

**679.** *The S<sub>N</sub> Mechanism in Aromatic Compounds. Part III.\**

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The reactions of 1-halogeno-2:4-dinitrobenzenes with sodium methoxide or sodium *p*-nitrophenoxide in absolute methanol have been examined quantitatively and shown to agree with the predictions made in Part I (Miller, *Rev. Pure Appl. Chem.*, 1951, **1**, 171). The variation of activation energies and frequency factors is discussed.

THE variation in the rate of nucleophilic replacement of chlorine, bromine, and iodine has received much study in both the aliphatic and the aromatic series (*e.g.*, Hughes and Ingold, *J.*, 1935, 244, and subsequent papers; Luloffs, *Rec. Trav. chim.*, 1901, **20**, 292). The replacement of fluorine has received much less attention; nevertheless, in the aromatic

\* Part II, preceding paper.

series Holleman (*ibid.*, 1904, **23**, 256) estimated that 1-fluoro-2:4-dinitrobenzene reacted some 600 times faster than the corresponding chloro-compound with methoxide ion in methanol. With aromatic amines as reagents, Chapman and Parker (*J.*, 1951, 3301) showed that the ratio for the same compounds was about 100—200. Bevan (*J.*, 1951, 2340), using the *p*-halogenonitrobenzenes and ethoxide ion in ethanol, gave rate constants which lead to the ratio F : Cl : Br : I = 228 : 1 : 0.87 : 0.74. On the other hand, Tronow and Kruger (*J. Russ. Phys. Chem. Soc.*, 1926, **58**, 1270), for reaction of the monohalogenobenzenes with methoxide in methanol, showed the reverse order, but with an extreme range I : F = 35.6 : 1. These may be compared with typical values for aliphatic compounds quoted by Hughes (*Quart. Reviews*, 1951, **5**, 245), *viz.*, F : Cl : Br : I = 10<sup>-3</sup> : 1 : 30 : 80, a range of 8 × 10<sup>4</sup>. Thus there is a change over between the monohalogenobenzenes and the *p*-halogenonitrobenzenes. In this paper, which deals with the reactions of 1-halogeno-2:4-dinitrobenzenes with methoxide or *p*-nitrophenoxide ion in methanol, the order F > Cl > Br > I which is found is regarded as the resultant of two opposing factors—a bond-strength factor leading to I > Br > Cl > F, and an electronegativity factor leading to F > Cl > Br > I, the latter being more important. It follows that a different relative weight can give the different orders found in aliphatic compounds, and halogenonitro- and dinitro-benzenes. The intermediate character of the halogenobenzenes agrees well with this, and they are now being investigated in this laboratory in confirmation.

The unusually high reactivity of aromatic fluoronitro-compounds is also involved in the use of 1-fluoro-2:4-dinitrobenzene for forming derivatives of amino-compounds (Sanger, *Biochem. J.*, 1945, **39**, 507) and alcohols (Whalley, *J.*, 1950, 2241). However, Whalley uses triethylamine as catalyst and it is almost certain that the actual reagent is then the 2:4-dinitrophenyltriethylammonium ion, the amine being re-formed by the reaction with the alcohol. Rarik, Brewster, and Dains (*J. Amer. Chem. Soc.*, 1933, **55**, 1289) used *p*-fluoronitrobenzene similarly.

In Part I (*loc. cit.*) it is shown, *inter alia*, that the replacement reaction generally will be facilitated by variation of the replaced group (X) as follows. (a) An electron-attracting group is able more easily to go off as X<sup>-</sup> (the negative sign being relative), and, by rendering the ring carbon atom to which it is attached more positive, facilitates attack by the reagent; within any polar category, the most electronegative atom or group is then most easily replaced: *e.g.*, F > Cl > Br > I. (b) The weaker the Ar-X bond the more easily is X replaced. Factors (a) and (b) are conflicting in the halogens, but the bond-energy factor is not the major one except when (i) the effects due to differences in electronegativity are small, (ii) there is little activation by other groups, and (iii) the nucleophilic power of the reagent is small. This follows because in nucleophilic attack on aromatic systems, it is of prime importance to denude the point of attack of π electrons, and also because the ease of breaking the Ar-X bond is of greater relative importance as the reagent becomes weaker.

The halogens form a particularly suitable group to illustrate these points, since the order of electronegativity is F > Cl > Br > I, and the order of bond strength, with its opposite result, is the same.

In the reactions discussed here: (i) the electronegativity differences are large between fluorine and the other halogens and considerably less between chlorine, bromine, and iodine; (ii) there is powerful activation by other groups, the S.R.F.s (substituent rate factors) of the *o*- and *p*-nitro-groups being 2.17 and 6.19 × 10<sup>5</sup> at 0° and 1.37 and 4.73 × 10<sup>4</sup> at 81.6° (preceding paper); (iii) the nucleophilic reagent is a powerful one. This leads to the predicted order F > Cl > Br > I.

The rate constants measured experimentally are shown in Table 1, together with some (shown in parentheses) calculated from them by using the experimental Arrhenius parameters. The activation energies and frequency factors are given in Table 2, and some physical data used in discussion in Table 3.

In Table 3, Ar-Hal bond strengths are for the halogenobenzenes (Landolt-Börnstein, "Tabellen," 6 Auflage, 1 Band, 2 Teil, p. 37). The additional ionic resonance energies were computed by the arithmetic mean method (Pauling, "Nature of the Chemical Bond," 2nd edn., p. 48), by use of halogen molecule bond strengths (*idem, ibid.*, p. 49) and bond

strength Ph-Ph = 102 kcal. (Landolt-Börnstein, *op. cit.*, p. 38). The differences between the computed values are given in the table.

Owing to the much more reactive nature of the fluoro-compound, rate constants for it were measured with sodium *p*-nitrophenoxide. A trial with the *m*-nitrophenoxide showed it to react inconveniently fast.

TABLE 1.

Halogen in 1-halogeno-2 : 4-dinitrobenzene	Temp.	10 <sup>3</sup> k <sub>2</sub> for reaction with :		Ratio (Cl = 1) at :				
		OMe <sup>-</sup>	<i>p</i> -NO <sub>2</sub> ·C <sub>6</sub> H <sub>4</sub> ·O <sup>-</sup>	0°	15°	25°	35°	50°
Fluorine .....	0·0°	—	(0·631)					
	15·0	—	3·42					
	25·0	—	9·62	2880	2150	1800	1520	1200
	35·0	—	25·3					
	50·0	—	(96·2)					
Chlorine .....	0·0	2·00	(0·000219)					
	15·0	10·6	(0·00159)					
	18·5	15·3	—					
	22·0	21·9	—	1	1	1	1	1
	25·0	29·6	(0·00535)					
	35·0	(76·7)	(0·0166)					
Bromine .....	0·0	1·38	—					
	15·0	7·10	—					
	20·0	11·8	—	0·690	0·670	0·659	0·640	—
	25·0	19·5	—					
	35·0	(49·1)	—					
Iodine .....	0·0	(0·308)	—					
	15·0	1·90	—	0·154	0·179	0·195	0·213	—
	25·0	5·76	—					
	35·0	16·3	—					

A preliminary run with the fluoro-compound and sodium *m*-nitrophenoxide gave  $k_2 \sim 1 \times 10^{-2}$  at 0°, and no further runs with this reagent were made.

TABLE 2.

Reagent	Arrhenius parameters	Halogen in 1-halogeno-2 : 4-dinitrobenzene :			
		F	Cl	Br	I
OMe <sup>-</sup> .....	<i>E</i> (kcal.)	(14·35)	17·43	17·07	18·97
	log <sub>10</sub> <i>B</i>	(12·28)	11·26	10·81	11·68
<i>p</i> -NO <sub>2</sub> ·C <sub>6</sub> H <sub>4</sub> ·O <sup>-</sup> .....	<i>E</i> (kcal.)	17·62	20·70	—	—
	log <sub>10</sub> <i>B</i>	10·91	9·89	—	—
Probable error in <i>E</i> .....		±0·02	±0·04	±0·04	±0·11

TABLE 3.

	Halogen in 1-halogeno-2 : 4-nitrobenzene :			
	F	Cl	Br	I
Ar-Hal bond strengths (kcal.) .....	115	90	76	54
Bond-strength differences .....	61	36	22	0
Ionic resonance-energy differences (kcal.) .....	47·3	25·2	17·0	0
Ar-Hal bond lengths (Å) .....	1·31	1·69	1·88	2·05
Aliph-Hal bond lengths (Å) .....	1·41	1·76	1·90	2·10
Van der Waals radii (Å) .....	1·35	1·80	1·95	2·15
Overlaps—planar aromatic compound (Å) .....	0·32	0·75	0·84	1·00
Overlaps—transition state (Å) .....	0	0·02	0·12	0·26

To relate fluorine through chlorine to the other compounds, the rates of attack by *p*-nitrophenoxide on the chloro-compound are required. They are given below, and the values of activation energy and frequency factor given in Table 2 are calculated from them. The latter are used to calculate the rate constants at lower temperatures given in Table 1.

Temp. ....	69·9°	74·2°	81·6°	100·8°
Rate constant (10 <sup>4</sup> k <sub>2</sub> ) .....	5·18	7·22	14·1	64·2

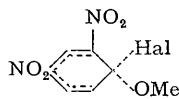
*Discussion of Results.*—The results show very clearly the order F ≫ Cl > Br > I; the actual ratios of course vary with temperature owing to differences in activation energy. The latter shows an interesting relationship; there is a marked rise from F to Cl, and a

further smaller rise from Cl and Br to I, but the value for Br is less than that for Cl. The frequency factors are also not in a simple relation, being in the order  $F > I > Cl > Br$ .

It is implicit in this discussion that the relationships which hold for the physical constants of the halogenobenzenes also hold for the halogenodinitrobenzenes, even though the absolute values may differ.

The main difference between the Ar-Hal bonds is that the Ar-F bond has much more ionic character than the others, and by rendering the carbon atom to which it is attached more positive it greatly facilitates attack by the reagent. This is shown clearly by the activation energy difference between the F and Cl compounds, *viz.*, 3.08 kcal.

Although the relatively small size of the fluorine atom implies less interference with the conjugation of the *o*-nitro-group and the ring, and thus its activating power (cf. Wheland and Danish, *J. Amer. Chem. Soc.*, 1940, **62**, 1125; Spitzer and Wheland, *ibid.*, p. 2995), yet the transition state may be assumed to have the entering and expelled groups not in the plane of the ring but in a plane at right angles to it, and thus steric effects are very much reduced. This is clearly shown if a model of the transition state of the type is constructed. It should also be noted that in contrast to the S<sub>N</sub>2 mechanism in aliphatic compounds, only four groups are bonded in the transition state.



A planar model for the 1-halogeno-2:4-dinitrobenzenes can be constructed by using Archer's experimental values (*Proc. Roy. Soc.*, 1947, *A*, **188**, 51) for the ring and the nitro-groups, and Landolt-Börnstein values for the Ar-Hal bond distances. The van der Waals radii of oxygen and the halogens (Pauling, *op. cit.*, p. 189) being used, values are obtained for overlaps (Table 3) which give an indication of the compression and distortion present in these compounds, although the differential effect will be proportional to some power of these overlap distances.

A similar model may be made for the transition state if it is assumed that (i) the six ring carbon atoms are in one plane with the two nitro-groups, (ii) the entering and expelled groups are in a plane at right angles to the ring plane, (iii) the C-O and C-Hal bonds are at 54° 44' ( $\frac{1}{2} \times$  tetrahedral angle) to the ring axis, and (iv) the C-O and C-Hal bond distances are those for aliphatic compounds (these would be minimum values). In this model it is found that the fluorine atom is now well clear, and that although the other halogen atoms still have overlaps, these are small, varying from 0.02 Å for Cl to 0.26 Å for I (Table 3). The methoxy-group does not interfere. In view of this, it is assumed that, where only the one *ortho*-group is present, the activation energy is not affected to any important extent. This is confirmed by comparison of *o*- and *p*-chloronitrobenzenes (Part II, preceding paper).

In these reactions the transition state has its charge distributed as compared with the reactants, *i.e.*, there is a loss of solvation energy in forming the transition state. However, (i) the greatest loss of solvation will be where the charge is most distributed, *i.e.*, in the most symmetrical bonding of O and Hal. From Pauling's electronegativity indices (*op. cit.*, p. 64), the asymmetry for F and Cl, relative to O, is similar though in opposite directions, and increases through Br to I. This alone would cause a loss of solvation energy in the order  $F = Cl > Br > I$ . On the other hand, (ii) that portion of the charge residing on the halogens causes solvation decreasing in the order  $F > Cl > Br > I$ . (iii) Reactions in which the charge does not change in magnitude, but merely in distribution, have comparatively small solvent effects (Hughes and Ingold, *Trans. Faraday Soc.*, 1941, **37**, 657). In view of these factors it is assumed that solvation is unimportant in its differential effect.

The conflicting factors of electronegativity and bond strength are thus left to explain the experimental results, and the data of Table 3 permit a crudely quantitative estimate of their relative importance. If *A* is the difference in ionic resonance energy, *B* the difference in bond strength, and *C* the difference in activation energy (all in kcal.), then the equation  $0.26B - 0.43A = C$  agrees quite well with the experimental values, as shown below :

	Halogen in 1-halogeno-2:4-dinitrobenzene :			
	F	Cl	Br	I
<i>C</i> (actual) .....	-4.62	-1.54	-1.90	0
<i>C</i> (calc.) .....	-4.48	-1.48	-1.59	0

In particular, the calculated values run parallel to the lowering of activation energy from I to Br, there is a slight rise from Br to Cl, and a considerable drop from Cl to F. An important result is that electronegativity is given about 1.65 times the weight of the bond strength, both being measured as stated above. Even small variations of the coefficients of the equation lead to loss of agreement.

The differences in values of the frequency factor do not lend themselves to such a detailed treatment, but a reasonable explanation of the order  $F > I > Cl > Br$  lies in the effect of two opposing factors on the entropies, which are included in the frequency-factor term, *viz.*, the frequency factors (i) decrease in the order  $F > Cl > Br > I$  owing to steric retardation of the approach of the anion to the ring carbon atom, and (ii) increase in the order  $F < Cl < Br < I$  owing to an increase, in the same order, of release of compression in passing from the initial to the transition states.

Bevan (*loc. cit.*), dealing with a similar group of reactions, regards his discussion as only a tentative one, and does not discuss the variations of activation energies and frequency factors. Chapman and Parker (*loc. cit.*) regard solvation as the main cause of the variation of these terms in their reactions. Hughes and Ingold's theory of solvent action (*loc. cit.*) leads to the conclusion that solvation is much more important in the reactions they studied.

#### EXPERIMENTAL

The runs were followed as in Part II; but the rate constants were obtained by a graphical method.

*Materials.—Fluorobenzene.* This was prepared by a standard procedure.

*1-Fluoro-2 : 4-dinitrobenzene.* Published procedures gave rather poor yields, but the following method of nitration gave an 80% yield of purified product. Dry fluorobenzene (30 g.) was added dropwise (1 hour) and with mechanical stirring to a mixture of nitric acid (*d* 1.5 ; 76 ml.) and concentrated sulphuric acid (136 ml.), the temperature being kept at 15—20°. The temperature was subsequently raised to 35—40° for an hour, 60—65° for an hour, and finally 80—85° for an hour, vigorous stirring being maintained. The mixture was then cooled and poured into iced water (1 l.). The supernatant liquid was poured off from the precipitated solid, which was washed (molten) with hot water three times and with iced water once. The white substance was dried in a cool vacuum-desiccator (yield 55 g., 96%), and then distilled under reduced pressure through a short column; a fraction, b. p. 163—164°/11 mm., was collected and gave white crystals of 1-fluoro-2 : 4-dinitrobenzene, m. p. 26° (lit., 25.8°).

*1-Chloro-2 : 4-dinitrobenzene.* The commercial product, purified by recrystallisation, had m. p. 50.5°.

*1-Bromo-2 : 4-dinitrobenzene.* This was prepared from bromobenzene by a procedure similar to that of Dame and Hoffmann (*J. Amer. Chem. Soc.*, 1919, **41**, 1015) for preparing the corresponding chloro-compound. The final product had m. p. 72.5—73°.

*1-Iodo-2 : 4-dinitrobenzene.* This was prepared from 2 : 4-dinitroaniline by standard procedures using nitrosylsulphuric acid, followed by aqueous potassium iodide. The final product had m. p. 88.5°.

*p-Nitrophenol.* The commercial product was recrystallised and had m. p. 114.5°.

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