74. *The Kinetics of Aromatic Halogenation. Part I. Bromination.*

By P. W. Robertson, P. B. D. de la Mare, and W. T. G. Johnston.

The bromination of acetanilide, aceto-*p*-toluidide, mesitylene, anisole, and *p*-tolyl methyl ether in acetic acid at room temperature shows in the concentration region M/40 third-order kinetics. This reaction, which has a low heat of activation, changes over to a bimolecular reaction at lower concentrations, with a higher E value. Addition of water to the solvent favours a bimolecular change, and addition of chloroform and carbon tetrachloride causes the initiation of chain reactions, with reaction order greater than 3. There is a formal similarity in mechanism between aromatic bromination and the addition of bromine to olefinic compounds.

The study of bromine substitution reactions is complicated by the formation of HBr_3 which reduces the active Br_2 concentration. If the value of K for the reaction $HBr + Br_2 \rightleftharpoons HBr_3$ were known, a modified expression for the rate might be obtained, as was done by Bradfield, Jones, and Orton (J., 1929, 2810) for aqueous acetic acid solutions. For pure acetic acid, however, K varies with the concentration (Jones, J., 1911, **99**, 392).

A further complication is that the reaction is acid-catalysed, as found from experiments with added sulphuric acid for phenol ethers and hydrocarbons. On the other hand, acids reduce the bromination rate of bases such as acetanilide. These facts unduly complicate the interpretation. Ultimately a procedure was adopted depending on the following considerations. In the initial stages of the reaction the influence of the liberated hydrogen bromide is small, and this effect becomes progressively less, the smaller the proportion of bromine absorbed. If the concentrations of the reactants are now doubled, the relative influence of hydrogen bromide becomes greater, but its actual effect on n, the reaction order for these two concentrations, is not considerable, and becomes progressively smaller as x, the percentage of bromine absorbed, approaches zero. Accordingly, the first 20% change of the reactions was followed, and the values of n calculated for each 5% change. Owing to the relatively rapid change in rate with altered initial concentrations of reactants, some compounds could be investigated only at a high and others only at a low concentration range. Aceto-p-toluidide has an intermediate rate and its order of reaction was measured over the range indicated below, in acetic acid at 24·0°.

x, % of Br_2 absorbed	5	10	15	20
n (M/10—M/20)	3·1	3·3	3·4	3·3
n (M/20—M/40)	3·1	3·1	3·1	3·1
n (M/40—M/80)	3·1	3·1	3·1	3·1

These results indicate third-order kinetics in this concentration range, with a slight upward drift in k_3 coefficients with the concentration. The following compounds were also investigated in acetic acid at 24·0°.

x, % of Br_2 absorbed	5	10	15	20
Acetanilide, n (M/40—M/80)	2·9	2·9	2·9	3·0
Mesitylene, n (M/40—M/80)	2·9	3·1	3·2	3·3
p-Tolyl methyl ether n (M/40—M/80)	3·1	3·1	3·0	2·9
p-Tolyl methyl ether, n (M/80—M/160)	3·0	3·1	3·1	3·2
Anisole, n (M/80—M/160)	—	3·0	2·9	2·8

The participation of the reactants, A and Br_2, in these termolecular reactions was determined by rate measurements with 2A + Br_2 and A + 2Br_2, and it was found that the reactions were bimolecular with respect to Br_2 and unimolecular with respect to A. Added sulphuric acid accelerated the reaction for anisole and mesitylene, but retarded it for acetanilide. This difference in behaviour is further revealed in a comparison of the k_3 coefficients for M/40-mesitylene and M/40-acetanilide for the reactions with M/40-bromine in acetic acid at 24·0° :

x, % of Br_2 absorbed	5	10	15	20	30	40	50
Mesitylene, k_3	870	920	940	920	870	840	820
Acetanilide, k_3	890	920	940	880	710	470	340

In the mesitylene reaction the acid catalysis increases as the reaction proceeds owing to formation of HBr and HBr_3 and offsets the fall in rate due to removal of bromine as HBr_3, whereas with acetanilide negative acid catalysis operates and the two effects combine to cause a rapid decrease in the k_3 values.

The reaction between bromine and acetanilide has been examined also at low concentrations in acetic acid at 24·0°. The relative rates are shown as bimolecular coefficients :

	M/20.	M/40.	M/80.	M/160.	M/320.	M/640.	M/1280.
k_2 (x = 20)	9·5	4·9	2·5	1·4	0·85	0·57	0·46
n		2·9		3·0		2·9	2·7	2·6	2·3
E (cals.)	—	3,300	—	—	—	11,000	—

The termolecular process dominant at M/40 changes over to a second-order reaction in the region M/1000, and correspondingly the heat of activation increases. As the temperature coefficient of the bimolecular reaction is greater, the termolecular reaction must be gradually replaced with rise in temperature. The n value for the range M/40—M/80, which is 3·0 at 24°, becomes 2·5 at 50°.

The influence of water on the brominations in acetic acid is to increase the rate and to cause a gradual change over to second-order kinetics. The effect of non-ionising solvents such as chloroform or carbon tetrachloride is initially to decrease the rate. With larger amounts of these solvents the nature of the reaction changes : the order becomes greater than 3, and the reactions become light-sensitive. These differences indicate the incursion of an atom chain-reaction, which in pure chloroform or carbon tetrachloride becomes rapid and non-reproducible. This is shown in the following table.

Relative initial rates (n values in parentheses) in acetic acid mixtures at 24·0°.

	0	50%	75%	90%	100%
CHCl₃ Anisole (M/80)	1 (3·0)	0·30 (2·8)	0·12 (3·1)	0·08 (3·6)	Variable

	0	60%	90%	100%
CCl₄ Acetanilide (M/40)	1 (2·9)	0·20 (3·5)	2·9 (5·7)	Variable

The alteration in the character of the reaction on dilution of the solvent with carbon tetrachloride is strikingly illustrated by a comparison of the rates of bromination of acetanilide in acetic acid and in 90% carbon tetrachloride + 10% acetic acid, the relative rates for M/160-reactants at 24·0° being shown as bimolecular coefficients :

x, % of Br_2 absorbed	10.	20	30	40	50	60
k_2 (HOAc)	1·56	1·34	1·16	0·92	0·75	0·55
k_2 (90% CCl₄ + 10% HOAc)	0·26	0·42	0·69	0·90	1·21	1·60

A similar type of curve was found for anisole in the same mixed solvent, indicating that the effect is not peculiar to the acetamido-group. Initially-added hydrogen bromide gave a very marked acceleration in rate, so the autocatalysis is due to the hydrogen bromide produced in the reaction.

Two compounds with relatively slow rates of bromination have been found to give reaction orders greater than 3 in acetic acid at $24 \cdot 0°$:

x, % of Br_2 absorbed	5	10	15	20
m-Xylene, n (M/5—M/10)	3·9	3·9	4·0	3·9
Naphthalene, n (M/5—M/10)	—	4·0	4·0	4·1
Naphthalene, n (M/10—M/20)	—	3·7	3·7	3·7
Naphthalene, n (M/20—M/40)	—	3·4	3·4	3·4

The fact that n does not increase as the reaction proceeds would seem to indicate that HBr_3 formation is not responsible for the order higher than 3. It is possible that atom chains may be formed even in acetic acid, becoming evident when the normal reaction is very slow. Dilution with carbon tetrachloride increases the contribution of the higher-order reaction, changing n for naphthalene from 4·0 to 4·5 in 50% carbon tetrachloride $+50\%$ acetic acid.

As the possibility of chain reactions appears here to be indicated in aromatic brominations in acetic acid, it might be argued that the effects observed in the bromination reactions in acetic acid, *viz.*, the increase in reaction order from $n = 2$ on increasing the concentration, could be explained as due to the same cause. It is believed that this is not so, and that the increase in n to 3 at the concentration region M/40 is due to a gradual dominance of a termolecular reaction. The constancy of the n values for aceto-*p*-toluidide at $x = 5\%$ (see p. 277) is a fairly definite indication that over the range M/10—M/80 there is no appreciable chain reaction. When a chain reaction is indicated, *e.g.*, by the light-sensitivity of the reaction, increase in concentration causes n to become greater; for instance, acetanilide in 90% carbon tetrachloride $+ 10\%$ acetic acid gives, for M/80—M/160, $n = 3 \cdot 4$, and for M/40—M/80, $n = 5 \cdot 7$.

EXPERIMENTAL.

The solvents, bromine, and general technique were as previously described (J., 1937, 335; 1939, 1510). The following compounds were used : acetanilide, m. p. 113°; aceto-*p*-toluidide, m. p. 148°; naphthalene, m. p. 80·0°; *m*-xylene, b. p. 138·0—138·5°/760 mm.; mesitylene, b. p. 165·0°/760 mm.; anisole, b. p. 151·5—152·0°/760 mm.; *p*-tolyl methyl ether, b. p. 174·0°/760 mm.

Rate measurements were carried out in duplicate or triplicate, the zero titration figure being obtained by mixing the bromine solution with acetic acid in a reaction bottle of similar dimensions, and titrating the same volume as that used for the reaction mixture. For the slow reactions this bottle was left in the thermostat for checking volatility losses (never >4%). From the curve relating t and x the values of t were read off at 5, 10, 15, and 20%, a small correction (never >1%) being made whenever the initial titre of the bromine varied from the normality under investigation. The following are the details of such a measurement.

M/20-*Aceto*-p-*toluidide* + M/20-Br_2 *in acetic acid at* $24 \cdot 0°$.
Reaction mixture, 10 ml.; 2 ml. samples titrated with $0 \cdot 05N$-$Na_2S_2O_3$.

Time (mins.)	0	2·60	7·40	30·00	0	4·12	14·10	24·7
Titre, ml.	4·06	3·89	3·67	3·16	4·06	3·80	3·46	3·23

The experimental times for aceto-*p*-toluidide, for which n values are shown in the first table, were :

x	5	10	15	20	x	5	10	15	20
t (mins.), M/10	0·75	1·62	2·82	5·01	t (mins.), M/40	14·0	33·5	62·0	101·5
t (mins.), M/20	3·2	7·9	14·7	23·9	t (mins.), M/80	60	149	270	440

For the compounds listed in the second table, the times (mins.) at $x = 10\%$ only are given : acetanilide, M/40, $t = 0 \cdot 82$; M/80, $t = 3 \cdot 02$; mesitylene, M/40, $t = 0 \cdot 82$; M/80, $t = 3 \cdot 55$; *p*-tolyl methyl ether, M/40, $t = 2 \cdot 10$; M/80, $t = 8 \cdot 9$; M/160, $t = 37 \cdot 3$; anisole, M/80, $t = 0 \cdot 54$; M/160, $t = 2 \cdot 09$.

The measurements to show the participation of the reactants were made with acetanilide (A) at $24 \cdot 0°$:

M/40-A + M/40-Br_2, t ($x = 20\%$ Br_2) 2·04; $k_2 = 4 \cdot 9$ M/40-A + M/80-Br_2, t ($x = 20\%$ Br_2) 3·82; $k_2 = 2 \cdot 5$
M/80-A + M/40-Br_2, t ($x = 20\%$ A) 1·76; $k_2 = 5 \cdot 3$ M/80-A + M/80-Br_2, t ($x = 20\%$ Br_2) 8·05; $k_2 = 2 \cdot 5$

The influence of acids and bases on bromination in acetic acid at $24 \cdot 0°$ is shown, as the ratio of catalysed to uncatalysed reaction :

Acetanilide, reactants M/40, $+0 \cdot 15M$-H_2SO_4 : 0·47
Mesitylene, reactants M/40, $+0 \cdot 10M$-H_2SO_4 : 1·53
Anisole, reactants M/80, $+0 \cdot 012M$-H_2SO_4 : 1·11

The times (mins.) for the values for acetanilide quoted in the fourth table are as follows (for $x = 20$) : At $24 \cdot 0°$, M/20, $t = 0 \cdot 53$; M/40, $t = 2 \cdot 04$; M/80, $t = 8 \cdot 05$; M/160, $t = 29 \cdot 8$; M/320, $t = 94 \cdot 0$; M/640, $t = 280$; M/1280, $t = 698$. At 16°, M/40, $t = 2 \cdot 27$. At $34 \cdot 6°$, M/40, $t = 1 \cdot 64$. At 34·8°, M/640, $t = 143$. At $49 \cdot 0°$, M/640, $t = 67 \cdot 4$.

The following measurements were made (for $x = 20$) in 20% water $+ 80\%$ acetic acid : At $24 \cdot 0°$: M/640, $t = 1 \cdot 00$; M/1280, $t = 2 \cdot 03$ ($n = 2$). At $16 \cdot 0°$, M/640, $t = 1 \cdot 32$. At $35 \cdot 6°$, M/640, $t = 0 \cdot 63$ ($E = 7,100$).

The following are the experimental details of the results quoted in the fifth table, the times being given for $x = 10\%$.

Anisole	50% $CHCl_3$, 50% HOAc :	M/80, $t = 2 \cdot 07$; M/160, $t = 7 \cdot 00$
	75% $CHCl_3$, 25% HOAc :	M/80, $t = 4 \cdot 35$; M/160, $t = 18 \cdot 7$
	90% $CHCl_3$, 10% HOAc :	M/80, $t = 4 \cdot 38$; M/160, $t = 27 \cdot 0$
Acetanilide	60% CCl_4, 40% HOAc :	M/40, $t = 4 \cdot 62$; M/80, $t = 26 \cdot 3$
	90% CCl_4, 10% HOAc :	M/40, $t \sim 0 \cdot 25$; M/80, $t = 11 \cdot 2$; M/160, $t = 65$

The experimental time values ($x = 10$) (sixth table) were : Naphthalene : M/5, $t = 4.8$; M/10, $t = 38.6$; M/20, $t = 260$; M/40, $t = 1405$. *m*-Xylene (HOAc + 1% H_2O) : M/5, $t = 0.82$; M/10, $t = 6.22$.
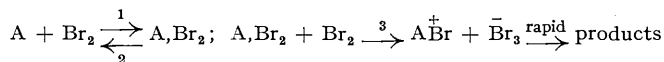
The bromination of certain hydrocarbons has been investigated by Lauer and Oda (*Ber.*, 1936, **69**, 978) in 1% water + 99% acetic acid. Their results appear to be vitiated by grave errors. The following is characteristic, our data being compared with theirs (in parentheses): naphthalene + Br_2, 18°, reactants 0·161M; $t = 10$, $k_2 = 9.0 \times 10^{-2}$ (22·7 × 10^{-2}); $t = 60$, $k_2 = 5.5 \times 10^{-2}$ (7·0 × 10^{-2}); reactants 0·056M, $t = 10$, $k_2 \sim 1.5 \times 10^{-2}$ (33·8 × 10^{-2}); $t = 60$, $k_2 = 1.1 \times 10^{-2}$ (7·95 × 10^{-2}). The fact that the divergences are greater (*a*) with smaller t, (*b*) at lower initial concentrations, and (*c*) for more slowly reacting compounds, indicates the presence of unsaturated impurity in their solvent, and this is also apparent in Fig. 5 (*loc. cit.*, p. 982).

DISCUSSION.

The bromination of acetanilide in acetic acid at 24° changes from a termolecular reaction at M/40 ($E = 3,300$) to a bimolecular reaction in the region M/1000 ($E = 11,000$). Under the same conditions bromine addition to allyl acetate, which proceeds at the same general rate, changes similarly in reaction order over the same concentration range, the values of E being respectively 4000 and 9000. Such a formal similarity cannot be regarded as accidental, and indeed can be explained as due to the operation of a similar rate-determining mechanism in the two reactions. A termolecular reaction may be considered kinetically as a simultaneous collision between three molecules, in this instance one of A and two of Br_2. If the time of contact between two of these molecular species becomes relatively considerable, the process may be regarded as proceeding *via* an intermediate compound, $(Br_2)_2$ or A,Br_2. An addition compound, Br–Br→Br–Br, in its various resonance forms, is theoretically possible. There is no evidence for the association of bromine in acetic acid, but for a mechanism showing third-order kinetics the concentration of $(Br_2)_2$ need be only very small. The second possibility, and this has equal theoretical justification, is that an intermediate, *e.g.*, (I) is formed   This mechanism

(I.) Me·CO>N<=<>< Br—Br / H   [Me/Me>N<=<>=CR—CH_2Br] Br_3   (II.)

is preferred, for substances similar to (I) have been obtained by Pfeffer and Wizinger (*Annalen*, 1928, **461**, 132) by the action of bromine on compounds of the type $(C_6H_4X)_2C:CH_2$, which undergo substitution in the ω-position. Thus, the isolation of (II) (R = $C_6H_4 \cdot NMe_2$) represents the actual fixing of one of the stages in a process, which is similar for substitution and addition :

$$A + Br_2 \underset{2}{\overset{1}{\rightleftharpoons}} A,Br_2; \quad A,Br_2 + Br_2 \overset{3}{\longrightarrow} A\overset{+}{Br} + \overset{-}{Br_3} \overset{rapid}{\longrightarrow} products$$

By application of the method of stationary concentrations, the kinetic form of such a reaction is given by the expression :

$$-d[A]/dt = k_1 k_3 [A][Br_2]^2/(k_2 + k_3[Br_2])$$

If $k_3 \gg k_2$: $-d[A]/dt = k_1[A][Br_2]$ (second-order kinetics)
If $k_2 \gg k_3$: $-d[A]/dt = k_1 k_3[A][Br_2]^2/k_2$ (third-order kinetics)

The reactions under consideration show within a given temperature and concentration range third-order kinetics, but the true bimolecular reaction may operate simultaneously. The latter is favoured by dilution, when the relative frequency of termolecular to bimolecular collisions decreases, and on raising the temperature, owing to the greater temperature coefficient of the bimolecular reaction. Addition of water to the solvent also favours second-order kinetics. Since E for the reactions in aqueous acetic acid is higher than that obtained for the termolecular change in pure acetic acid, it is concluded that the effect of water is to favour the bimolecular mechanism, rather than to cause the termolecular reaction to show second-order kinetics.

VICTORIA UNIVERSITY COLLEGE, WELLINGTON, N.Z.