

The Kinetics and Mechanisms of Aromatic Halogen Substitution. Part 34.¹ Comments on the Physical Interpretation of High Kinetic Orders in Bromine

By Nicholas H. Briggs, Peter B. D. de la Mare,* and David Hall, Chemistry Department, University of Auckland, Private Bag, Auckland, New Zealand

Reactions of bromine with aromatic and with olefinic compounds in acetic acid show kinetic behaviour which varies with solvent and initial concentration of bromine, and can indicate the presence of one, or of more than one, molecule of bromine in the transition state. Additional kinetic disturbances can result from complexing of bromine with added, or with developing, bromide ion, from environmental (salt) effects, and from the reversible formation of a carbocation. Some of the important criteria necessary for interpretation of the results in terms of the composition of the transition state, and in particular of the number of bromine molecules concerned in the transition state, are analysed.

THE establishment of the kinetic form of a reaction involves first a determination of the rate of formation of products, or disappearance of reactants, or both, under a number of different initial concentrations of the reactants sufficiently great to enable the establishment of the dependence of the rate (or rates) on the initial concentrations of the separate reactants. Since the concentrations of products of reaction vary with time, and may influence the rate in a number of different ways, it is often important to establish also the dependence of rates on product concentrations.

The purpose of determining the kinetic form may, of course, be empirical; concerned for example with optimising the yield of a particular product. Mathematical analyses of the relationship between concentration of reactant or product against time can then be carried out in whatever way is most convenient: since most such relationships involve smooth curves, polynomial functions may be found appropriate to describe the courses of reactions in particular ranges of concentration. More usually, however, such measurements are made with the intention of establishing the stoichiometry of the transition state of the reaction; and, in the case of a multistage process, of obtaining information concerning the composition of intermediates concerned in the reaction path. Under these circumstances, on the one hand the mathematical analysis needs to be more sophisticated, and to relate precisely to the proposed

reaction scheme; and on the other, the conditions investigated experimentally need to be chosen so as to enable real distinction to be made between alternative mechanistic pathways. The interpretation of the results is not always easy; but it has become abundantly clear that useful new information concerning reactions can often be obtained when experiments are well designed.

The kinetic forms of halogenations, whether substitutions or additions, have been much investigated from this point of view. Comprehensive accounts of the kinetic behaviours which have been identified have been given for the former type of reaction by Taylor,² and for the latter by Bolton;³ they describe, *inter alia*, reactions of order greater than one in bromine which have been interpreted by many workers (the first group being that of Robertson)^{4,5} in terms of the participation under certain conditions of a reaction pathway in which more than one molecule of bromine is concerned in the transition state. We shall describe this as the 'high-order' mechanism, which is usually associated with a second-order process. It is expressed in a general form in equation (1), which includes both a third- and a fourth-order term; for the conditions over which the kinetics have been most extensively defined, the fourth-order term is negligible.

$$-\frac{d[\text{ArH}]}{dt} (= -\frac{d[\text{Br}_2]}{dt} = \frac{d[\text{Products}]}{dt}) \\ = k_2'[\text{ArH}][\text{Br}_2] + k_3'[\text{ArH}][\text{Br}_2]^2 + k_4'[\text{ArH}][\text{Br}_2]^3 \quad (1)$$

¹ Part 33, P. B. D. de la Mare, B. N. B. Hannan, and N. S. Isaacs, *J.C.S. Perkin II*, 1976, 1389.

² R. Taylor, in 'Comprehensive Chemical Kinetics,' eds. C. H. Bamford and C. F. H. Tipper, Elsevier, Amsterdam, 1972, vol. 13, pp. 113—135.

³ R. Bolton, in ref. 2, vol. 9, pp. 26—28.

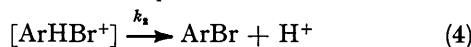
⁴ P. W. Robertson, P. B. D. de la Mare, and W. T. G. Johnston, *J. Chem. Soc.*, 1943, 276.

⁵ P. W. Robertson, N. T. Clare, K. J. McNaught, and G. W. Paul, *J. Chem. Soc.*, 1937, 335.

Recently Schubert and Dial⁶ have examined the kinetics of bromination of *N*-methylacetanilide in 50% acetic acid at 25° over a particular range (0.001—0.0001M) of concentration of bromine. Under these conditions, reactions of the second kinetic order (first order in each reactant) are to be expected in the light of previous studies by many groups of workers. It was noted that second-order rate coefficients calculated through a single kinetic run fell off as the reaction proceeded. Several interpretations are possible to account for this behaviour. First, the accumulating bromide ion from the product HBr would progressively reduce the effective concentration of bromine through the well-known equilibrium of equation (2). Given the



known equilibrium constant, $K = 27.6 \text{ l mol}^{-1}$ in this solvent, however, this perturbation of the second-order kinetic form would not be sufficient to account for the observed kinetic results. Schubert and Dial noted, therefore, that the reaction mechanism expressed by equations (3) and (4) could contribute to the observed behaviour if the relative values of the rate coefficients k_{-1} and k_2 were suitable, since the progressive build-up of bromide ions could progressively reverse the equilibrium of equation (3) and hence progressively retard the



formation of the measured product. They noted also, as has been established by other workers for similar cases,^{7,8} that such a result carried the implication that both the rate and the primary kinetic deuterium isotope effect will vary with concentration of added bromide ion in predictable ways, and they provided experimental results in which the initial rates of reaction accorded semi-quantitatively with the predictions of the above mechanistic interpretation. We shall describe this as the 'second-order, reversible first-step' mechanism; it can co-exist with the high-order mechanism, just as the more commonly encountered second-order process does normally [cf. equation (1)].

The rate coefficients for a reaction having third or higher kinetic order in reactants, when calculated by using the second-order equation, fall off with time in a manner qualitatively similar to that observed in their experiments. Apparently remembering this, Schubert and Dial⁶ commented that a reaction following the mechanism appropriate to their experimental conditions [equations (3) and (4)] has the *same* (their italics) kinetic behaviour as a reaction in which several reaction pathways, involving one, two, or three molecules of bromine in the respective rate-limiting transition states [equation (1)], contribute to the total reaction.

They represented, therefore, that their results could

⁶ W. M. Schubert and J. L. Dial, *J. Amer. Chem. Soc.*, 1975, **97**, 3877.

⁷ E. Berliner, J. B. Kim, and M. Link, *J. Org. Chem.*, 1968, **33**, 1160.

be expressed in terms of equation (5), in which $[\text{Br}_2]_0$ is the initial concentration of bromine; three terms only of the nominally infinite series comprising the polynomial expansion were considered sufficient to describe the results adequately.

$$\begin{aligned} -d[\text{ArH}]/dt & (= -d[\text{Br}_2]/dt = d[\text{Products}]/dt) \\ & = A[\text{ArH}][\text{Br}_2] + B[\text{ArH}][\text{Br}_2]^2 + C[\text{ArH}][\text{Br}_2]^3 + \dots \\ & \approx \frac{k_1 k_2 [\text{ArH}]}{k_{-1} [\text{Br}_2]_0 + k_2} [\text{Br}_2] + \\ & \quad \frac{k_1 k_2 [\text{ArH}]}{k_{-1} [\text{Br}_2]_0 + k_2} \left\{ \frac{k_{-1} + 2k_{-1} K [\text{Br}_2]_0}{k_{-1} [\text{Br}_2]_0 + k_2} \right\} [\text{Br}_2]^2 + \\ & \quad \frac{k_1 k_2 [\text{ArH}]}{k_{-1} [\text{Br}_2]_0 + k_2} \left\{ \frac{k_{-1} + 2k_{-1} K [\text{Br}_2]_0}{k_{-1} [\text{Br}_2]_0 + k_2} \right\} \\ & \quad \left\{ \frac{k_{-1} - 2k_2 K}{k_{-1} [\text{Br}_2]_0 + k_2} \right\} [\text{Br}_2]^3 \quad (5) \end{aligned}$$

This resembles equation (1) by being a polynomial in $[\text{Br}_2]$.

The representation of experimental curves following the course of brominations by polynomial functions with empirical coefficients has been found useful by other workers,^{9,10} who found that curves for the disappearance of bromine could be reproduced empirically by equations of the form $t = x + Bx^2 + Cx^3 + Dx^4$, x being the proportion of bromine used up, and used such curves to calculate dt/dx and hence dx/dt . Both these groups of workers used the coefficients so determined to support the mechanism for aromatic brominations in mixtures of acetic acid and water based on equation (1), with k_4' normally negligible.

In this paper, we support this view, and consider Schubert and Dial's⁶ representation. First, we analyse their experimental results, show that they are consistent with earlier work in the field, and establish values of the ratio k_{-1}/k_2 and of the primary deuterium isotope effect which best accord with their findings. Secondly, we show that their statements (a) that the *same* kinetic behaviour will be shown by the two mechanisms [based respectively on equations (3) and (4) and on equation (1)] and (b) that the general rate expression for the simple two-stage mechanism is the *equivalent* of the power-series equation, are both incorrect except under the trivial circumstances specifically excluded by Schubert and Dial, namely that $k_{-1}[\text{Br}^-]/k_2$ does not grow to significance during a kinetic run as the result of the production of Br^- (and only then with the additional proviso that both k_3' and k_4' are negligible). Thirdly, we establish the types of circumstances under which reactions following the pathways represented by the equations (3) and (4) on the one hand, and (1) on the other, can be expected to be distinguishable experimentally. Fourthly, we establish that the coefficients in the polynomial equation (5), considered by Schubert

⁸ E. Berliner, *Progr. Phys. Org. Chem.*, 1964, **2**, 253.

⁹ A. E. Bradfield, G. I. Davies, and E. Long, *J. Chem. Soc.*, 1949, 1389.

¹⁰ U.-J. Zimmerman and E. Berliner, *J. Amer. Chem. Soc.*, 1962, **84**, 3953.

and Dial to be equivalent to equation (1), are not rate coefficients and have no mechanistic significance. Fifthly, we consider the consequences of more elaborate mechanistic combinations, and of other kinetic disturbances. Sixthly, we review briefly the mechanisms available for brominations by molecular bromine in the light of current knowledge.

Computations.—The second-order, reversible first-step mechanism [equations (3) and (4)].—The mechanism represented by equations (3) and (4), analysed in terms of a stationary concentration of the intermediate [ArHBr⁺] in accordance with Schubert and Dial's treatment, leads to equation (6). We put [ArH]₀ = a;

$$-d[\text{ArH}]/dt = k_1 k_2 [\text{ArH}][\text{Br}_2]/(k_{-1}[\text{Br}^-] + k_2) \quad (6)$$

[ArH]_t = a - x; [Br₂]₀ + [Br₃⁻]₀ = b; [Br₂]_t + [Br₃⁻]_t = b - x; [Br₃⁻]₀ + [Br⁻]₀ = c; [Br₃⁻]_t + [Br⁻]_t = c + x. From the consequences of the initial conditions and stoichiometry of the reaction, equation (7) follows.

$$\frac{dx}{dt} = \frac{k_1(a-x) \left[b - c - 2x - \frac{1}{K} + \sqrt{\left(b - c - 2x - \frac{1}{K} \right)^2 - \frac{4(x-b)}{K}} \right]}{2 + \frac{k_{-1}}{k_2} \left[c + 2x - b - \frac{1}{K} + \sqrt{\left(b - c - 2x - \frac{1}{K} \right)^2 - \frac{4(x-b)}{K}} \right]} \quad (7)$$

This equation corresponds as far as the numerator is concerned with that derived by Bradfield *et al.*⁹ for the more normal second-order process. Exact integration of this equation is difficult with or without inclusion of the complication that the equilibrium constant for equation (2) ($K = [\text{Br}_3^-]/[\text{Br}_2][\text{Br}^-]$) is not negligible. Numerical evaluation of the course of the reaction as a function of time is, however, straightforward by standard computational methods. In this study a fourth-order Runge-Kutta procedure¹¹ has been used. Details of the computer programmes, and of the output related to the material presented in subsequent Tables, are deposited as a Supplementary Publication No. SUP 21823 (65 pp., 2 microfiche).*

It is then possible to evaluate x, the change in titratable or otherwise measurable bromine (*i.e.*, the progress of reaction) as a function of time, appropriate values of the parameters being chosen. It is useful also in the present context to evaluate over a range of chosen values [the mechanism of equations (3) and (4), from which equations (6) and (7) are derived, being assumed] the time-dependence of the formal second- and third-order rate coefficients which would be appropriate to represent the course of hypothetical reactions following respectively the first and second terms of equation (1) under circumstances in which the kinetic disturbances resulting from reversibility of the first stage and from

the formation of tribromide ion are negligible. These rate coefficients are respectively:

$$\beta = \frac{1}{t(a-b)} \ln \frac{b(a-x)}{a(b-x)} \text{ l mol}^{-1} \text{ min}^{-1};$$

$$\gamma = \frac{1}{t(b-a)^2} \left\{ \left[\ln \frac{a(b-x)}{b(a-x)} \right] - \frac{x(b-a)}{b(b-x)} \right\} \text{ l}^2 \text{ mol}^{-2} \text{ min}^{-1}.$$

The high-order mechanism. The effect of the kinetic disturbance resulting from the tribromide equilibrium on the combination of mechanisms represented by equation (1) can be treated similarly. For the purpose of the present illustration, we have made the simplification that the value of k_4' is zero, so that only the terms of first- and second-order in bromine need be considered; equation (8) then needs to be evaluated, along with new values of β and α .

$$\frac{dx'}{dt} = \frac{k_2'(a-x')}{2} \left[b - c - 2x' - \frac{1}{K} + \sqrt{\left(b - c - 2x' - \frac{1}{K} \right)^2 - \frac{4(x'-b)}{K}} \right] + \frac{k_3'(a-x')}{4} \left[b - c - 2x' - \frac{1}{K} + \sqrt{\left(b - c - 2x' - \frac{1}{K} \right)^2 - \frac{4(x'-b)}{K}} \right]^2 \quad (8)$$

DISCUSSION

(a) *Analysis of Schubert and Dial's Experimental Results.*—For numerical illustration, we have used Schubert and Dial's experimental results for the bromination of *N*-methylacetanilide in aqueous (50%) acetic acid. With the appropriate value of K (27.6 l mol⁻¹), a value of $k_{-1}/k_2 = 5.7$ l mol⁻¹ is required to fit the values of β at the extremes of concentration of bromide ion. In Table 1, the calculated values of β extrapolated to $t = 0$ (β_{init}) are compared with experiment. The agreement between observed and calculated values is reasonable; the fit cannot be made perfect at all concentrations of bromide ion, probably because salt effects on the rate coefficients and on K are not negligible and are influenced by ion-pairing.

Schubert and Dial's experimental values of the primary deuterium isotope effect can also be fitted (as is shown in Table 1), the assumption being made that $k_1^{\text{H}}/k_1^{\text{D}}$ is 0.9 (a reasonable value for a reaction in which a trigonal carbon atom becomes nearly tetrahedral in the transition state⁸); $k_{-1}^{\text{H}}/k_{-1}^{\text{D}}$ is 1, as expected; and $k_2^{\text{H}}/k_2^{\text{D}}$ is 3.05. The latter ratio, being a proton transfer from a carbocation to the solvent, would be subject to a substantial primary hydrogen-deuterium isotope effect. Values of 4.2 and 3.8 have been recorded for similar transfers in acetic acid and in slightly aqueous (95%) acetic acid,¹² so the value now recorded as best fitting

¹¹ *E.g.* F. Scheid, 'Theory and Problems of Numerical Analysis,' McGraw-Hill, New York, 1968, ch. 19.

¹² P. B. D. de la Mare, A. Singh, J. G. Tillett, and M. Zeltner, *J. Chem. Soc. (B)*, 1971, 1122.

* Details of the Supplementary Publications scheme are given in *J.C.S. Perkin II*, 1975, Index Issue, Notices to Authors, No. 7.

Schubert and Dial's result accords with the observed trend of such isotope effects with change of solvent. A slightly higher value (3.48) has been reported as possibly applicable to the bromination of perdeuterionaphthalene in 50% acetic acid,¹³ but both this and the value derived from Schubert and Dial's experiments are to be regarded as approximations only, because specific salt effects could influence the rates of the individual processes unpredictably.

(b) *Comparison of the Kinetic Forms expected for Reactions following Equations (3) and (4) on one Hand, and (1) on the Other.*—Equation (7), applicable to the

the disturbance by the build-up of bromide formed in the reaction.

The most direct method of distinguishing between a reaction following this pathway and one following the high-order mechanism with a significant contribution from the third-order kinetic term is to follow the original workers,^{4,5} and their many successors, and determine the initial rate of reaction over a wide range of concentration of bromine. The focusing of attention on the initial rate enables the complicating factor of complexing between bromide ion and bromine [equation (2)] to be eliminated; and reversibility of the second-order term

TABLE 1

Observed and calculated values (β l⁻¹ mol min) of second-order rate coefficients for bromination of *N*-methylacetanilide in 50% acetic acid at 25°

Initial [Br ⁻]/M	Other added electrolytes (M)	β_{init} calc. with $b = 0.000\ 2$	β_{init} calc. with $b = 0.002$	β_{init} found $b = 0.000\ 2-0.002$	$k_{\text{H}}/k_{\text{D}}$ calc.†	$k_{\text{H}}/k_{\text{D}}$ found
0.000		0.086	0.086	0.086 *	0.90	0.93
0.05	NaClO ₄ (0.25)	0.028	0.029	0.023	1.31	1.41
	NaOAc (0.25)	0.028	0.029	0.020	1.31	1.18
0.15	NaClO ₄ (0.25)	0.009 0	0.009 1	0.006 5	1.75	1.85
0.30		0.003 4	0.003 5	0.002 5	2.06	2.14
0.50		0.001 5	0.001 5	0.001 5	2.27	2.27

* 0.086 at $b = 0.000\ 2$; 0.079 at $b = 0.002$. † See text.

second-order, reversible first step mechanism [equations (3) and (4)], does *not* (our italics) predict the *same* (Schubert and Dial's italics) kinetic behaviour as will be found for the high-order mechanism (more strictly, for a combination of this with the second-order mechanism) [equation (1) to which equation (8) is appropriate], except under the trivial circumstance that $k_{-1}[\text{Br}^-]/k_2$ is insignificant (a situation specifically excluded by Schubert and Dial), and also that k_3' is negligible. Numerical evaluation is necessary, however, to establish the extent to which the mechanisms differ, and the circumstances under which the differences would be large enough to be distinguishable experimentally.

Illustrative values (β l⁻¹ mol min) of experimental second-order rate coefficients expected for a reaction following Schubert and Dial's mechanism with the parameters already mentioned are given in Table 2 to

TABLE 2

Illustrative values (β l⁻¹ mol min) of computed formal second-order rate coefficients for a reaction following Schubert and Dial's mechanism [equations (3) and (4)], with $a = 0.1$ mol l⁻¹; $c = 0$; $K = 27.6$ l mol⁻¹; $k_{-1}/k_2 = 5.7$ l mol⁻¹; $k_1 = 0.086$ l mol⁻¹ min⁻¹

10 ⁴ b/mol l ⁻¹	1	2	16	32	256	512
$x/b = 0.02$	0.086	0.086	0.086	0.086	0.086	0.085
$x/b = 0.04$	0.086	0.086	0.086	0.086	0.085	0.085
$x/b = 0.06$	0.086	0.086	0.086	0.086	0.085	0.084
$x/b = 0.08$	0.086	0.086	0.086	0.086	0.084	0.083
$x/b = 0.10$	0.086	0.086	0.086	0.086	0.084	0.083
$x/b = 0.15$	0.086	0.086	0.086	0.085	0.083	0.081
$x/b = 0.20$	0.086	0.086	0.086	0.085	0.081	0.079

show what would be expected for the first 20% of reaction over a wide range of concentration of bromine.

At each value of b , β extrapolates to an initial value equal to k_1 . The higher the value of b , the greater is

[equations (3) and (4)] would provide a problem only with the most extreme and improbable values of k_{-1}/k_2 . In Table 3, illustrative values of β are given for a

TABLE 3

Illustrative values (β l⁻¹ mol min) of computed formal second-order rate coefficients for a reaction following equation (1), with $a = 0.1$ mol l⁻¹; $k_2' = 0.086$ l mol⁻¹ min⁻¹; $k_3' = 8.6$ l² mol⁻² min⁻¹; $k_4' = 0$; $K = 27.6$ l mol⁻¹

10 ⁴ b/mol l ⁻¹	1	2	16	32	256	512
$x/b = 0.02$	0.086 9	0.087 8	0.099 7	0.113 3	0.302 7	0.518 8
$x/b = 0.04$	0.086 9	0.087 7	0.099 4	0.112 8	0.297 8	0.507 2
$x/b = 0.06$	0.086 9	0.087 7	0.099 2	0.112 4	0.293 2	0.496 4
$x/b = 0.08$	0.086 8	0.087 6	0.099 0	0.112 0	0.288 6	0.485 8
$x/b = 0.10$	0.086 8	0.087 6	0.098 8	0.111 6	0.284 0	0.475 2
$x/b = 0.15$	0.086 8	0.087 6	0.098 3	0.110 5	0.272 6	0.448 4
$x/b = 0.20$	0.086 8	0.087 5	0.097 8	0.110 0	0.261 1	0.421 4

hypothetical reaction following equation (1), for comparison with the results given in Table 2.

The extrapolated initial second-order rate coefficients now (contrast Table 2) vary with initial bromine concentration; when the ratio of k_3'/k_2' is 100 l mol⁻¹, as here, the variation is small when b is below 0.001M, and increases so that β becomes nearly proportional to the bromine concentration when b approaches 0.1M. Under these circumstances, if the reaction can be followed over a sufficient range of concentration of bromine, a clear distinction between reactions following the two mechanisms can be made. Robertson *et al.*⁴ first established in this way the incursion of a third-order term in aromatic substitution for the bromination of acetanilide, of mesitylene, and of anisole in acetic acid; many other

¹³ E. Erlich and E. Berliner, *J. Org. Chem.*, 1972, **37**, 4186.

¹⁴ P. B. D. de la Mare and B. N. B. Hannan, *J.C.S. Perkin II*, 1973, 1586.

workers have confirmed their findings,² which apply also to additions,^{3,4} by extending them to other substrates.

(c) *Kinetic Form as determined by Measurements through a Single Kinetic Run.*—It is useful also to

TABLE 4

Illustrative values (β l⁻¹ mol min) of computed formal second-order rate coefficients expected for a reaction following Schubert and Dial's mechanism [equations (3) and (4)] with $a = 0.1$ mol l⁻¹; $b = 0.0002$ mol l⁻¹; $c = 0$; $k_1 = 0.086$ l mol⁻¹ min⁻¹

K/l mol ⁻¹	27.6	27.6	27.6	1—100	10 ⁴	10 ⁶
$(k_{-1}/k_2)l$ mol ⁻¹	0—100	10 ⁴	10 ⁶	5.7	5.7	5.7
$x/b = 0.02$	0.086	0.084	0.029	0.086	0.085	0.085
$x/b = 0.04$	0.086	0.083	0.017	0.086	0.085	0.084
$x/b = 0.06$	0.086	0.081	0.012	0.086	0.084	0.083
$x/b = 0.08$	0.086	0.080	0.0095	0.086	0.084	0.082
$x/b = 0.10$	0.086	0.078	0.0077	0.086	0.083	0.081
$x/b = 0.15$	0.086	0.075	0.0053	0.086	0.081	0.078
$x/b = 0.20$	0.086	0.071	0.0040	0.086	0.080	0.075

consider what can be expected if a reaction is followed through a single kinetic run. In Table 4, we show the effect of keeping b constant at 0.0002 (in the range

The same is seen also to be true if K is chosen to be 27.6 (as is relevant to Schubert and Dial's experiments) and k_{-1}/k_2 is varied. A value of $k_{-1}/k_2 = ca. 4000$ makes γ constant over about the first 10% of reaction; but thereafter γ rises; and if a value is chosen to make γ the same at (say) 0 and 50% reaction (*viz. ca. 8000*) the values of γ go through a minimum value which if these conditions corresponded to reality might even be detectable experimentally if no other kinetic complications contributed; they then rise sharply towards the end of the reaction.

For approximate simulation of third-order behaviour through a single run at this low concentration of bromine, experimentally rather large values of K or of k_{-1}/k_2 would be necessary; the values experimentally applicable to Schubert and Dial's experiments are much less. For reaction at higher concentrations of bromine, however, smaller values would suffice, as is illustrated in Table 6. Approximate (though not exact) constancy over 50% reaction is now maintained with $K = 27.6$ and $k_{-1}/k_2 = 65$; or with $k_{-1}/k_2 = 5.7$ and $K = 200$. The values of

TABLE 5

Illustrative values (γ l⁻² mol² min) of computed formal third-order rate coefficients expected for a reaction following Schubert and Dial's mechanism [equations (3) and (4)] with $a = 0.1$ mol l⁻¹; $b = 0.0002$ mol l⁻¹; $c = 0$; $k_1 = 0.086$ l mol⁻¹ min⁻¹

K/l mol ⁻¹	20 000	22 000	24 000	26 000	27.6	27.6	27.6	27.6
$(k_{-1}/k_2)l$ mol ⁻¹	5.7	5.7	5.7	5.7	4 000	6 000	8 000	10 000
$x/b = 0.02$	431	431	431	431	431	429	429	426
$x/b = 0.04$	432	432	431	431	432	429	425	422
$x/b = 0.10$	434	434	433	433	436	427	419	412
$x/b = 0.20$	437	436	435	434	445	428	413	399
$x/b = 0.30$	438	436	434	432	458	434	412	393
$x/b = 0.40$	437	434	430	427	478	445	416	391
$x/b = 0.50$	435	429	423	418	507	464	429	398
$x/b = 0.60$	434	425	416	407	551	497	453	410
$x/b = 0.70$	442	427	414	402	623	553	498	450
$x/b = 0.80$	475	455	436	420	760	665	591	532

examined by Schubert and Dial), but assuming that either K or k_{-1}/k_2 could be varied.

If both K and k_{-1}/k_2 are negligibly small, β is constant through the reaction, as it should be; sufficient increase in either of these quantities makes β fall off. It is of interest to establish what values of k_{-1}/k_2 or of K are required to ensure that third-order rate coefficients (γ) approximate to constancy through a substantial part of a single run. The values required vary with the initial concentration of bromine, as can be appreciated if Table 2 is studied. In Table 5, some illustrative values of γ are given.

If k_{-1}/k_2 is taken to be 5.7, the value which we have deduced as a reasonable fit to Schubert and Dial's experiments, it can be seen that a value of $K = 22000$ would result in sufficient constancy of γ over 70% reaction that deviations from the expected behaviour could not be expected to be detectable experimentally. Beyond this point in the reaction, however, the values of γ would rise. The computations show, indeed, that the kinetic form for a third-order reaction is not precisely simulated over the full course of the reaction by this choice of k_{-1}/k_2 with any value of K .

γ (formal third-order rate coefficients) now of course extrapolate to a much lower value than in Table 5; despite their approximate constancy over the major

TABLE 6

Illustrative values (γ l⁻² mol² min) of computed formal third-order rate coefficients for a reaction following Schubert and Dial's mechanism [equations (3) and (4)], with $a = 0.1$ mol l⁻¹; $b = 0.02$ mol l⁻¹; $c = 0$; $k_1 = 0.086$ l mol⁻¹ min⁻¹

K/l mol ⁻¹	276	276	276	180	190	200	210
$(k_{-1}/k_2)l$ mol ⁻¹	60	75	70	5.7	5.7	5.7	5.7
$x/b = 0.02$	4.31	4.31	4.31	4.32	4.33	4.33	4.33
$x/b = 0.04$	4.30	4.29	4.29	4.32	4.32	4.32	4.32
$x/b = 0.10$	4.28	4.27	4.25	4.34	4.34	4.34	4.34
$x/b = 0.20$	4.27	4.24	4.21	4.37	4.36	4.36	4.35
$x/b = 0.30$	4.27	4.23	4.19	4.38	4.37	4.36	4.35
$x/b = 0.40$	4.31	4.25	4.19	4.36	4.36	4.34	4.32
$x/b = 0.50$	4.40	4.32	4.25	4.34	4.33	4.29	4.26
$x/b = 0.60$	4.57	4.48	4.38	4.36	4.31	4.25	4.26
$x/b = 0.70$	4.91	4.77	4.68	4.44	4.36	4.29	4.21
$x/b = 0.80$	5.15	5.49	5.33	4.78	4.67	4.52	4.46

course of a hypothetical kinetic run at a single initial concentration of reactants, they represent in both of these examples a mechanistically inappropriate method of calculation.

(d) *Interpretation of Equation (5)*.—Equation (5) is a polynomial in $[\text{Br}_2]$, considered by Schubert and Dial⁶ to be not only a satisfactory approximation to the kinetic form required by equations (3) and (4) but also *equivalent* (their italics) to equation (1). In its expanded form it comprises an infinite series which, provided it is convergent, can certainly in principle reproduce the results required in terms of the mechanism of equation (3) and (4) to any required degree of accuracy if sufficient terms are included in the polynomial expansion. Successive coefficients in the power series after the first two increase by a factor $F = (k_{-1}/k_2 - 2K)/(bk_1/k_2 + 1)$ and will alternate in sign if F is negative. If $|bF| > 1$ the series is divergent, which is the case for $b > 0.046$ with values of $k_{-1}/k_2 = 5.7$ and $K = 27.6 \text{ l mol}^{-1}$.

In Table 7 we illustrate that to reproduce the mechan-

TABLE 7

Illustrative values of the parameters derived by applying equation (5) to a reaction proceeding by Schubert and Dial's mechanism, with $a = 0.1 \text{ mol l}^{-1}$; $b = 0.0001 - 0.0256 \text{ mol l}^{-1}$; $K = 27.6 \text{ l mol}^{-1}$; $k_{-1}/k_2 = 5.7 \text{ l mol}^{-1}$; $k_1 = 0.086 \text{ l mol}^{-1} \text{ min}^{-1}$

	' k_I '	' k_{II} '	' k_{III} '	β
$10^4 b = 1$; $x/b = 0.02-0.20$	0.086 0	0.492	-24.4	0.086 0
$10^4 b = 16$; $x/b = 0.02-0.20$	0.085 2	0.524	-25.7	0.086 0-0.085 5
$10^4 b = 256$; $x/b = 0.02$	0.075 0	0.901	-38.9	0.072 7-0.072 5

ism of equations (3) and (4) with these values of k_{-1}/k_2 and K , three terms in the expansion are sufficient over Schubert and Dial's range of concentration of bromine (0.0001-0.001M). At the higher concentrations appropriate to a test of the incursion of the third-order mechanism, however, (*viz.* 0.01-0.025M) this is not so.

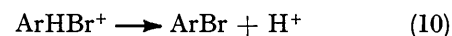
In this Table, the successive first three coefficients of the polynomial equation (5) are represented as ' k_I ', ' k_{II} ', ' k_{III} '. Several points can be illustrated from this tabulation. (i) The coefficients ' k_I '-' k_{III} ' are not constant with changed initial concentration of bromine. Indeed, they are specific functions of this concentration and so are inapplicable for mechanistic discussion of equation (1). (ii) These coefficients are not necessarily positive in sign. The condition that ' k_{III} ' and successive odd-numbered terms be positive is that $k_{-1}/k_2 > 2K$, and this is not satisfied with the chosen experimental values. The very fact that the coefficient k_{III} can be negative illustrates that this quantity could not have the physical significance of a rate coefficient. (iii) With values for the experimental constants as are appropriate for Schubert and Dial's experiments, the coefficients of the polynomial are of increasing magnitude. Except when the concentration of bromine is low, truncation of the polynomial at three terms does not provide a satisfactory reproduction of the exactly derived equation (7), results from which are illustrated in Table 2. As we have already noted, the expansion becomes non-convergent with $b > 0.046$.

(e) *More Elaborate Mechanistic Combinations*.—The computations of Table 3 relate to a combination of

reaction pathways respectively of first and second order in bromine. Inclusion of a significant term of third order in bromine (fourth order overall) would produce an initial rate increasing still more steeply with concentration of bromine, so that the contrast with the results to be obtained by Schubert and Dial's mechanism would be more marked even than in the comparison of Tables 2 and 3.

It is evident also that a mechanism of second order in bromine could be superimposed on a mechanism like that of Schubert and Dial without any alteration of principle. Comparison of Tables 2-4 shows that, with values of K and k_{-1}/k_2 reasonably approximate to reality, the incursion of the mechanism of second order in bromine would be easily recognisable provided that the reaction were studied over the early part (*e.g.* the first 20%) of its course.

An interesting question exists, whether the mechanisms of order greater than one in bromine could themselves involve reversible formation of the carbocationic species just as can the reaction of the first order in bromine. As far as we are aware, this possibility has not been tested; most examples of brominations showing primary isotope effects relate to reactions carried out under second-order conditions. If the reaction sequence shown in equations (9) and (10) is compared with that of equations (3) and (4), it becomes apparent that reversibility of the first (composite) stage of equation (9) would become significant under circumstances in which Br_3^- became approximately as effective as Br^- in removing Br^+ from the carbocation ArHBr^+ .



(f) *Scope of the Various Mechanisms for Aromatic Bromination*.—(i) *The second-order, first-stage reversible mechanism*. Berliner and his co-workers^{8,13} have surveyed the situations in which the second-order mechanism is available and can be made reversible. For most substrates, incursion of processes of order higher than one in bromine can be avoided if the concentration of bromine is kept below 0.001M, and this can often be achieved by including a source of bromide ions in the initial reaction mixture. Reversibility of the formation of the carbocationic intermediate becomes more important as congestion around the attached centre becomes greater; it is likely also that other specific structural influences can affect the ratio of k_{-1}/k_2 , but not enough examples have been studied to allow generalisation.

The kinetic criterion for reversibility of the equilibrium of equation (3) to an extent which will make it have a significant effect on the overall rates of bromination [expressed mathematically in equation (6)] depends on the assumption that the developed bromide ion reacts nucleophilically with the carbocation ArHBr^+ only to remove Br^+ , and in no other way. There are, however, at least two other ways in which the bromide

ion could function. One of these is by acting as a nucleophile for hydrogen instead of, or as well as, for bromine. The sequence of reactions then includes equation (11). The full rate-expression then becomes



that of equation (12). A new situation then would arise

$$-d[\text{Br}_2]/dt = \frac{k_1[\text{ArH}][\text{Br}_2](k_2 + k_N[\text{Br}^-])}{k_2 + k_N[\text{Br}^-] + k_{-1}[\text{Br}^-]} \quad (12)$$

if $k_{-1}[\text{Br}^-] \gg k_N[\text{Br}^-] \gg k_2$. Under these circumstances the rate would be represented by equation (13). Since

$$-d[\text{Br}_2]/dt = k_N k_1 [\text{ArH}][\text{Br}_2]/k_{-1} \quad (13)$$

k_N is subject to a large primary isotope effect, whereas k_1 and k_{-1} are not, the rate would be overall of the second kinetic order (first-order in bromine) but would be subject to a large hydrogen-deuterium isotope effect which would not vary with the concentration of bromide ions. Some examples previously studied,^{7,13} including that described by Schubert and Dial,⁶ have not been of this kind; since isotope effects varying with concentration of bromide ion have been noted. Acetic acid, rather than bromide ion, is then the nucleophile involved in proton removal. That bromide ion can engage in competitive removal of H^+ and Br^+ from some substrates, however, is well known;¹⁴ and situations intermediate between those represented by equations (6) and (12) can be envisaged also. Salt effects, however, further complicate the kinetic analysis.^{13,15}

(ii) *The third-order mechanism [the second term in equation (1)].* Robertson, de la Mare, and Johnston's⁴ generalisations concerning the third-order mechanism still stand; it has become dominant for many substrates of widely different chemical type at concentrations of bromine around 0.025M, and is more prominent the less ionising the solvent. Many of its characteristics, apart from that revealed by the kinetics, resemble those of second-order halogenations of the same substrates.¹⁶

(iii) *The third-order mechanism; comparison with bromine additions.* The third-order kinetic form (second

order in bromine) was first discovered for bromine additions,⁵ and has characteristics similar to those noted for the aromatic substitutions discussed in this paper.^{4,17} Full comparison of the two reactions, however, requires consideration also of the fact that both the second molecule of bromine and added or formed bromide ion might for additions act in a way impossible for substitutions; *i.e.*, by attacking the carbocationic intermediate nucleophilically to give the product of addition. Mechanisms of this kind have been considered by various workers, as is summarised by Bolton;³ it suffices here to note that complicated kinetic relationships are to be expected as the result of these additional mechanistic possibilities.

(iv) *The bromination of N-methylacetanilide.* The kinetic forms available for the bromination of *N*-methylacetanilide have not yet been established fully. Schubert and Dial⁶ appear to have shown that in 50% acetic acid the normal second-order form [the first term of equation (1)] applies in the range of concentration of bromine below *ca.* 0.001M, and that the mechanism is on the borderline between the situations in which the first stage is and is not effectively irreversible; addition of sufficient bromide ion produces a transition between the two kinetic situations.

Whether processes of high order in bromine can become effective for this substrate is not yet known. The reaction is rather fast for convenient study in 50% acetic acid, and it is known also that the contributions of high-order processes diminish with increased polarity of the solvent. Furthermore, it is known² that the relative values of k_2 and k_3 vary with the substrate in a way which has not been defined fully for aromatic systems. The present computations must not be taken as implying a prediction that the high-order reactions [included in equation (1)] will be found to be accessible for *N*-methylacetanilide in this or in other solvents; nor is there any evidence to exclude the possibility that still further reaction pathways are available for this substrate.

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