

## Nucleophilic Reactivity

### Part 9. Kinetics of the Reactions of Hydroxide Ion and Water with Picrylic Compounds

JUHANI MURTO

*Department of Chemistry, University of Helsinki, Helsinki, Finland*

The kinetics of the reactions of several picryl alkyl and picryl aryl ethers, picryl fluoride, and picryl chloride with hydroxide ion and water, and of 1,2,4,6-tetranitrobenzene with water have been studied, in most cases at 25°. With the exception of the alkaline hydrolysis of tetranitrobenzene and diol ethers, no formation of red colour was observed. The results are interpreted in terms of Brønsted  $\log k - \text{p}K_a$  plots. The slopes of the Brønsted plots are about  $-0.2$  for both alkaline and water hydrolyses of the alkyl ethers. The results are compared with those obtained previously for 1-substituted 2,4-dinitrobenzenes, and the mechanisms of the reactions are discussed. The results emphasize the importance of charge density at the site of reaction as a factor that determines the rate of reaction, and show that the attachment of the reagent is a similar process in the alkaline alcoholysis of 1-substituted 2,4-dinitrobenzenes, in the alkaline alcoholysis of picryl compounds, and in the water hydrolysis of picryl compounds. The F/Cl replacement ratio in the water reactions of picryl compounds is unusually high, about 22 000; in the corresponding alkaline reactions the ratio is about 1400 (at 25°). The action of hydroxide ion on the pyridine analogues of picryl compounds, 2-methoxy- and 2-chloro-3,5-dinitropyridines, was also studied; green complexes were found.

It is well known that the action of alkoxide ions on picryl alkyl ethers produces strongly coloured ionic Meisenheimer compounds,<sup>1-8</sup> but little is known about the action of hydroxide ion on picryl compounds. It was thus thought appropriate to study the reactions of these compounds with hydroxide ion. The corresponding reactions of 1-substituted 2,4-dinitrobenzenes were discussed in Part 7.<sup>9</sup> Also the neutral water hydrolysis of picryl compounds is discussed in the present paper.

Picryl and Meisenheimer compounds have been subjects of numerous spectrophotometric investigations, but papers on the kinetics of their alkaline hydrolysis are few in number.<sup>2,10</sup> The study of Gold and Rochester<sup>10</sup> on the

hydrolysis of 2,4,6-trinitroanisole in phosphate buffers seems to be the only case where the kinetics of the reaction of a picryl compound with hydroxide ion has been studied previously. Neutral solvolysis reactions of picryl chloride have been studied by Bevan and Hirst<sup>11</sup> and by Swain *et al.*<sup>12</sup>

## EXPERIMENTAL

**Chemicals.** The following compounds were prepared by known methods: 2,4,6-trinitroanisole,<sup>13</sup> m.p. 57.5° (labile form<sup>14</sup>); 2,4,6-trinitrophenetole,<sup>13</sup> m.p. 78.5°; 2,4,6-trinitrophenyl propyl ether,<sup>13</sup> m.p. 40°; 2,4,6-trinitrophenyl isopropyl ether,<sup>15</sup> m.p. 95°; 1-[2-hydroxyethoxy]-2,4,6-trinitrobenzene,<sup>16</sup> m.p. 61.5°; 2,4,6-trinitrodiphenyl ether,<sup>13</sup> m.p. 155°; 2,4,6,2'-tetranitrodiphenyl ether,<sup>17</sup> m.p. 173°; 2,4,6,3'-tetranitrodiphenyl ether,<sup>18</sup> m.p. 173°; 2,4,6,4'-tetranitrodiphenyl ether,<sup>17</sup> m.p. 153°; 1,2,4,6-tetranitrobenzene,<sup>19</sup> m.p. 127°; 2,4,6,2',4'-pentanitrodiphenyl ether,<sup>20</sup> m.p. 210°; 2-chloro-3,5-dinitropyridine,<sup>21</sup> m.p. 64° (*cf.* also Ref. 22). 2-Methoxy-3,5-dinitropyridine, m.p. 92°, was prepared from 2-chloro-3,5-dinitropyridine and sodium methoxide in methanol (*cf.* also Ref. 23). Picryl chloride (purum grade, Fluka A. G.) was crystallized twice from methanol, after which it melted at 83°.

**2,4,6-Trinitrophenyl 2,2,2-trifluoroethyl ether** (new compound). 10 g of picryl chloride was dissolved in 40 ml of dioxan, and 10 ml of 2,2,2-trifluoroethanol was added. To this solution was added at room temperature drop by drop 8.8 ml of 9.2 N aqueous potassium hydroxide solution. The reaction mixture was then decolorized by adding dilute hydrochloric acid. The precipitate was filtered and washed with water until free from picric acid. The compound was crystallized several times from diethyl ether. It crystallized as small white leaflets that melted at 107°.  
(Found: C 30.98; H 1.32. Calc. for C<sub>8</sub>H<sub>4</sub>F<sub>3</sub>N<sub>3</sub>O<sub>7</sub>: C 30.86; H 1.30).

**Adduct** of 2,4,6-trinitrophenyl 2,2,2-trifluoroethyl ether with potassium 2,2,2-trifluoroethoxide and dioxan. 344 mg of the ether was dissolved in a mixture of 2 ml of dioxan and 1 ml of 2,2,2-trifluoroethanol. The solution was cooled in ice, and 80  $\mu$ l of 14.5 N aqueous potassium hydroxide solution was added slowly from a Hamilton syringe. 3 ml of benzene was then added. After some time the orange-red precipitate was filtered, washed with cold dioxan, and dried over phosphorus pentoxide. Yield 400 mg. (Found: C 29.60; H 2.11; F 23.39; K 7.90. Calc. for C<sub>10</sub>H<sub>6</sub>F<sub>6</sub>KN<sub>3</sub>O<sub>8</sub> + 1/2 C<sub>4</sub>H<sub>8</sub>O<sub>2</sub>: C 29.22; H 2.04; F 23.11; K 7.93).]

No adduct precipitated if the solution did not contain dioxan, and dilute solutions of the ether in alkaline trifluoroethanol were colourless. The colour of the crystalline

*Table 1.* Reaction of 2,4,6-trinitrophenetole with hydroxide ion in water at 25.00°. *p* is the percentage of trinitrophenetole that had reacted. [NaOH] = 0.00494 N.

Time seconds	<i>A</i> (380 m $\mu$ )	<i>p</i> %	<i>k</i> l mole <sup>-1</sup> s <sup>-1</sup>
15.0	0.043	7.4	1.036
30.0	0.081	13.9	1.011
60.0	0.152	26.1	1.021
90.0	0.207	35.6	0.989
120.0	0.253	43.5	0.962
200.0	0.362	62.2	0.985
300.0	0.448	77.0	0.991
$\infty$	0.582		
			Mean 0.999

When corrected for solvent expansion,  $k = 1.000$  l mole<sup>-1</sup> s<sup>-1</sup>.

adduct described above was lighter orange than that of the Meisenheimer compounds, and it is highly probable that the adduct was not of the latter type. In water the colour disappeared instantaneously.

The ordinary distilled water of the laboratory (which was distilled in a Fontavapor-61 apparatus (W. Büchi, Switzerland) that was equipped with iron electrodes), although boiled before use, gave rate constants that were 2–4 times too high and reproducible results were not obtained. Good rate constants (reproducibility within 1%) resulted if the water was purified by three successive distillations in an apparatus where the first distilling flask contained potassium permanganate, the second barium hydroxide, and the third no reagent.

The kinetic measurements were carried out spectrophotometrically (at 380 m $\mu$ ) as described previously.<sup>9,24</sup> The alkaline reactions were arrested by adding 5 ml of 0.02 N hydrochloric acid. When the hydrolysis of 2-methoxy-3,5-dinitropyridine was studied, the reaction was arrested with a neutral citric acid-Na<sub>2</sub>HPO<sub>4</sub> buffer solution. Most neutral hydrolyses were so slow that the reaction solutions could be kept in thermostatted flasks, from which samples were drawn with a pipette; arresting of the reactions was not necessary. Picryl fluoride and tetranitrobenzene react with water so rapidly that their reactions were allowed to take place in the thermostatted cells<sup>24</sup> of the photometer. The substrate was dissolved in dioxan, and 10  $\mu$ l of the resulting solution was injected into 10 ml of water in the cell of the spectrophotometer.

Table 2. Kinetic data for the alkaline hydrolyses 2,4,6-(NO<sub>2</sub>)<sub>3</sub>C<sub>6</sub>H<sub>2</sub>R + OH<sup>-</sup> → 2,4,6-(NO<sub>2</sub>)<sub>3</sub>C<sub>6</sub>H<sub>2</sub>OH + R<sup>-</sup> in water. Initial concentrations: [NaOH] ≈ 0.005 N (unless otherwise stated); [substrate] = 10<sup>-6</sup> – 10<sup>-5</sup> M. For references concerning the pK<sub>a</sub> values see Refs. 33 and 9.

No.	R	pK <sub>a</sub> of RH (25°)	k (l mole <sup>-1</sup> s <sup>-1</sup> )				E kcal mole	log A
			0.00°	15.00°	25.00°	40.00°		
1	OCHCH <sub>3</sub>	17.1			0.632			
2	$\begin{array}{c}   \\ \text{CH}_3 \\ \text{OCH}_2\text{CH}_2\text{CH}_3 \end{array}$	16.1			1.00			
3	OCH <sub>2</sub> CH <sub>3</sub>	15.93	0.112	0.443	1.00	3.10	14.11	10.34
	"	"			1.00 <sup>a</sup>			
4	OCH <sub>3</sub>	15.09			1.28			
5	OCH <sub>2</sub> CF <sub>3</sub>	12.39			9.12 <sup>b</sup>			
6	OCH <sub>2</sub> CCl <sub>3</sub>	12.25			5.6 <sup>c</sup>			
7	OC <sub>2</sub> H <sub>5</sub>	9.97			1.56			
8	OC <sub>2</sub> H <sub>4</sub> NO <sub>2</sub> (3')	8.42			3.06			
9	OC <sub>2</sub> H <sub>4</sub> NO <sub>2</sub> (2')	7.23			2.13			
10	OC <sub>2</sub> H <sub>4</sub> NO <sub>2</sub> (4')	7.15			3.50			
11	OC <sub>2</sub> H <sub>3</sub> (NO <sub>2</sub> ) <sub>2</sub> (2',4')	4.02			3.38			
12	F <sup>d</sup>	3.17	120	340	700		11	11
	F <sup>e</sup>	"	120					
13	Cl	-7	0.0593	0.211	0.506	1.74	15.13	10.80

<sup>a</sup> [NaOH] = 0.0025 N. <sup>b</sup> The value 8.9 l mole<sup>-1</sup> s<sup>-1</sup> was obtained for the reaction in water that contained 0.231 wt.% 2,2,2-trifluoroethanol (in connection with the product ratio determinations<sup>24</sup>). <sup>c</sup> In water that contained 0.167 wt.% 2,2,2-trichloroethanol (in connection with the product ratio determinations<sup>24</sup>). <sup>d</sup> [NaOH] = 0.000350 N. <sup>e</sup> [NaOH] = 0.001708 N.

Table 3. Rate constants of the neutral hydrolyses  $2,4,6-(\text{NO}_2)_3\text{C}_6\text{H}_2\text{R} + \text{H}_2\text{O} \rightarrow 2,4,6-(\text{NO}_2)_3\text{C}_6\text{H}_2\text{OH} + \text{RH}$  in water. Initial concentration of the substrate was between  $2 \times 10^{-6}$  and  $2 \times 10^{-5}$  M.

No.	R	[HCl] N	$10^5 k$ (s <sup>-1</sup> ) at 25.00°
1	OCHCH <sub>3</sub>   CH <sub>3</sub>	10 <sup>-5</sup>	0.174
2	OCH <sub>2</sub> CH <sub>2</sub> CH <sub>3</sub>	10 <sup>-4</sup>	0.144
3	OCH <sub>2</sub> CH <sub>3</sub>	10 <sup>-4</sup>	0.121
	"	10 <sup>-5</sup>	0.123
4	OCH <sub>3</sub>	10 <sup>-4</sup>	0.199
5	OCH <sub>2</sub> CH <sub>2</sub> OH	10 <sup>-4</sup>	0.150
6	OCH <sub>2</sub> CF <sub>3</sub>	10 <sup>-4</sup>	0.927
7	OC <sub>6</sub> H <sub>5</sub>	10 <sup>-2</sup>	0.114
	"	10 <sup>-5</sup>	0.115
8	OC <sub>6</sub> H <sub>4</sub> NO <sub>2</sub> (2')	10 <sup>-2</sup>	0.157
9	OC <sub>6</sub> H <sub>4</sub> NO <sub>2</sub> (4')	10 <sup>-2</sup>	0.181
10	OC <sub>6</sub> H <sub>3</sub> (NO <sub>2</sub> ) <sub>2</sub> (2',4')	10 <sup>-2</sup>	0.21 <sub>2</sub>
11	NO <sub>2</sub>	10 <sup>-4</sup>	75.7 <sup>a</sup>
	"	10 <sup>-2</sup>	73.6 <sup>a</sup>
12	F	10 <sup>-4</sup>	144 <sup>a</sup>
13	Cl	10 <sup>-4</sup>	0.00644

<sup>a</sup> At 24.8°.

The alkaline hydrolysis of picryl fluoride is very fast, and only rough estimates of the rate constants could be obtained although a special technique<sup>25</sup> was used. As the alkali concentrations were low, the reaction vessels were flushed with nitrogen before filling them to exclude carbon dioxide.

The solubility of the polynitrodiphenyl ethers in water is extremely low, and hence the results concerning these compounds are less accurate than those for the alkyl ethers.

The rate constants given in the tables are the means of values from at least two runs. In the case of diaryl ethers they are the means of values from 3–4 runs.

*Action of sodium hydroxide on 2-chloro-3,5-dinitropyridine.* The green colour developed in a fast, approximately second-order reaction. In 0.00514 N aqueous sodium hydroxide,  $k = 1.25 \text{ l mole}^{-1} \text{ s}^{-1}$  at 0.00°,  $7.8 \text{ l mole}^{-1} \text{ s}^{-1}$  at 15.00°, and  $23 \text{ l mole}^{-1} \text{ s}^{-1}$  at 25.00°, giving  $E = 18.9 \text{ kcal mole}^{-1}$  and  $\log A = 15.2$ . In 0.00232 N sodium hydroxide  $k = 27 \text{ l mole}^{-1} \text{ s}^{-1}$  at 25.00°, and if the substrate was introduced in ethanol (0.2 %) instead of dioxan,  $k = 28 \text{ l mole}^{-1} \text{ s}^{-1}$  at this temperature.

The colour faded rapidly in alkaline solution, but was restored on adding hydrochloric acid to give a solution  $10^{-2} - 10^{-3}$  N in the acid. In this solution  $\lambda_{\text{max}} = 427 \text{ m}\mu$  and  $\epsilon_{\text{max}} = 25\,000 \text{ l mole}^{-1} \text{ cm}^{-1}$ . The rate constants reported above were computed from the absorbance readings after acidification. In 1 N hydrochloric acid the colour faded again rapidly.

The colour cannot be due to the anion of 2-hydroxy-3,5-dinitropyridine, as the latter was found to absorb below  $400 \text{ m}\mu$  and its colour was stable in alkaline but not in acid solution. The values of  $\lambda_{\text{max}}$  and  $\epsilon_{\text{max}}$  are nearly the same as those for one of the two absorption peaks of Meisenheimer adducts of picryl compounds,<sup>5,6,26</sup> but the fact that the colour is more stable in acid than in alkaline solution makes improbable the assumption that the colour is that of a Meisenheimer adduct. The positive value of the activation entropy is probably apparent and due to complicated kinetics.

It has been reported<sup>27</sup> that 2-substituted 3,5-dinitro-4,6-dimethylpyridines give brown-purple colours with alkoxides. Similar colours are observed if the 3-nitro group is replaced by a cyano group.<sup>27</sup> However, the values of  $\epsilon_{\max}$  are in these cases only about  $2601 \text{ mole}^{-1} \text{ cm}^{-1}$  ( $\lambda_{\max} = 540 \text{ m}\mu$ ).<sup>27</sup>

## RESULTS AND DISCUSSION

The results for the alkaline reactions are collected in Table 2 and Fig. 1, and those for the neutral hydrolysis in Table 3 and Fig. 2. The rate constants for the alkaline alcoholysis of picryl fluoride in water (see preceding paper<sup>24</sup>) are also plotted in Fig. 2.

The reactions followed second-order kinetics (see the results for trinitrophenetole in Tables 1 and 2), and good Arrhenius plots were obtained for trinitrophenetole and picryl chloride. Most of the reactions were studied at 25° only, as the values of  $E$  and  $\log A$  obviously vary relatively little from compound to compound, as observed for the reactions of 1-substituted 2,4-dinitrobenzenes.<sup>9</sup>

Most of the reactions studied proceeded without visible complex formation at the low concentrations used. Diol ethers and 1,2,4,6-tetranitrobenzene are completely in brown complex form in alkaline solutions; these cases are discussed elsewhere.<sup>26,28</sup> Internal cyclic Meisenheimer compounds are formed from the diol ethers,<sup>28,29</sup> whereas the coloured compounds formed from tetra-

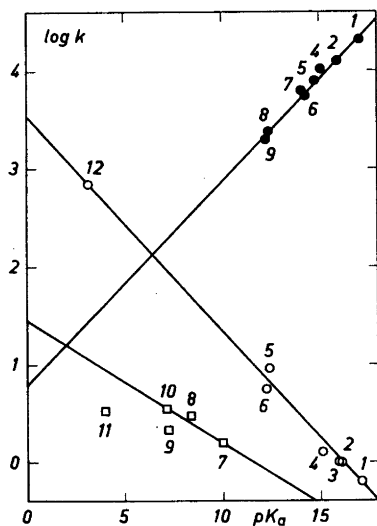


Fig. 1. Brønsted plots for alkaline hydrolyses at 25°. Filled circles: alkaline de-fluoroalkoxylation reactions of picryl fluoride;<sup>24</sup> the numbering of these reactions refers to Table 1 in the preceding paper.<sup>24</sup> Open circles: alkyl ether hydrolyses (Table 2), open squares: aryl ether hydrolyses (Table 2).

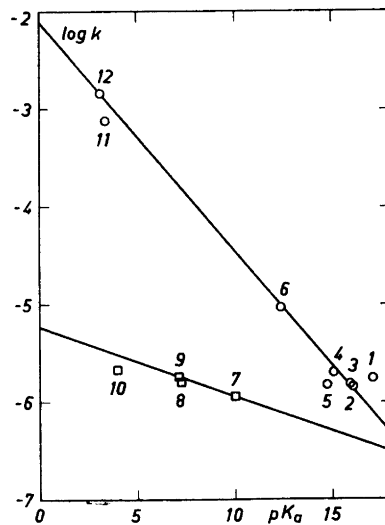


Fig. 2. Brønsted plots for the neutral water hydrolyses at 25° (first-order rate constants). The numbering refers to Table 3.

nitrobenzene are probably not of the Meisenheimer type, as deduced<sup>26</sup> from the identical rates of decomposition of the alkoxide and hydroxide adducts in water.

The Brønsted plots  $\log k = \alpha \text{p}K_a + \beta$  (where  $\text{p}K_a$  refers to the conjugate acid of the leaving anion) for the alkaline and neutral alkyl ether hydrolyses (Figs. 1 and 2) were drawn through the points of picryl fluoride (*cf.* Part 7<sup>9</sup>). From Fig. 2 it is seen that the neutral hydrolyses of tetranitrobenzene and the glycol ether are nearly "normal" reactions.

The straight lines for the reactions of diaryl ethers in Figs. 1 and 2 were drawn through the points of the phenoxy and 4'-nitrophenoxy compounds (*cf.* also Part 7<sup>9</sup>), as the steric interaction of nitro groups of the other ring is a minimum in these compounds.

The slopes and intercepts of the Brønsted plots in Figs. 1 and 2 are given in Table 4. For comparison, results for various reactions of 1-substituted 2,4-dinitrobenzenes are also included. It can be seen that the absolute value of slope is about 0.2 in many cases; the slope is about +0.2 for the defluoroalkoxylation reactions and about -0.2 for the dealkoxyhydroxylation reactions.

For comparison, it may be mentioned in this connection that straight lines of approximately unit slope are obtained for the reactions of amines with 2,4-dinitrochlorobenzene or 2-chloro-3-cyano-5-nitropyridine, when  $\log k$  is plotted against the  $\text{p}K_a$  of the amine.<sup>30</sup> Systematic studies of the leaving ability of substituent groups as a function of  $\text{p}K_a$  in amination reactions seem not to have been carried out. The rate data reported by Suhr<sup>31</sup> indicate that the dependence of the rate constant on the  $\text{p}K_a$  of the leaving oxygen anion is

Table 4. Brønsted relationships  $\log k = \alpha \text{p}K_a + \beta$  for reactions with oxygen nucleophiles (at 25° unless otherwise stated). The  $\text{p}K_a$ 's refer to water.

Reaction	Solvent	$\alpha$	$\beta$	Ref.
2,4-(NO <sub>2</sub> ) <sub>2</sub> C <sub>6</sub> H <sub>3</sub> F + AlkO <sup>-</sup>	Water <sup>a</sup>	0.215	-2.56	33
2,4-(NO <sub>2</sub> ) <sub>2</sub> C <sub>6</sub> H <sub>3</sub> Cl + ArO <sup>-</sup>	Methanol	0.941 <sup>b,c</sup>		34,9
2,4-(NO <sub>2</sub> ) <sub>2</sub> C <sub>6</sub> H <sub>3</sub> Cl + ArO <sup>-</sup>	80 % dioxan-water <sup>d</sup>	0.85 <sup>c</sup>		35
1,4-Cl <sub>2</sub> -2-NO <sub>2</sub> C <sub>6</sub> H <sub>3</sub> + ArO <sup>-</sup>	80 % dioxan-water <sup>d</sup>	0.83 <sup>c</sup>		35
2,4-(NO <sub>2</sub> ) <sub>2</sub> C <sub>6</sub> H <sub>3</sub> Cl + benzoate ions	60 % dioxan-water <sup>e</sup>	0.30 <sup>c</sup>		32
2,4-(NO <sub>2</sub> ) <sub>2</sub> C <sub>6</sub> H <sub>3</sub> OAlk + OH <sup>-</sup>	Water	-0.218	-0.20	9
2,4-(NO <sub>2</sub> ) <sub>2</sub> C <sub>6</sub> H <sub>3</sub> OAr + OH <sup>-</sup>	Water	-0.215	-1.56	9
2,4-(NO <sub>2</sub> ) <sub>2</sub> C <sub>6</sub> H <sub>3</sub> OAr + MeO <sup>-</sup>	Methanol <sup>f</sup>	-0.40 <sup>c</sup>		9
2,4,6-(NO <sub>2</sub> ) <sub>3</sub> C <sub>6</sub> H <sub>2</sub> F + AlkO <sup>-</sup>	Water <sup>a</sup>	0.209	0.79	24
2,4,6-(NO <sub>2</sub> ) <sub>3</sub> C <sub>6</sub> H <sub>2</sub> OAlk + OH <sup>-</sup>	Water	-0.219	3.53	
2,4,6-(NO <sub>2</sub> ) <sub>3</sub> C <sub>6</sub> H <sub>2</sub> OAlk + H <sub>2</sub> O	»	-0.233	-2.12 <sup>g</sup>	
2,4,6-(NO <sub>2</sub> ) <sub>3</sub> C <sub>6</sub> H <sub>2</sub> OAr + OH <sup>-</sup>	»	-0.125	1.45	
2,4,6-(NO <sub>2</sub> ) <sub>3</sub> C <sub>6</sub> H <sub>2</sub> OAr + H <sub>2</sub> O	»	-0.070	-5.24 <sup>g</sup>	

<sup>a</sup> The solvents contained small amounts of the alcohols. <sup>b</sup> See Part 7<sup>9</sup> for a discussion. <sup>c</sup> The  $\text{p}K_a$  values in methanol or dioxan-water differ, to a first approximation, from those in water by a constant increment, and thus the slope of the Brønsted plot is not much affected, although the  $\text{p}K_a$ 's refer to water. <sup>d</sup> At 65°. <sup>e</sup> At 93°. <sup>f</sup> At 20°. <sup>g</sup> Note that  $k$  is the first-order rate constant.

much more marked in the reactions of 1-substituted 4-nitrobenzenes with piperidine in dimethyl sulphoxide than in the hydroxylation reactions of Table 4.

*Influence of electron density at the site of reaction on the rate.* The results in Table 4 can be understood if the charge at the 1-position of the substrate and the charge at the oxygen of the incoming anion are considered to be the factors that govern the rate of reaction:<sup>36</sup> the more positive the carbon at the 1-position, and the more negative the oxygen of the attacking reagent, the more easily does the reaction occur. If the number of nitro groups in the substrate is increased, or if the electron-withdrawing ability of the leaving group is increased (which is reflected in the higher acidity of its conjugate acid), the electron density at the 1-position is diminished and the reaction proceeds more rapidly. Increase of the electron-withdrawing in the reagent diminishes the negative charge of the attacking oxygen atom and thus retards the reaction.

The two benzene rings in diaryl ethers are probably far from coplanar,<sup>36</sup> and thus much of the conjugative electron withdrawal cannot be transmitted from the nitrophenoxide part to the site of reaction. However, the phenols and nitrophenols owe their relatively high acidity and low  $pK_a$  values (as compared to aliphatic alcohols) to the partial conjugative delocalization of negative charge over the aromatic system in the anionic form. Thus it can be understood why the Brønsted plots of diaryl ethers run lower than those of aryl alkyl ethers. A similar reasoning may explain the fact that the point of 2,4-dinitrophenyl propargyl ether (Fig. 1 in Part 7<sup>9</sup>) is below the straight line (the angle C—O—C is much less than 180°).

The 1-substituents that yield data that satisfy the Brønsted  $\log k - pK_a$  relationships are fluorine and the nitro (allowing for steric effects), alkoxy, and aryloxy groups. In these cases the elements attached to the carbon at the 1-position (fluorine, nitrogen, and oxygen) are all first-row elements, and changes in acidity of the conjugate acid of the leaving group parallel changes in reactivity.

Data for 1-chloro compounds do not satisfy these linearities. However, these compounds behave "normally" if  $\log k$  is plotted,<sup>36</sup> not as a function of  $pK_a$ , but against the LCAO-MO  $\pi$ -electron charge density at the 1-position.

The low acidity of hydrofluoric acid compared to that of the other hydrogen halides has been considered<sup>37</sup> to be due to the very high dissociation energy of the H—F bond and to the increased stability of the hydrogen fluoride molecules in aqueous solution due to hydrogen bonding. Thus it is surprising that the fluoro compounds obey the Brønsted relationship and the chloro compounds do not. Also in alcohols considerable hydrogen bonding occurs, and in this sense the  $pK_a$  of hydrogen fluoride may be "normal", when compared with the  $pK_a$  values of alcohols. As the  $pK_a$  of hydrogen fluoride is ten logarithmic units higher than that of hydrochloric acid,<sup>37</sup> the reactivity of the chloro compounds is 5–7 powers of ten lower than the "normal" reactivity.

The most unusual feature of the neutral hydrolysis reactions of picryl compounds observed in the present study was the high F/Cl replacement ratio, about 22 000 (at 25°); this is probably the highest F/Cl ratio that has been

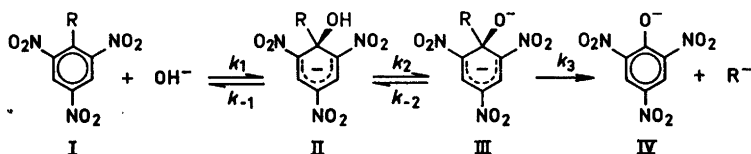
recorded for an aromatic nucleophilic substitution reaction. In the alkaline reactions the corresponding ratio was about 1400.

The F/Cl ratio is about 700 in the reactions of 1-substituted 2,4-dinitrobenzenes with hydroxide ion,<sup>9</sup> and the ratio in the reactions of monitrohalobenzenes with methoxide ion in methanol at 50° is, according to Miller *et al.*,<sup>38</sup> about 700 for 2-nitro and 300 for 4-nitro compounds. In the reactions with aniline,<sup>39</sup> the F/Cl replacement ratio of picryl compounds was also higher than that of the 2,4-dinitrophenyl compounds (100 and 62, respectively). Thus the activation due to nitro groups *increases* the F/Cl ratio. This behaviour is in accordance with the computed<sup>36</sup> LCAO-MO  $\pi$ -electron densities at the 1-position: the  $\pi$ -electron density difference between the chloro and fluoro compounds *increases* somewhat with increasing nitro activation.

Steric interactions seem to be negligible in the neutral reactions (see the Brønsted plot for the diaryl ethers in Fig. 2 and the results for fluoronitrobenzenes discussed in the preceding paper<sup>24</sup>). However, the enhanced reactivity of the isopropyl ether (*cf.* Fig. 2) may be a case of steric acceleration; also the decomposition of the picrylic 1,1-di-isopropoxy Meisenheimer adduct in water is much more rapid than the acidity of 2-propanol would suggest<sup>7</sup> (see also Ref. 4, p. 5167).

The aromatic alkyl ether hydrolyses are known to occur by aryl-oxygen fission; this has been shown experimentally for 2,4-dinitroanisole<sup>40</sup> and 2,4,6-trinitroanisole<sup>41</sup> using <sup>18</sup>O-labeled alkoxides. In the reactions of the polyhalogenoalkyl ethers one must bear in mind also the possibility of a concurrent alkyl-oxygen fission, as the strong inductive electron-withdrawal of the halogens may produce a positive charge on the carbon atom bonded to the ether oxygen, sufficient for the reaction to occur at considerable speed.

*Mechanisms of the reactions.* Bearing in mind the formation of relatively stable intermediates in the analogous reactions of picryl ethers with alkoxide ions, a discussion of the hydroxide reactions of picryl compounds in terms of the intermediate complex mechanism<sup>42-44</sup> of the aromatic substitution reactions seems well founded.



The first stage of the reaction, attachment of the reagent, is rate-determining; this is evident from the role played by the charge density at the site of reaction. Also the high F/Cl replacement ratios point in the same direction,<sup>42,43,45</sup> as the strength of a C—F bond is greater than that of a C—Cl bond, the stretching of the bonds cannot be considerable in the rate-determining transition state.

The proton transfers  $\text{II} \rightleftharpoons \text{III}$  are very rapid, and the existence of a negative charge on oxygen in III would cause also the reaction  $\text{III} \rightarrow \text{IV}$  to be rapid.<sup>46,47,10</sup> Thus the existence of a dissociable proton in II would explain,



in part, the fact that no visible Meisenheimer complexation (II + III) is observed at low initial concentration of I; the concentrations of the coloured species will be too low for detection. — This does not exclude the possibility that, were the reactions to occur without proton dissociation, the first transition state could still be rate-determining.

There seems still to prevail some controversy about the importance of intermediates of the Meisenheimer type in the less activated nucleophilic substitution reactions. Some authors<sup>42,43,48</sup> think that every reaction goes through such an intermediate, whereas others favour a one-stage mechanism (for recent discussions, see Refs. 4, 49, and 50). Unfortunately, however, many writers use the concept "one-stage mechanism" without accurately defining what they mean by this term. In most cases a structure of Meisenheimer type is thought to contribute to the hybrid transition state. In some papers the incoming and leaving groups are thought to lie in the plane of the aromatic ring (the Meisenheimer structure cannot then contribute to the transition state).

An interesting recent formulation of the mechanism in terms of a one-stage mechanism is given by Simonetta and Carrà.<sup>51</sup>

The slopes of the  $\log k - pK_a$  plots of the reactions of 2,4-dinitrophenyl compounds are similar to those of the reactions of picryl compounds (Table 4), although the latter reactions are  $10^3 - 10^4$  times faster. Also, the slope of the plot for the dechloroaryloxylation of 2,4-dinitrochlorobenzene in dioxan-water is about the same as that for the 1-dechloroaryloxylation of 1,4-dichloro-2-nitrobenzene. In the latter case the reaction is activated by only one nitro group and is thus relatively slow.

The value of the selectivity constant  $\alpha$  in the Brønsted equation  $\log k = \alpha pK_a + \beta$  is usually considered to indicate the extent of formation of the new bond in the rate-determining transition state. The more rapid the reaction, the less should be the extent of this bond formation, and the smaller the value of  $\alpha$ .

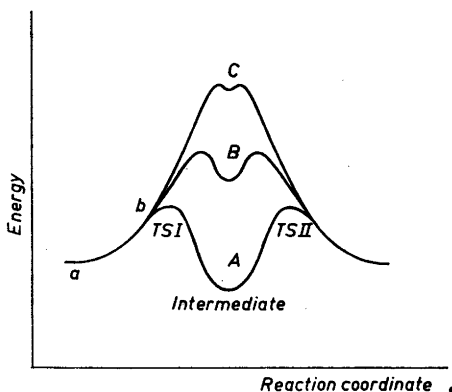
The low absolute values found for  $\alpha$  (Table 4) could thus be interpreted as indicating that the extent of bond formation in the first transition state is small. The constancy of  $\alpha$  with decreasing nitro activation implies that at least the initial stages of the reactions are very similar irrespective of the extent of nitro activation.

It is also possible that the selectivity constant for the reactions studied is not a measure of the extent of bond formation in the first transition state, or that the extent of bond formation does not vary appreciably with the nitro activation. We may illustrate these points by the following, somewhat hypothetical example.

In Fig. 3 schematic energy profiles are drawn for reactions differing in the extent of nitro activation. For convenience, the curves were taken to start from a common point *a*, and the incoming and leaving groups were taken to be the same; hence the curves are symmetric.

We then assume that the approach of a given reagent  $RO^-$  causes a similar perturbation (point *b* in the energy profile) in the reactions A, B, and C. Thus it is highly probable that another, slightly different reagent  $R'O^-$  would also cause a similar perturbation in these three cases, but one slightly different from that caused by  $RO^-$ . Thus the selectivity constant  $\alpha$  could still be the

Fig. 3. Schematic energy profiles for the reactions  $\text{Ar-OR} + \text{RO}^- \rightleftharpoons \text{Ar(OR)}_2$ ,  $\rightleftharpoons \text{Ar-OR} + \text{RO}^-$  in terms of a two-stage mechanism. A, reactions of highly activated compounds such as picryl compounds; B, moderately activated reactions; C, unactivated reactions.



same in the cases A, B, and C. The situation is the same if the reagent remains the same and the leaving group is altered slightly.

The charge density at the attacking atom obviously does not vary with  $pK_a$  in a similar way for different types of reagents. Thus one must be cautious in comparing the values of  $\alpha$  for alkoxylation, aryloxylation, and amination reactions, and in drawing conclusions concerning the relative extent of bond formation in the transition states of these reactions (see Parts 4,<sup>36</sup> 7,<sup>9</sup> and Ref. 48).

The variation of the rate constants of the relatively rapid reactions, the alkaline methanolysis and hydrolysis of DNFB, with pressure<sup>52</sup> also supports the view that the extent of bond formation in the first transition state is small: the curvature of the  $\log k$  - pressure plots is positive, which might imply that the compressibility of the rate-determining transition state is greater than that of the initial state, *i.e.*, that the transition state is a loose complex.

Brower<sup>53</sup> studied the influence of pressure on the reactions of various bromoquinolines and bromonaphthalenes with piperidine, and concluded that the faster reactions involve transition states more closely resembling the reactants. However, the mechanisms of the reactions of these relatively unreactive compounds may differ greatly from those of the reactions in Table 4, and thus these two classes of reactions may not be directly comparable.

The Brønsted plot for the *neutral hydrolysis* of picryl compounds resembles that for the alkaline reactions, and also the  $\log k$  -  $\pi$ -electron charge density plots<sup>36</sup> seem to be very similar in these two cases. These facts and the similar solvent dependence of the alkaline and neutral product ratio quantities,  $B'_{ha}$  and  $N'_{wa}$ , in the preceding paper<sup>24</sup> suggest that the reaction mechanisms of the alkaline and neutral reactions are very similar.

If the neutral water hydrolysis of DNFB is assumed to occur by the two-stage mechanism, it may be concluded also from the variation of the rate constant of this reaction in dimethyl sulphoxide-water mixtures that the first stage of the reactions is slower than the second.<sup>54</sup>

In the water hydrolysis the reagent is a water molecule, not a hydroxide ion (which is always formed to a slight extent by the autoprotolysis of water)

as the variation of rate constants with hydrochloric acid concentration (see Table 3) is very small. This variation is of the same order of magnitude as salt effects in the reactions of aromatic compounds with alkali.<sup>55</sup>

As the attacking species in the neutral solvolysis reactions is a water or an alcohol molecule, its attachment to the carbon at the 1-position is accompanied by a simultaneous proton transfer to a solvent molecule. In this respect the neutral solvolyses resemble the reactions with amines.<sup>39</sup> Values of  $E$  and  $\log A$  are low for the latter reactions,<sup>39</sup> and this seems to be the case also for the solvolysis reactions: Bevan and Hirst<sup>11</sup> report the values  $E = 18.1$  kcal mole<sup>-1</sup> and  $\log A = 6.64$  ( $A$  in l mole<sup>-1</sup> s<sup>-1</sup>) for the methanolysis of picryl chloride. The rate constant in methanol at 25°,  $7.55 \times 10^{-9}$  l mole<sup>-1</sup> s<sup>-1</sup>,<sup>11</sup> is 6.5 times greater than that found for the water hydrolysis in the present study ( $1.16 \times 10^{-9}$  l mole<sup>-1</sup> s<sup>-1</sup>).

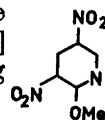
It is also possible that the rate-determining *attachment* of the water molecule in the reaction of the fluoro compound is assisted by simultaneous hydrogen bond formation between the fluorine atom and a hydrogen atom of the water molecule (the planes of the benzene ring and the hydrogen bonded ring in V are thought to be mutually perpendicular). Analogous transition states have been proposed for the amination reactions.<sup>56,57</sup> As the  $pK_a$  value of hydrochloric acid is ten  $pK_a$  units lower than that of hydrofluoric acid,<sup>37</sup> the chloro compound would not form such a cyclic transition state.

Summarizing, it may be said that the first stage of the reaction, the attachment of the reagent, has some features in common in all of the cases studied: in the alkaline hydrolysis of 2,4-dinitrophenyl compounds,<sup>9</sup> alkaline hydrolysis of picryl compounds, and water hydrolysis of picryl compounds. Thus there seems not to be any radical mechanistic differences between the reactions of picryl compounds and the reactions of less activated compounds. If a pure two-stage mechanism is accepted, for example, for the dealkoxyhydroxylation reactions of picryl alkyl ethers, it seems very probable also for the corresponding less activated reactions. However, the present evidence does not exclude the possibility that the reaction proceeds from TS I directly to TS II (Fig. 3) in the less activated reactions. A mechanism of this kind might be presented in terms of the Simonetta-Carrà formalism.<sup>51</sup>

It may be mentioned in this connection that the picryl ether of the acidic alcohol, 2,2,2-trifluoroethanol, seems not to form Meisenheimer compounds with alkoxide ions easily (see the experimental part). Phenyl picryl ether behaves similarly in this respect.<sup>4,58</sup> Thus there is in the alkoxide exchange reactions of picryl ethers a gradual change from a visible Meisenheimer complexation towards a reaction without visible complexation as the basicity of the alkoxide decreases.

*Pyridine analogues of picryl compounds.* It is known<sup>59</sup> that a hetero nitrogen atom *ortho* to the site of reaction activates nucleophilic substitution reactions nearly as effectively as a similarly situated nitro group. In the present study, some experiments were run with 2-substituted 3,5-dinitropyridines, *i.e.*, compounds which should be nearly as reactive as picryl compounds. As the second *ortho* nitro group is missing, the steric requirements of the reactions are similar to those of the reactions of 1-substituted 2,4-dinitrobenzenes.

The rate constant of the reaction of 2-methoxy-3,5-dinitropyridine (VI) with hydroxide ion in water at 25° was  $0.292 \text{ l mole}^{-1} \text{ s}^{-1}$  ( $[\text{NaOH}] = 0.00242 \text{ N}$ ); *i.e.*, about one fourth of the value for the corresponding picryl compound.



VI

2-Chloro-3,5-dinitropyridine has been reported<sup>60</sup> to react with water more rapidly than picryl chloride. In the present study an attempt was made to measure the rate constant of the reaction of the chloro compound with hydroxide ion in water, but this was not possible as a very strong green colour resulted (see the experimental part for details).

The methoxy compound VI does not give red Meisenheimer type complexes with alkoxide ions, as does trinitroanisole. In the present study it was found that dilute alkaline solutions of VI were almost colourless, whereas concentrated solutions were green (complexation?).

The *two ortho* nitro groups in picryl compounds may contribute to the stability of the Meisenheimer compounds; it is possible that these *ortho* nitro groups are more coplanar with the benzene ring in the intermediate than is possible in the initial state. The influence of such a coplanarity effect would be much less marked in reactions of 1-substituted 2,4-dinitrobenzenes or 2-substituted 3,5-dinitropyridines.

*Acknowledgement.* The author is indebted to the *Finnish State Commission for Natural Sciences (Valtion Luonnontieteellinen Toimikunta)* for financial aid.

## REFERENCES

1. Meisenheimer, J. *Ann. Chem.* **323** (1902) 205.
2. Ainscough, J. B. and Caldin, E. F. *J. Chem. Soc.* **1956** 2528.
3. Farmer, R. C. *J. Chem. Soc.* **1959** 3425.
4. Dyall, L. K. *J. Chem. Soc.* **1960** 5160.
5. Foster, R. and Mackie, R. K. *J. Chem. Soc.* **1963** 3796.
6. Gold, V. and Rochester, C. H. *J. Chem. Soc.* **1964** 1687; Crampton, M. R. and Gold, V. *J. Chem. Soc.* **1964** 4293.
7. Murto, J., Vainionpää, J. and Viitala, A. *Suomen Kemistilehti. To be published.*
8. Abe, T. *Bull. Chem. Soc. Japan* **34** (1961) 21; **37** (1964) 508.
9. Murto, J. and Murto, M.-L. *Acta Chem. Scand.* **20** (1966) 297.
10. Gold, V. and Rochester, C. H. *J. Chem. Soc.* **1964** 1710.
11. Bevan, C. W. L. and Hirst, J. *J. Chem. Soc.* **1956** 254.
12. Swain, C. G., Dittmer, D. C. and Kaiser, L. E. *J. Am. Chem. Soc.* **77** (1955) 3737.
13. Willgerodt, C. *Ber.* **12** (1879) 1277.
14. Ovenston, T. C. *J. Nature* **159** (1947) 437; Damschroder, R. E. and Shriner, R. L. *J. Am. Chem. Soc.* **59** (1937) 931.
15. Philbrook, G. E. and Massey, D. J. *J. Chem. Soc.* **73** (1951) 3454.
16. Blanksma, J. J. and Fohr, P. G. *Rec. Trav. Chim.* **65** (1946) 711.
17. Willgerodt, C. and Hüetlin, E. *Ber.* **17** (1884) 1764.
18. Okón, K. *Bull. Acad. Polon. Sci. Ser. Sci. Chim., Geol., Geogr.* **6** (1958) 310.
19. Borsche, W. *Ber.* **56** (1923) 1939.
20. Ryan, H. and Drumm, P. *J. Sci. Proc. Roy. Dublin Soc.* **17** (1924) 313; *Chem. Abstr.* **18** (1924) 1655.
21. Plažek, E. *Rec. Trav. Chim.* **72** (1953) 569.
22. Berrie, A. H., Newbold, G. T. and Spring, F. S. *J. Chem. Soc.* **1951** 2590.
23. Talik, Z. and Plažek, E. *Roczniki Chem.* **34** (1960) 165.
24. Murto, J. *Acta Chem. Scand.* **20** (1966) 303.
25. Tommila, E. and Lindholm, M. *Acta Chem. Scand.* **5** (1951) 647.

26. Murto, J. *Suomen Kemistilehti* B 38 (1965) 251.
27. Mariella, R. P., Callahan, J. J. and Jibril, A. O. *J. Org. Chem.* 20 (1955) 1721.
28. Murto, J. *Suomen Kemistilehti* B 38 (1965) 255.
29. Foster, R., Fyfe, C. A. and Morris, J. W. *Rec. Trav. Chim.* 84 (1965) 516.
30. Chapman, N. B., Chaudhury, D. K. and Shorter, J. J. *J. Chem. Soc.* 1962 1975.
31. Suhr, H. *Chem. Ber.* 97 (1964) 3268.
32. Parks, L. R., Hammond, G. S. and Hawthorne, M. F. *J. Chem. Soc.* 77 (1955) 2903.
33. Murto, J. *Acta Chem. Scand.* 18 (1964) 1043.
34. Leahy, G. D., Liveris, M., Miller, J. and Parker, A. J. *Australian J. Chem.* 9 (1956) 382.
35. Knowles, J. R., Norman, R. O. C. and Prosser, J. H. *Proc. Chem. Soc.* 1961 341.
36. Murto, J. *Suomen Kemistilehti* B 38 (1965) 246.
37. McCoubrey, J. C. *Trans. Faraday Soc.* 51 (1955) 743.
38. Bolto, B. A., Miller, J. and Williams, V. A. *J. Chem. Soc.* 1955 2926; Miller, J. and Wong, K. W. *Australian J. Chem.* 18 (1965) 117.
39. Parker, R. E. and Read, T. O. *J. Chem. Soc.* 1962 9.
40. Gitis, S. S., Tereskevich, M. O., Garus, L. I., Glaz, A. I. and Skarre, O. K. *Zh. Obshch. Khim.* 31 (1961) 2902; *Chem. Abstr.* 56 (1962) 14141.
41. Gitis, S. S., Gragerov, I. P. and Glaz, A. I. *Zh. Obshch. Khim.* 32 (1962) 2803; *Chem. Abstr.* 58 (1962) 7852.
42. Bunnett, J. F. and Zahler, R. E. *Chem. Rev.* 49 (1951) 273; Bunnett, J. F. *Quart. Rev. (London)* 12 (1958) 1.
43. Miller, J. *J. Am. Chem. Soc.* 85 (1963) 1628, and earlier papers.
44. Kirby, A. J. and Jencks, W. P. *J. Am. Chem. Soc.* 87 (1965) 3217.
45. Bunnett, J. F., Garbisch, E. W. and Pruitt, K. M. *J. Am. Chem. Soc.* 79 (1957) 385.
46. Bunnett, J. F. and Davis, G. T. *J. Am. Chem. Soc.* 76 (1954) 3011.
47. Murto, J. *Acta Chem. Scand.* 18 (1964) 1029.
48. Bunnett, J. F. *Ann. Rev. Phys. Chem.* 14 (1963) 271.
49. Illuminati, G. *Advan. Heterocycl. Chem.* 3 (1964) 285, p. 352.
50. Shepherd, R. G. and Fedrick, J. L. *Advan. Heterocycl. Chem.* 4 (1965) 145, p. 155.
51. Simonetta, M. and Carrà, S. In Urbanski, T. *Nitro Compounds, Proceedings of the International Symposium in Warsaw, Sept. 1963.* Pergamon Press 1964, p. 383; and *Tetrahedron* 19 Suppl. 2 (1963) 467.
52. Murto, J. and Kiuttu, M. *Suomen Kemistilehti* B 39 (1966) 14.
53. Brower, K. R. *J. Am. Chem. Soc.* 80 (1958) 2105.
54. Murto, J. and Hiironen, A. M. *Suomen Kemistilehti* B 37 (1964) 177.
55. Lulofs, P. K. *Rec. Trav. Chim.* 20 (1901) 292; *Z. physik. Chem.* 49 (1904) 341.
56. Chapman, N. B. and Parker, R. E. *J. Chem. Soc.* 1951 3301.
57. Bamkole, T. O., Bevan, C. W. L. and Hirst, J. *Chem. Ind. (London)* 1963 119.
58. Farmer, R. C. *J. Chem. Soc.* 1959 3430.
59. Bishop, R. R., Cavell, E. A. S. and Chapman, N. B. *J. Chem. Soc.* 1952 437.
60. Talik, Z. *Roczniki Chem.* 34 (1960) 917.

Received October 12, 1965.