sup>-3</sup>) were, in each case, approximately linear. Parameters *A* and *B* of equation (3) obtained by least-squares correlation are given in Table 1.

$$\ln(k/s^{-1}) = \ln A + B \ln(M/\text{mol dm}^{-3}) \quad (3)$$

**Kinetics of Reaction in Solutions of Nitronium Tetrafluoroborate in Nitric Acid.**—These were not so extensively investigated but where comparisons could be made, behaved entirely similarly to the solutions of nitronium triflate of comparable concentration. Some results for nitration of 1,3-dimethyl-4,6-dinitrobenzene are included in Table 1.

Two isolated experiments illustrate the stability of these

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**Table 1.** Observed first-order rate coefficients  $k$  for nitrations in solutions of nitronium salt of stoichiometric concentration  $S$  or dinitrogen pentaoxide of stoichiometric concentration  $P$  in nitric acid.

Nitronium salt <sup>a</sup>						Dinitrogen pentaoxide		
$T/^\circ\text{C}$	$S/\text{mol dm}^{-3}$	$M^b/\text{mol dm}^{-3}$	$k/10^{-4} \text{ s}^{-1}$	$10^4 A^c$	$B^c$	$T/^\circ\text{C}$	$P/\text{mol dm}^{-3}k/10^{-4} \text{ s}^{-1}$	
1,2-Dichloro-4-nitrobenzene								
30	0	0.27	0.26 <sup>d</sup>	1.09	1.10	See ref. 2		
	3.11	3.19	4.0					
	3.78	3.85	4.7					
	4.11	4.18	5.3					
	4.7	4.76	6.0					
1,3-Dimethyl-4,6-dinitrobenzene								
30	0	0.27	3.4	13.7	1.04	30	1.58	16.9
	1.44	1.56	27	14.0 <sup>e</sup>	1.03 <sup>e</sup>		1.74	18.8
	1.44	1.56	23				2.19	25
	2.14	2.24	33				2.30	44
	2.14	2.24	34				2.63	46
	3.23	3.31	48				3.12	98
	3.23	3.31	45				3.74	69
	4.33	4.40	55			20	0	2.6
	0.42 <sup>f</sup>	0.61	8.1				1.20	4.4
	0.68 <sup>f</sup>	0.84	12.9				1.32	4.6
	0.84 <sup>f</sup>	0.99	10.6				1.70	0.9
	1.10 <sup>f</sup>	1.23	19.2				2.99	22
	1.35 <sup>f</sup>	1.47	22				3.34	30
	2.19 <sup>f</sup>	2.29	29				3.55	41
	2.41 <sup>f</sup>	2.50	32			<i>g</i>		
	2.70 <sup>f</sup>	2.79	46					
2-Nitrobenzoic acid								
36	2.57	2.65	0.98	0.31	1.09	36	3.7	1.4
	3.73	3.80	1.32				4.0	2.2
	4.28	4.34	1.72				4.5	1.6
							4.6	2.0
							5.2	2.2
3-Nitrobenzoic acid								
36	2.57	2.65	0.175	0.036	1.63	36	4.0	0.41
	3.27	3.34	0.26					
	3.73	3.80	0.35					
	4.50	4.56	0.42					
2-Chloro-3-nitrobenzoic acid								
36	0	0.26	0.7	2.9	1.04	36	1.52	4.8
	2.57	2.65	9.0				1.58	5.7
	3.27	3.34	10.2				3.16	7.9
	4.50	4.56	12.9				3.80	16
							4.0	13
							4.5	15
							4.8	21
4-Chloro-3-nitrobenzoic acid								
36	3.27	3.34	0.28			36	3.71	0.44
							5.2	0.55

<sup>a</sup> Triflate unless otherwise noted. <sup>b</sup> Concentration of nitronium ion. See text and equation (2). <sup>c</sup> Parameters in equation (3). <sup>d</sup> Estimated from a rate constant measured at 32 °C. See ref. 2. <sup>e</sup> Parameters derived for runs using nitronium triflate only. <sup>f</sup> Salt used was nitronium tetrafluoroborate. <sup>g</sup> Rate coefficients for 10 and 40 °C also have been measured. See ref. 6.

solutions and their usefulness for the nitration of very strongly deactivated aromatic compounds. 2,4-Dinitrotoluene was nitrated with a solution of 2.99 mol dm<sup>-3</sup> nitronium tetrafluoroborate at 60 °C to give, quantitatively, by <sup>1</sup>H NMR 2,4,6-trinitrotoluene in a kinetically first-order process,  $k$  9.4 × 10<sup>-5</sup> s<sup>-1</sup>. 1,3-Dinitrobenzene in a solution of the same concentration after 12 h at 70 °C had diminished in concentration by approximately 37%. The yield of 1,3,5-

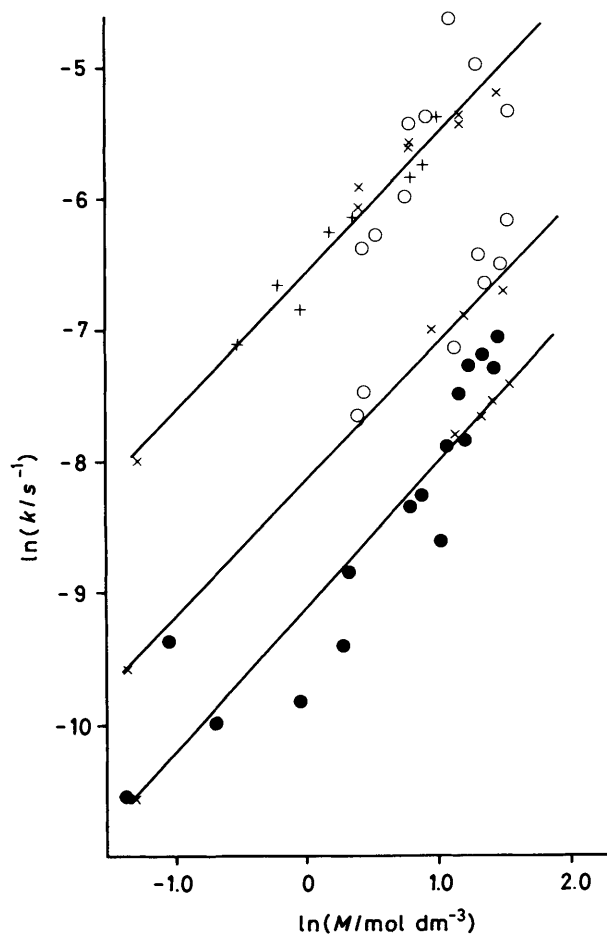
trinitrobenzene from the consumed substrate was 31%, similar to yields obtained for nitrations in sulphuric acid at 150 °C.<sup>5</sup>

*Kinetics of Reaction in Solutions of Dinitrogen Pentaoxide in Nitric Acid.*—The instability of these media as previously discussed<sup>2</sup> makes it impossible to obtain closely reproducible results particularly with the slower reactions. Individual reactions were kinetically first order. First-order rate

**Table 2.** Observed first-order rate coefficients  $k$  for nitration of 1,2,4-trichloro-5-nitrobenzene in nitric acid containing mixtures of dinitrogen pentaoxide and nitronium triflate at 30 °C.

$P^a/\text{mol dm}^{-3}$	5.1	5.1	4.2	3.4	2.5	1.7	0
$S^a/\text{mol dm}^{-3}$	0	0	0.9	1.7	2.6	3.4	5.1
$k^b/10^{-5} \text{ s}^{-1}$	32 <sup>c</sup>	23 <sup>c</sup>	14	11	13	8.0	6.0

<sup>a</sup> In these solutions  $P + S = 5.1 \text{ mol dm}^{-3}$ .  $P$  and  $S$  are the stoichiometric concentrations of dinitrogen pentaoxide and nitronium triflate respectively. <sup>b</sup> From observation of the disappearance of substrate. <sup>c</sup> Rate coefficients derived from observation of the appearance of aromatic product were *ca.* 50% smaller.



**Figure.** Plots of  $\ln(k/\text{s}^{-1})$  against  $\ln M$  for 1,3-dimethyl-4,6-dinitrobenzene at 30 °C (top line), 2-chloro-3-nitrobenzoic acid at 36 °C (middle line), and 1,2-dichloro-4-nitrobenzene at 30 °C (bottom line). Lines are derived by least-squares analysis of the points for pure nitric acid and for solutions of nitronium salts (nitronium triflate,  $\times$ ; nitronium tetrafluoroborate,  $+$ ). Circles are for solutions of dinitrogen pentaoxide (first two substrates,  $\circ$ ; 1,2-dichloro-4-nitrobenzene,  $\bullet$ ).

coefficients,  $k$  for reactions in nitric acid containing stoichiometric concentrations,  $P$  of dinitrogen pentaoxide are given in the last two columns of Table 1.

**Kinetics of Reaction in Solutions Containing Both Dinitrogen Pentaoxide and Nitronium Triflate.**—Various mixtures of dinitrogen pentaoxide and nitronium triflate, the sum of their stoichiometric concentrations,  $S + P$ , being constant at  $5.1 \text{ mol dm}^{-3}$ , were used for the nitration of 1,2,4-trichloro-5-nitrobenzene. The results are given in Table 2.

**Table 3.** Observed first-order rate coefficients  $k$  for nitration of 1,3-dimethyl-4,6-dinitrobenzene in aqueous sulphuric acid containing 1.0  $\text{mol dm}^{-3}$  nitric acid at 40 °C.

$\text{H}_2\text{SO}_4$ (%)	88.3	89.9	91.0	92.2	94.2	98.1
$k/10^{-4} \text{ s}^{-1}$	8.0	10.9	12.8	11.4	6.0	1.9

**Kinetics of Reaction in Mixed Acid.**—For comparison, some studies were made of the kinetics of reaction of 1,3-dimethyl-4,6-dinitrobenzene in aqueous sulphuric acid containing nitric acid. Results are given in Table 3.

## Discussion

**Nitronium Salt Solutions.**—The plots of  $\ln(\text{rate coefficient for nitration})$  against  $\ln(\text{concentration of nitronium ion})$  have slopes ( $B$  in Table 1) between 1.04 and 1.10, except for 3-nitrobenzoic acid where a considerably higher slope was observed probably reflecting lower precision with these very slow runs. The most reasonable interpretation of these slightly greater than unit slopes for diverse substrates is that these are normal nitronium ion nitrations. The slopes are greater than unity because of a medium effect. Quantitative product studies are as yet incomplete and will be reported in a later paper but for all the compounds in Table 1 the major products were as expected, which reinforces this conclusion.

Pure nitric acid is equivalent in acidity (using  $H_0$  values<sup>7</sup>) to 74%  $\text{H}_2\text{SO}_4$ . 3-Nitrobenzoic acid requires 88%  $\text{H}_2\text{SO}_4$  to effect half-protonation<sup>8</sup> and would not be substantially protonated in pure nitric acid. The question arises, however, as to whether the addition of nitronium salt increases the acidity of nitric acid enough to cause substantial protonation of the carboxyl group. The fact that the plots for the substituted benzoic acids even at high salt concentrations run parallel to the plots for the other substrates indicates that it does not.<sup>9</sup> They also show that it is unlikely that there is substantial formation of the benzoyl nitrate.

Relative reactivities of the neutral benzoic acids are indicated by the parameters  $A$  in Table 1. These may be regarded as values of  $k/\text{s}^{-1}$  for nitration in a nitric acid solution of nitronium salt containing  $1 \text{ mol dm}^{-3}$  nitronium ion. With 3-nitrobenzoic acid, 2-chloro-3-nitrobenzoic acid and 4-chloro-3-nitrobenzoic acid nitration occurs mainly at C-5. The *ca.* 80-fold activation of this position by the 2-chloro substituent is noteworthy, and may reflect the greater importance of the  $+M$  effect of Cl in a deactivated ring, and/or the reduction, through twisting from the ring plane, of the  $-M$  effects of the carboxyl and nitro substituents.<sup>10</sup> The 4-chloro substituent, which twists only one of the  $-M$  substituents, is neither activating nor deactivating (Table 1). 2-Nitrobenzoic acid is more reactive than 3-nitrobenzoic acid which is not in accord with additivity calculations<sup>9</sup> again indicating the importance of twisting of  $-M$  substituents.

**Nitrations with Dinitrogen Pentaoxide.**—The comparison of the rate coefficients for nitration with those for the nitronium salt solutions requires an assumption about the extent of ionic dissociation of dinitrogen pentaoxide into nitronium ion and nitrate ion in these solutions. There is evidence from Raman spectral studies<sup>11</sup> that this ionisation is very nearly complete. Assuming complete ionisation the concentrations  $M$  of nitronium ion have been calculated using equation (4) which

$$M_0^3 = M^2(M - P) \quad (4)$$

follows from equation (1). Values of  $M$  are very similar to those of  $P$  and are not, therefore, listed in Table 1. Plots of  $\ln k$  against  $\ln M$  for three of the substrates are in the Figure. Results for the other substrates are similar.

These plots show that differences in nitrating power between the nitronium salt solutions and those of dinitrogen pentaoxide even at high concentrations of nitronium ion are rather small. It seems likely that for all the substrates reported in Table 1 the normal nitronium ion mechanism is at least the major one operating in the dinitrogen pentaoxide solutions as well. For 1,3-dimethyl-4,6-dinitrobenzene a comparison can be made between the specific second-order rate coefficient  $k_2$  for reaction between the nitronium ion and the aromatic compound in nitric acid containing dinitrogen pentaoxide and in aqueous sulphuric acid. The activation energy for nitration in 1 mol dm<sup>-3</sup> dinitrogen pentaoxide in nitric acid is 63 kJ mol<sup>-1</sup>. This leads to an estimated value of  $k_2$  for nitric acid containing 1 mol dm<sup>-3</sup> nitronium ion at 40 °C of  $3.0 \times 10^{-3}$  mol<sup>-1</sup> dm<sup>3</sup> s<sup>-1</sup>. In 89.9% H<sub>2</sub>SO<sub>4</sub> nitric acid is 86% ionised to nitronium ion so from Table 3,  $k_2$   $1.3 \times 10^{-3}$  mol<sup>-1</sup> dm<sup>3</sup> s<sup>-1</sup>. Specific rate constants for reaction between nitroaromatics and nitronium ion are known to be somewhat medium dependent<sup>9</sup> so these values may be regarded as being in reasonable accord.

For 1,2-dichloro-4-nitrobenzene enhanced rates in very concentrated dinitrogen pentaoxide solutions may be present (see the Figure) but this is uncertain in view of the much larger errors in the rate coefficients, arising from the instability of the medium, as previously discussed.<sup>2</sup> Intrusion of another mechanism may be more easily recognised from product studies, on which we shall report in a later paper.

In one case we have clear evidence for enhanced rates in dinitrogen pentaoxide compared with nitronium salt solutions. 1,2,4-trichloro-5-nitrobenzene reacts too slowly to be conveniently studied in other than very concentrated solutions so that a rate profile like those in the Figure could not be produced. The results in Table 2, however, show that in solutions in which the sum of the concentrations of dinitrogen pentaoxide and nitronium triflate is held constant, the rate coefficient increases steadily with the concentration of dinitrogen pentaoxide. This substrate gives substantial quantities of cyclohexadiene products.<sup>2</sup> We now report that these products are only formed when dinitrogen pentaoxide is used. The nitronium triflate solution gives rise only to the expected dinitroaromatic. This then is a case where a mechanism other than normal nitronium ion nitration definitely does intrude in sufficiently concentrated solutions of dinitrogen pentaoxide in nitric acid.

In summary then the comparative investigation of nitronium salts and dinitrogen pentaoxide has reinforced the view that the enhanced rates in concentrated solutions compared with what would be expected from the nitronium ion concentration alone arise largely from a medium effect, though the intrusion of another mechanism has been confirmed in one case.

Both the nitronium salt and the dinitrogen pentaoxide solutions in nitric acid have exploitable advantages over normal nitration media for preparative work. Both provide the possibility of very high (5 mol dm<sup>-3</sup>) concentrations of nitronium ion leading to unusually rapid rates of nitration for deactivated substrates. The solutions are less acidic than mixed acid solutions in which nitric acid ionisation to nitronium ion is substantial, offering a further advantage with weakly basic substrates like the carboxylic acids studied here. Dinitrogen pentaoxide can readily be removed along with solvent nitric acid after reaction under reduced pressure but has the disadvantage of instability, precluding long reaction times or high temperatures. The nitronium salt solutions require more expensive materials, and work up is not quite so easy, but they have the advantage of high stability.

## Experimental

**Materials.**—The following were recrystallised from available

laboratory reagents: 3-Nitrobenzoic acid (m.p. 141–142 °C, EtOH–H<sub>2</sub>O), 2-nitrobenzoic acid (m.p. 146–147 °C, H<sub>2</sub>O), 2-chloro-3-nitrobenzoic acid (m.p. 184–186 °C, EtOH–H<sub>2</sub>O), and 4-chloro-3-nitrobenzoic acid (m.p. 187–188 °C, EtOH). 1,3-Dimethyl-4,6-dinitrobenzene was prepared as described<sup>12</sup> (m.p. 93–93.5 °C, EtOH). Dinitrogen pentaoxide and 1,2-dichloro-4-nitrobenzene were prepared as described previously.<sup>2</sup> The concentrations of solutions of dinitrogen pentaoxide in nitric acid were estimated by density measurement.<sup>13</sup>

Nitronium trifluoromethanesulphonate (nitronium triflate) was prepared by the addition to excess dinitrogen pentaoxide in dichloromethane of trifluoromethanesulphonic acid. Residual dinitrogen pentaoxide, dichloromethane, and nitric acid were removed under high vacuum. The nitronium salt (white crystals) was dried under vacuum and used without further purification (m.p. 208–210 °C). Nitronium tetrafluoroborate, hexafluorophosphate, and hexafluoroantimonate were available commercially and were used without further purification.

Solutions of nitronium salts were prepared by adding pure nitric acid to a known mass of the salt in a volumetric flask. The weighings and solution preparation were performed using a dry glove box.

**Kinetic Studies.**—The NMR method was used as previously described<sup>2</sup> except that in many cases it was found to be more accurate and more convenient to use peak heights rather than peak areas, and for the runs at 36 °C the machine used was a 60 MHz Hitachi Perkin-Elmer R-24B spectrometer. For the very slow runs with 3-nitrobenzoic acid, points were taken during the first half-life only.

## Acknowledgements

We thank Dr. P. Golding for helpful discussions. This work has been carried out with the support of Procurement Executive, Ministry of Defence. This included maintenance grants (to A. J. S. and R. W.).

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Received 17th November 1989

Accepted 12th December 1989