181. *Mechanism of Substitution at a Saturated Carbon Atom. Part L.* Kinetic Effects of Phenyl and Halogen Substituents in Alkyl Halides on their Reactions with Halide Ions in Acetone.*

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The effects of phenyl and halogen substituents on the rates of halogen exchange of alkyl halides in acetone have been examined by investigation of bromine or chlorine exchange, by the use of radio-isotopes of the halogens, in the compounds CH_3Cl, $Ph{\cdot}CH_2Cl$, CH_3Br, $Ph{\cdot}CH_2Br$, Ph_2CHBr, Ph_3CBr, CH_2Br_2, CBr_4. In bimolecular substitution, corresponding methyl and benzyl halides react at similar rates, though the phenyl substituent decreases the activation energy. The introduction of a second phenyl substituent reduces the rate by a factor of about 300 and the activation energy is now increased. It is concluded that the polar and steric influences of the first phenyl substituent have approximately balancing effects on rate but that the steric effect of the second phenyl group is dominant. Exchange in triphenylmethyl bromide was too rapid for measurement under our conditions, and it is likely that the unimolecular mechanism of substitution is here in control. In methylene bromide, bimolecular exchange occurred 3500 times more slowly than in methyl bromide and, under the same conditions, carbon tetrabromide underwent exchange too slowly for measurement. The measured retarding effect of the halogen substituent is attributed mainly to a polar influence, which increases the activation energy.

THIS paper records a preliminary survey of the effect of introducing phenyl and halogen substituents into alkyl groups on the rates of bimolecular halogen exchange of alkyl halides with halide ions in acetone. The reactions examined were those of chlorine exchange and bromine exchange, both by the use of radio-isotopes of the halogens.

The effects of phenyl substituents were explored in the series methyl, benzyl, benzhydryl, triphenylmethyl. Some rates of bimolecular chlorine exchange between methyl chloride

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* Part XLIX, *J.*, 1955, 3200.

and lithium radio-chloride in solvent acetone were recorded in Part XLII.[1] Rate data for the corresponding reaction of benzyl chloride are given in Table 3 (Experimental section). They refer to approximately the same salt concentration as the previous measurements on methyl chloride. It is found that methyl and benzyl chloride undergo the exchange reaction at similar rates, which, however, depend on different Arrhenius parameters, as will be discussed below. In the same conditions, benzhydryl chloride undergoes the corresponding reaction somewhat too slowly for convenient measurement, and the series of alkyl bromides was therefore examined.

Some rates of bimolecular exchange of bromine between methyl bromide and lithium radio-bromide in acetone are already given in Part XLV.[2] Some rate measurements referring to the corresponding reaction of benzyl bromide are recorded in Table 3. Again it is found that the methyl and benzyl halides react at similar rates. In the same conditions, benzhydryl bromide undergoes the analogous reaction at rates which can be measured, but are about 300 times smaller than the rates for methyl or benzyl bromide. Some measurements on benzhydryl bromide are included in Table 3. These measurements were made at various salt concentrations. The second-order rate coefficients showed a negative salt effect, somewhat smaller than those encountered previously.[2] The magnitude of the effect having been determined, rates were corrected to the salt concentration which was taken as standard in the earlier work.[2] An attempt to extend the measurements to the exchange reactions of triphenylmethyl bromide was frustrated by the great rapidity of the exchange, which, below —20° in acetone, was complete before the first measurement could be made.

The rates at common temperatures, and the parameters of the Arrhenius equation, for the halogen exchanges of the successively phenyl-substituted alkyl chlorides and bromides are collected in Table 1. The figures suggest that the phenyl substituent has two effects on the rates of these bimolecular substitutions. The first is an accelerating polar effect of a type discussed several times before:[3] the phenyl substituent, facilitating bond fission by the electromeric process $\mathrm{Ph}\overset{\curvearrowright}{-}\mathrm{C}\overset{\curvearrowright}{-}\mathrm{Hal}$, allows a reduced amount of bond establishment by the attacking reagent to stimulate disproportionately extensive bond-loosening, with the result that the transition state can be formed at a reduced energy of interaction. The second and third phenyl substituents should repeat this polar energetic effect, and so, if steric effects did not intervene, the energy of activation should fall with continued phenyl substitution in successive comparable decrements.

The second kinetic effect of the phenyl substituent will indeed be its steric effect. In principle, this should influence both the energy and the entropy of activation; but it will not make its first prominent appearance in these two factors of reaction rate at the same stage of successive phenyl substitution. The first phenyl group should reduce the entropy of activation, and therefore the frequency factor of reaction rate, partly by its ponderal effect,[4] and partly by stopping the interconversion of conformations; for the stereochemistry of bimolecular benzyl transition states is somewhat similar to that of 2 : 6-disubstituted diphenyl molecules. On the other hand, as an examination of models shows, the first phenyl substituent will have only a trifling effect on the energy of activation. Whether the second and the third phenyl substituent will further depress the entropy of activation, it is hard to say, without a more elaborate theoretical investigation than has yet been made. But the second phenyl group will certainly introduce the first large steric contribution to the energy of activation; and the third will add a much larger contribution still.

The interpretation of the observations, which follows from these principles, is that the polar energetic and the steric entropic effects of the first phenyl substituent have approximately balancing effects on the rate, but that the steric effect of the second phenyl group is much larger, and, indeed, is dominating. A possible explanation of the great

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[1] de la Mare, *J.*, 1955, 3169.

[2] de la Mare, *J.*, 1955, 3180.

[3] Hughes, Ingold, and Shapiro, *J.*, 1936, 225; Hughes, *Trans. Faraday Soc.*, 1941, **37**, 207; Vernon, *J.*, 1954, 4462; de la Mare, Fowden, Hughes, Ingold, and Mackie, *J.*, 1955, 3223, footnote.

[4] de la Mare, Fowden, Hughes, Ingold, and Mackie, *J.*, 1955, 3200.

increase of rate which follows the introduction of the third phenyl group is that the unimolecular mechanism of substitution now takes control. We have no proof of this, but it is a reasonable assumption, inasmuch as the unimolecular mechanism is subject to only small steric effects, whilst, as rate is determined by a bond fission, without any accompanying bond formation, each phenyl substituent must introduce a large factor of polar acceleration.

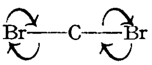
TABLE 1. *Rates* (k_2 *in sec.*$^{-1}$ *mole*$^{-1}$ *l.*) *at common temperatures, and Arrhenius frequency factors* (B_2 *in sec.*$^{-1}$ *mole*$^{-1}$ *l.*) *and activation energies* (E *in kcal. mole*$^{-1}$) *in isotopic exchanges of halogen between arylethyl halides and lithium halides in acetone.*

	With LiCl, 0·028M		With LiBr at or corrected to 0·024M			
	CH_3Cl	Ph·CH_2Cl	CH_3Br	Ph·CH_2Br	Ph_2CHBr	Ph_3CBr
10^5k_2 (0°)	0·16	0·16	1120	1120	3·3	Large
10^5k_2 (25°)	3·9	2·8	13,000	—	45	Large
$\log_{10} B_2$	10·4	8·9	10·7	—	9·2	—
E	20·2	18·3	15·8	—	17·2	—

The present inspection of the kinetic effect of halogen substituents on the bimolecular exchanges is confined to a comparison of the rate of exchange of bromine of methyl bromide, and of methylene bromide, with lithium bromide in acetone, together with qualitative observations on the behaviour of carbon tetrabromide towards this reagent. The rate data for methyl bromide are in Part XLV,[2] whilst those for methylene bromide are in Table 4 (Experimental section). It is found that methylene bromide undergoes the exchange 3500 times more slowly than methyl bromide, if we compare equal numbers of molecules, or 7000 times more slowly, if the comparison is with equal numbers of bound bromine atoms. Further, practically the whole of this kinetic effect is found in the energy factor of reaction rate. Carbon tetrabromide underwent exchange too slowly for measurement at the temperatures of the other measurements, *e.g.*, 25°; and, when the temperature was raised to 87° to obtain an appreciable, though still slow, exchange, the reaction, to judge from indications such as colour development, seemed to take a complex form. It thus appears that bimolecular nucleophilic exchange with this halide is very slow indeed.

The rates at common temperatures, and the Arrhenius frequency factors and activation energies for the exchange reactions of the bromomethanes are in Table 2. The values for methyl bromide have been corrected by means of the relation given in Part XLV,[2] to correspond to the salt concentration (0·06M) applying to this comparison.

It appears that, in the absence of any strongly electron-releasing substituent, the effect of one, or of several, halogen substituents is to retard exchange, essentially by raising the energy of activation. In methylene bromide at least, this effect is too large to be ascribed to steric hindrance; and it is accordingly to be classified as a polar effect. It may be suggested that the effect arises mainly from an increased stability conferred by the second halogen atom on the initial state of the organic molecule, perhaps by a hyperconjugative analogue of the balanced two-way electron-redistribution, which so greatly increases the stability of carbon dioxide:



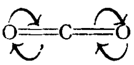


TABLE 2. *Rates at common temperatures, and Arrhenius frequency factors and activation energies* (*units as in Table* 1) *in isotopic exchange of bromine between bromomethanes and lithium bromide in acetone at the common salt concentration* 0·060M.

	CH_3Br	CH_2Br_2	CBr_4
10^5k_2 (0°)	860	0·18	Small
10^5k_2 (25°)	10,000	2·9	Small *
$\log_{10} B_2$	10·6	10·7	—
E	15·8	20·9	—

* $k_2 \not\gg 10^{-5}$ l. mole^{-1} sec.$^{-1}$ at 87°.

EXPERIMENTAL

The organic substances were prepared or purified by standard methods, and the inorganic as described in Parts XLII and XLV.[1,2] The methods of studying the exchanges were as described in the same papers, except for the special points noted below.

The separations of organic from inorganic halide, prior to the measurements of radioactivity, in the exchange reactions of benzyl and benzhydryl bromide, and that of carbon tetrabromide, were effected by partition between benzene and water.

In the reaction of benzhydryl bromide, the formula, deduced from the results, and used for the standardisation of rates with respect to salt effects, was

$$\log_{10}\{k_2^{(b)}/k_2^{(b_0)}\} = -0{\cdot}22 \log_{10} (b/b_0)$$

The rapidity of exchange between triphenylmethyl bromide and lithium radio-bromide was shown as follows. Solutions of the reagents in acetone were cooled to −80° and mixed, then warmed just enough to secure dissolution of the separated triphenylmethyl bromide, and again cooled to −80°. The crystals of triphenylmethyl bromide were collected and shaken with

TABLE 3. *Second-order rate-constants (k_2 in sec.$^{-1}$ mole^{-1} l.) of exchange between arylalkyl halides and lithium radio-halides in acetone.*

			Counting rates					
Temp.	a = [RHal]	b = [LiHal]	C	$C - X_1$	$C - X_2$	$t_2 - t_1$ (min.)	$10^5k_2^{(b)}$	Mean $10^5k_2^{(b)}$
Benzyl chloride and lithium radio-chloride								
48·2°	0·1015	0·0281	876·8	880·2	765·2	77·0	30·0	
					784·5	73·5	25·0	
					788·9	68·5	26·8	27·5
25·0	0·1050	0·0290	889·8	889·8	719·4	1254	2·76	
					725·9	1163	2·86	
					673·3	1567	2·95	
					689·5	1540	2·73	2·83
18·6	0·1061	0·0293	891·5	886·7	695·6	2787	1·44	
					668·3	2840	1·65	
					693·9	2834	1·43	
					698·1	2853	1·38	1·47
Benzyl bromide and lithium radio-bromide								$10^5k_2^{(0\cdot024)}$
0·0	0·0618	0·0368	1117	1116	994·2	10·6	970	
					973·4	11·5	1080	
					937·6	16·5	990	
					1010·0	10·9	810	1120
Benzhydryl bromide and lithium radio-bromide								
35·4	0·0445	0·0409	1186	1199	873·4	131·7	106·9	
					855·7	142·0	107·6	
					861·0	149·5	99·6	
					813·6	160·0	114·9	
					802·3	180·2	107·3	118·6
25·0	0·0451	0·0415	1186	1199	897·3	307·3	40·4	
					891·9	322·4	39·5	
					884·7	334·2	39·5	
					880·2	346·9	38·8	
					864·2	353·5	41·0	44·6
10·5	0·0286	0·0532	322·1	320·5	275·1	1304	8·41	
					270·1	1346	9·14	
					267·8	1386	9·46	10·7
	0·0287	0·0267	322·1	320·5	253·8	1438	10·7	
					255·3	1411	10·2	
					246·4	1617	11·0	11·1
	0·0287	0·0178	322·1	320·5	236·3	1711	11·5	
					238·3	1727	11·1	10·6
−0·1	0·0630	0·0407	1057	1065	793·9	3018	2·85	
					784·1	3042	2·95	
					805·0	3073	2·64	
					608·4	7078	2·74	
					608·2	7089	2·75	3·13

water. The neutralised solution was evaporated, and the sodium bromide in the residue was taken up in water. The filtrate from the triphenylmethyl bromide was evaporated, and the residue was extracted with benzene and then dissolved in water. The two solutions of saline bromide, thus obtained, were shown to have the same specific activity to within the experimental error of a few units per cent.

In the reaction of methylene bromide the separation of organic from inorganic bromide was effected by the evaporation method. For the calculations of rate constants a slight modification of the usual formula was required, *viz.*:

$$k_2 = \frac{2 \times 2\cdot303}{(2a + b)(t_2 - t_1)} \log_{10}\left\{\left[1 - \frac{X_1}{C}\left(1 + \frac{b}{2a}\right)\right]\left[1 - \frac{X_2}{C}\left(1 + \frac{b}{2a}\right)\right]^{-1}\right\}$$

The details of some kinetic runs are recorded in Tables 3 and 4. The headings of the Tables are explained in Part XLII.[1] Excepting the cases mentioned above, the rate coefficients at specific ionic strength (*e.g.*, $k_2^{0\cdot024}$) were obtained by the procedure previously described.[2]

TABLE 4. *Second-order rate-constants (k_2 in sec.$^{-1}$ mole^{-1} l.) of halogen exchange between methylene dibromide and lithium radio-bromide in acetone.*

			Counting rates					
Temp.	$a =$ [CH$_2$Br$_2$]	$b =$ [LiBr]	C	$C - X_1$	$C - X_2$	$t_2 - t_1$ (min.)	$10^5k_2^{(b)}$	Mean $10^5k_2^{(0\cdot060)}$
44·6°	0·0911	0·0571	1254	1238	1058	70·2	19·8	
					1007	82·0	22·4	
					979·0	93·0	22·5	
					954·6	102·0	22·8	
					928·8	120·0	21·4	
					921·2	120·0	22·0	21·3
25·0	0·1968	0·0588	1802	1820	1188	1354	2·74	
					1175	1379	2·73	
					1153	1415	2·82	
					1177	1416	2·68	
					1144	1492	2·72	2·72
−0·1	0·0239	0·0610	398·8	413·6	327·1	18,910	0·096	
					318·4	18,914	0·107	
					327·6	18,924	0·096	
					330·6	18,894	0·091	
					323·4	19,964	0·095	
					323·8	19,954	0·094	0·097

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