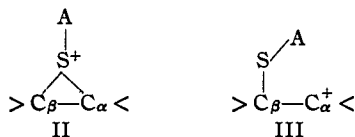


I, 1120; *trans*-OAc, 0.305; *trans*-Br, 7.18×10^{-2} ; *trans*-OCH₃, 5.28×10^{-2} ; *cis*-OAc, 1.31×10^{-4} ; *trans*-Cl, 0.94×10^{-4} ; *cis*-OSO₂C₆H₄Br, 1.6×10^{-5} ; *trans*-OSO₂C₆H₄Br, 1.4×10^{-5} . Variations in rate are largely due to variations in ΔH^\ddagger .

The rate-determining ionization step appears to be largely a direct formation of the cycle II (rate constant k_Δ) in the case of neighboring *trans*-I, Br, and OAc and predominantly the formation of carbonium ion III (rate constant k_c) with neigh-



boring *trans*-Cl and OSO₂C₆H₄Br and *cis*-OAc and OSO₂C₆H₄Br.

Using k/k_H for neighboring Cl to determine an effective dielectric constant, the interaction energy between the C_β-SA and C_α-O dipoles in the transition state for formation of III has been calculated for neighboring I, Br and OCH₃. Thus estimates of k_c/k_H have been obtained and corresponding values of k_Δ/k_c have been calculated from the relation $k_\Delta/k_c = [(k/k_H)/(k_c/k_H)] - 1$.

The driving force L due to the *trans*-neighboring groups, defined as $RT \ln (k_\Delta/k_c)$, has the following values in kcal./mole at 25°: I, 8.49; OAc, 4.60; Br, 3.53; OCH₃, 0.86.

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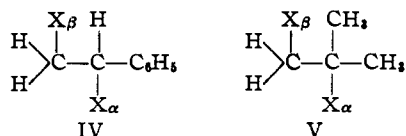
[CONTRIBUTION FROM THE CHEMISTRY DEPARTMENT OF THE UNIVERSITY OF CALIFORNIA, LOS ANGELES]

The Role of Neighboring Groups in Replacement Reactions. XIII.¹ General Theory of Neighboring Groups and Reactivity

BY S. WINSTEIN AND ERNEST GRUNWALD

In the previous^{2,3} rate work involving effects of neighboring groups, C_α and C_β were both secondary in the molecules (I)² whose ionization rates were measured. In considering further structural variations, it must be expected that the relative energies of the closed and open forms of the ionic intermediate,² II and III, respectively, will change with *alpha* and *beta* substitution. Thus there will be a change in L , the driving force,³ which reflects that portion of the free energy difference between II and III which already appears in the transition states for ionization of I. In this paper, with the aid of relative reactivities here reported and others from the literature, we attempt to generalize the theory to cover the whole range of possible structures for the *alpha* and *beta* carbon atoms. Also, the discussion will logically lead to a consideration of the nucleophilic closure of small rings of the classical sort, most attention being given the ethylene oxide ring.

Rate Comparisons.—A group of the rate constants to be considered deals with solvolysis in alcohol or aqueous alcohol of some of the styrene dihalides IV and isobutylene dihalides V.



Although there were some difficulties in the determination of the desired solvolysis rates, it was

(1) Much of the material in this paper was presented before the Organic Division at the Atlantic City meeting of the American Chemical Society, April, 1946.

(2) Winstein, Grunwald, Buckles and Hanson, *THIS JOURNAL*, **70**, 816 (1948).

(3) Winstein, Grunwald and Ingraham, *ibid.*, **70**, 821 (1948).

possible to obtain rate constants reliably enough for the purpose. The rates were in some cases so slow that the measurements were complicated by reaction of hydrogen bromide, produced by solvolysis of a dibromide, with the ethanol solvent. This difficulty was met by determination of the initial rate of solvolysis. With olefin iodochlorides, the solvolysis was accompanied by a slight amount of iodine production but analyses for iodine showed this was not extensive enough to be very serious.

The first-order rate constants determined as described in a later section are summarized in Table I. It seems clear from our procedure in obtaining initial rate constants and from the chemistry of the materials IV and V and analogous ones that the rate constants relate to the solvolysis of the first and most reactive halogen atom, labelled *alpha* in IV and V. Thus styrene iodochloride is reported⁴ to react with water to give iodohydrin and with silver nitrate to yield first its chlorine atom and next its iodine atom. Similarly, isobutylene iodochloride gives the *beta*-iodo-*t*-butyl methyl ether⁵ on refluxing with methanol. Analogous to the styrene derivatives are such materials as indene dibromide^{6a} VI and 1-phenyl-1,2-dibromopropane^{6b} VII.

The rate constants for solvolysis are interpreted as rates of unimolecular⁷ solvolysis.⁸ In

(4) Ingle, *J. Soc. Chem. Ind.*, **21**, 587 (1902).

(5) Istomin, *J. Russ. Phys.-Chem. Ges.*, **36**, 1199 (1904); *Chem. Centr.*, **76**, 1, 429 (1905).

(6) (a) Porter and Suter, *THIS JOURNAL*, **57**, 2022 (1935); (b) Spaeth and Koller, *Ber.*, **58**, 1269 (1925).

(7) (a) Bateman, Church, Hughes, Ingold and Taher, *J. Chem. Soc.*, 979 (1940); (b) Hughes, *Trans. Faraday Soc.*, **37**, 603 (1941).

(8) Hammett, "Physical Organic Chemistry," McGraw-Hill Book Co., Inc., New York, N. Y., 1940, Chapters V and VI.

TABLE I
RATE CONSTANTS FOR THE SOLVOLYSIS OF STYRENE AND ISOBUTYLENE DIHALIDES

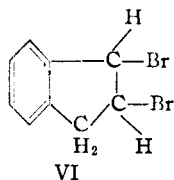
Halide	Solvent	Temp., °C.	k (sec. ⁻¹)	k/k_H
BrCH ₂ CHBrC ₆ H ₅	C ₂ H ₅ OH	54.95	1.90×10^{-7}	0.99×10^{-3}
BrCH ₂ CHBrC ₆ H ₅	C ₂ H ₅ OH, 0.1369 <i>M</i> NaClO ₄	54.95	2.85×10^{-7}	
ICH ₂ CHClC ₆ H ₅	C ₂ H ₅ OH	69.95	4.9×10^{-6}	1.3
BrCH ₂ CHBr(CH ₃) ₂	80% C ₂ H ₅ OH	25.10	5.8×10^{-8}	1.60×10^{-4}
ICH ₂ CCl(CH ₃) ₂	80% C ₂ H ₅ OH	25.00	4.44×10^{-6}	0.486
ICH ₂ CCl(CH ₃) ₂	80% C ₂ H ₅ OH	35.00	15.0×10^{-6}	
CH ₃ CCl(CH ₃) ₂	48.61 wt. % dioxane	34.86	6.30×10^{-4}	
ICH ₂ CCl(CH ₃) ₂	48.61 wt. % dioxane	34.86	1.45×10^{-4}	
CH ₃ CHClCH=CH ₂	H ₂ O	27.2	1.06×10^{-3}	

TABLE II
COMPARISON OF SOME SOLVOLYSIS RATES

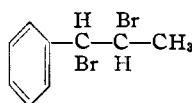
Compound		Solvent	Temp., °C.	k_A/k_B	Ref.
A	B				
CH ₃ CH ₂ CCl(CH ₃) ₂	CH ₃ CCl(CH ₃) ₂	80% ethanol	25.0	1.67	14
(CH ₃) ₂ CHCCl(CH ₃) ₂	CH ₃ CCl(CH ₃) ₂	80% ethanol	25.0	0.92	14
(CH ₃) ₃ CCl(CH ₃) ₂	CH ₃ CCl(CH ₃) ₂	80% ethanol	25	1.19	14
CH ₃ CHBrCBr(CH ₃) ₂	BrCH ₂ CBr(CH ₃) ₂	2:3 dioxane-water	45	17.5	15
(CH ₃) ₂ CBrCBr(CH ₃) ₂ ^a	CH ₃ CBr(CH ₃) ₂	Ethanol, 50.1 mole % water	18.5	3.25×10^{-2}	16
(CH ₃) ₂ CClCCl(CH ₃) ₂ ^b	CH ₃ CCl(CH ₃) ₂ ^c	80% ethanol	100.0	5.8×10^{-4}	13, 17
ClCH ₂ CCl(CH ₃) ₂	CH ₃ CCl(CH ₃) ₂ ^c	80% ethanol	79.0	3.3×10^{-4}	13, 18
ClCH ₂ CCl(CH ₃) ₂ (C ₂ H ₅) ^c	CH ₃ CCl(CH ₃) ₂ ^c	80% ethanol	79.0	6.1×10^{-4}	13, 18
HOCH ₂ CCl(CH ₃) ₂	CH ₃ CCl(CH ₃) ₂ ^d	H ₂ O	18.0	6.5×10^{-3}	19, 20
CH ₃ CH(OH)CCl(CH ₃) ₂	CH ₃ CCl(CH ₃) ₂ ^d	H ₂ O	18.0	3.4×10^{-3}	19, 20
(CH ₃) ₂ C(OH)CCl(CH ₃) ₂	CH ₃ CCl(CH ₃) ₂ ^d	H ₂ O	18.0	6.0×10^{-3}	19, 20
HOCH ₂ CHClCH=CH ₂ ^e	CH ₃ CHClCH=CH ₂ ^f	H ₂ O	18.0	7.3×10^{-3}	21, Table I

^a Specific rate constant multiplied by a statistical factor of $1/2$. ^b Specific rate constant calculated from the data of Tischchenko¹⁷ on the assumption that the solvolysis of the dichloride is slow compared to that of the daughter monochloride. ^c Extrapolated from data¹³ at lower temperatures. ^d The specific rate in 5% acetone-95% water reported by Swain²⁰ was used. E^\ddagger was taken as 22.9 kcal./mole.¹³ ^e Extrapolated from data²¹ at higher temperatures. ^f E^\ddagger was taken as 23.5 kcal./mole.

the case of the very slow reactions (e. g., in the case of styrene dibromide), there is the possibility that at least part of the solvolysis is bimolecular involving solvent. In this sense the values are



VI



VII

upper limits. For styrene dibromide, the effect of added salt (sodium perchlorate) on the rate of alcoholysis was observed. This was quite high and to be anticipated⁷ for a unimolecular solvolysis, much higher than for the alcoholysis (S_N2) of ethyl bromide as we report elsewhere.⁹

Comparison of the rate constants in Table I with the corresponding values k_H for α -phenylethyl bromide,¹⁰ α -phenylethyl chloride,¹¹ *t*-butyl bromide¹² and *t*-butyl chloride¹³ gives the relative rates k/k_H listed in the last column of Table I. Further pertinent rate comparisons are

(9) Grunwald and Winstein, *THIS JOURNAL*, **69**, 2051 (1947).

(10) Hughes, Ingold, Masterman and McNulty, *J. Chem. Soc.*, 899 (1940).

(11) Hughes, Ingold and Scott, *ibid.*, 1201 (1937).

(12) Cooper and Hughes, *ibid.*, 1183 (1937).

(13) Hughes, *ibid.*, 255 (1935).

available from the literature and these are summarized in Table II.

The rate comparisons so far reported in Tables I and II and those for the cyclohexyl and 2-butyl systems reported in the two preceding papers^{2,3} have been converted to values of k/k_H at 25° which are given in Table III for neighboring I, Br, Cl, OH or OCH₃ groups. Ratios have been calculated to 25° either with the help of activation energies when available, or otherwise, on the assumption that a rate difference between two similar substances is due to a difference in activation energy. For the cases on which information is available,³ this is a fair approximation for the rough and small corrections being made. From Table II it is clear that the rate of solvolysis of RCl(CH₃)₂ is very constant to variations in R from CH₃ to (CH₃)₃C. In deriving the values of k/k_H for Table III, the value of k for CH₃CCl(CH₃)₂ was used for k_H for materials of the type RCl(CH₃)₂ and k for CH₃CBr(CH₃)₂ was used for k_H for materials of the type RBr(CH₃)₂. The body of Table III is based on data with systems of the charge type actually represented by formulas I, II and III, that is, the departing group is XC₆H₄SO₃⁻ or halide ion. The footnotes give the data in which the departing group is OH₂. In the Table, the nature of C _{β} and C _{α} is indicated by P,

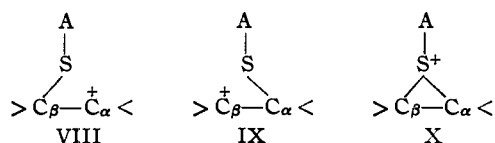
TABLE III
 SUMMARY OF VALUES FOR k/k_H AND k_Δ/k_c

Neighboring group C_β C_α	I			Br			Cl		OH or OCH ₃		
	k/k_H obs. 25°	k_Δ/k_c	k_Δ/k_c calcd. Eq. 9	k/k_H obs. 25°	k_Δ/k_c	k_Δ/k_c calcd. Eq. 9	k/k_H obs. 25°	k/k_H obs. 25°	k_Δ/k_c	k_Δ/k_c calcd. Eq. 9	
P T	0.486	7.2×10^2	1.1×10^3	1.6×10^{-4}	1.1	1.0	0.78×10^{-4d}	7.3×10^{-3d}	...	$4.5 \times 10^{-}$	
S T				2.3×10^4	3.4×10^{-3c}	44	21	3.8×10^{-3d}	...	$9.3 \times 10^{-}$	
T T				4.7×10^5	3.5×10^{-2}	4.7×10^2	4.3×10^2	0.85×10^{-1}	...	1.9	
P allyl								8.2×10^{-3d}	...		
P CHC ₆ H ₅	1.3	1.9×10^3	.....	4.9×10^{-4}	6.5	.....	.....	.....	.....	.....
P S			5.2×10^4			47	.....	.....	.....	0.21
S S ^e	1120	1.7×10^3	1.1×10^6	7.2×10^{-3}	3.9×10^3	9.5×10^2	0.94×10^{-4}	5.3×10^{-2b}	4.3	4.3	
T S			2.2×10^7			2.0×10^4				91	
P P			2.4×10^6			2.1×10^3				9.9	
S P			4.9×10^7			4.4×10^4				2.0×10^2	
T P			1.0×10^9			9.0×10^3				4.0×10^2	

^a Neighboring OH. ^b Neighboring OCH₃. ^c Calculated from the data of Suter and Zook in 2:3 dioxane-water¹⁵ and the value of k/k_H for isobutylene dibromide in 80% ethanol. ^d The reported value refers to isobutylene dichloride. k/k_H for 2-methyl-1,2-dichlorobutane, 1.4×10^{-4} . ^e The corresponding values of k/k_H from reactions of cyclohexanols and 2-butanols with hydrobromic or hydrochloric acid are: cyclohexanols, *trans*-Br, $1200 \gg \text{trans-Br}$, $0.08 \gg \text{trans-Cl}$, 1.6×10^{-4} ; 2-butanols, *trans*-Br, 0.4.

S and T for *primary*, *secondary* or *tertiary*, respectively, or more specifically for the α -phenylalkyl or α -allyl types.

Qualitative Theory of the Effect of α and β Substitution.—To understand the general reactivity situation it is necessary to refer to intermediates II and III. It is possible to predict the effect of α and β substitution on the relative energies of II and III and therefore on the relative free energies of the corresponding transition states for the ionization of I. Intermediate II receives contributions²² from such structures as VIII–X. Now the effect of α methyl



or phenyl in stabilizing the carbonium ion III by hyperconjugation²³ or ordinary resonance is well understood.⁷ The same substitution will also favor the contribution of structure VIII to intermediate II so that there will be less bond character between the neighboring group and C_α in II. This will decrease any superiority of II over III and decrease k_Δ relative to k_c . Thus, α methyl or phenyl groups will lower the driving force due to a neighboring group.

The stability of structure IX and therefore its contribution to the stabilization of the hybrid intermediate II will depend on the structure of C_β, being greatest for *tertiary* and least for *primary*.

(14) H. C. Brown, abstract of paper presented before the Organic Division at the Atlantic City meeting of the American Chemical Society, April, 1946.

(15) Suter and Zook, *THIS JOURNAL*, **66**, 738 (1944).

(16) Petrenko-Kritschenko, *Ber.*, **61**, 852 (1928).

(17) D. V. Tischenko, *J. Gen. Chem. (U. S. S. R.)*, **9**, 1380 (1939).

(18) Brown, Kharasch and Chao, *THIS JOURNAL*, **62**, 3435 (1940).

(19) Lennart Smith, *Z. physik. Chem.*, **186A**, 135 (1933).

(20) Swain, *THIS JOURNAL*, **68**, 658 (1946).

(21) Kadesch, *ibid.*, **68**, 46 (1946).

(22) Winstein and Lucas, *ibid.*, **61**, 1576 (1939).

(23) Mulliken, Rieke and Brown, *ibid.*, **63**, 41 (1941).

Thus β methyl groups will increase k_Δ relative to k_c and the driving force L will increase as C_β varies from *primary* to *tertiary*.

The same conclusions are reached in another way. There has long been a feeling that the transition in C–C bond type from ethylene to cyclopentane is gradual. Thus certain features of the ethylenic linkage remain in the cyclopropane ring. For example, there is spectroscopic evidence²⁴ of conjugation of the carbonyl group with a cyclopropane ring. Also, the dipole moment of cyclopropyl chloride²⁵ is intermediate between vinyl chloride and ethyl chloride. Another characteristic feature of the ethylenic linkage, stabilization by alkyl substitution, is expected to be retained in three-membered rings including the heterocyclic ring compounds of the type II.

On the basis that methyl substitution on a three-membered ring should give rise to what amounts to hyperconjugation energy,²³ it is clear that either an α or a β methyl group will stabilize intermediate II and increase k_Δ . In the case of a β methyl group this will result in a greater driving force L . In the case of an α methyl group, the hyperconjugative stabilization of an open carbonium ion III is expected to be greater than that of II, and k_c will increase more than k_Δ . The driving force L will consequently decrease even though the rate increases.

In discussing the effect of α substitution on k_Δ , we are in effect discussing the effect of substitution on an internal variety of a bimolecular displacement. Thus we are dealing with a phase of the general question of the factors involved in understanding concerted nucleophilic displacements on carbon. There have been some recent discussions^{26,27} of some of these factors and we hope to contribute elsewhere on this general ques-

(24) (a) Carr and Burt, *ibid.*, **40**, 1590 (1918); (b) Klotz, *ibid.*, **66**, 88 (1944).

(25) Rogers and Roberts, *ibid.*, **68**, 843 (1946).

(26) Dostrovsky, Hughes and Ingold, *J. Chem. Soc.*, 173 (1946).

(27) (a) Evans, *Nature*, **157**, 438 (1946); (b) Hughes and Ingold, *ibid.*, **158**, 94 (1946).

tion. In discussing k_{Δ} we have focused attention on only those considerations which are most important in the present connection. Some of these considerations are helpful in the general case, although the aspect of the stabilization of a small ring is unique with the present problem.

Neighboring Cl and OH. Structure and k_c/k_H .—Inspection of Table III reveals very constant values of k/k_H for neighboring chlorine and hydroxyl groups. For neighboring chlorine, the values however near 0.86×10^{-4} . This is very near the value of 0.94×10^{-4} calculated for k_c/k_H by the simplified electrostatic treatment previously³ described. In this treatment one calculates, after some geometrical assumptions, the extra work involved in the generation of the transition state dipole due to the effect of the neighboring group dipole.

For neighboring hydroxyl the values of k/k_H hover near 6.5×10^{-3} while 1.07×10^{-2} is estimated (Table IV) as the value of k_c/k_H from the electrostatic treatment ($D_E = 1.23$) for a *trans*-chlorohydrin. As explained previously,³ when k is of the order of magnitude expected for k_c , it is not possible to make any good estimate of the extent of operation of mechanism A. It is possible to conclude that k_c is at least comparable to k_{Δ} . Judging by the lack of any large effects of *beta* methyl groups, this last conclusion follows even when C_{β} is *tertiary* for neighboring hydroxyl with C_{α} *tertiary* and for neighboring chlorine with C_{α} *secondary* or *tertiary*. This kind of diagnosis on the basis of effects of *beta* substitution should prove to be very helpful.

TABLE IV

DEPENDENCE OF CALCULATED RELATIVE RATE k_c/k_H ON

N. group	DEPARTING GROUP		k_c/k_H
	Departing group	W^a (cal./mole)	
<i>trans</i> -Br	$\text{O}\text{SO}_2\text{C}_6\text{H}_4\text{Br}$	5090	1.87×10^{-4}
<i>trans</i> -Br	Br^-	5630	0.75×10^{-4}
<i>trans</i> -Br	Cl^-	5500	0.94×10^{-4}
<i>trans</i> -OH	Cl^-	2640	1.07×10^{-2}
<i>trans</i> -OH	$\text{O}\text{SO}_2\text{C}_6\text{H}_4\text{Br}$	2510	1.45×10^{-2}

^a D_E assumed equal to 2.23. Dipole moments and distances selected as in a previous paper.³

The constancy in the values of k/k_H (not far from k_c/k_H) for neighboring chlorine and hydroxyl is instructive in another way. It indicates how insensitive are the values of k_c/k_H to change in solvent, structure of C_{α} and C_{β} , and the nature of the departing group. This insensitivity is, to a considerable degree, expected on the basis of the electrostatic model previously³ used in estimating k_c/k_H . As pointed out previously,³ the effective dielectric constant D_E is very close to the internal one for dipole-dipole interactions. Thus the effects of change in external solvent and change in structure on D_E are very slight. Because of the geometry of the situation the effect of change in the departing group is also slight and this is shown in Table IV. In this Table, the calculated extra

work W (see previous paper³) of ionization in the presence of neighboring groups Br or OH is summarized for departing Cl^- , Br^- or $\text{BrC}_6\text{H}_4\text{SO}_3^-$.

Actually, the value of k/k_H (essentially k_c/k_H) in the case of neighboring chlorine for the chlorohydrin-hydrobromic acid reaction is very nearly equal to the others, so it remains to be seen how gross may the changes in reaction type be with maintenance of essentially constant values of k_c/k_H .

Neighboring Br and I. Comparison with Qualitative Theory.—Turning to neighboring bromine and iodine in Table III, the values of k/k_H are far from constant as they would be if k were always substantially equal to k_c . For neighboring bromine k/k_H varies all the way from 1.6×10^{-4} to 7.2×10^{-2} . The calculated³ values of k_c/k_H (Table IV) are 0.75×10^{-4} for departing Br^- and 1.87×10^{-4} for departing $\text{O}\text{SO}_2\text{C}_6\text{H}_4\text{Br}$. Values of k_{Δ}/k_c are listed in Table III ranging from borderline values such as 1.1 to the value of 4.7×10^2 .

For neighboring iodine the values of k/k_H vary over a thousandfold from 0.486 to the value 1120 reported previously³ in the cyclohexyl system. Even the low value is much larger than the value of 6.7×10^{-4} anticipated for k_c/k_H from the electrostatic approach.³ The corresponding values of k_{Δ}/k_c are given in Table III and are quite high (7.2×10^2 to 1.7×10^6).

For neighboring iodine there is further evidence that at least a substantial part of the rate-determining ionization is by mechanism A. First, for solvolysis of isobutylene iodochloride in 80% alcohol, ΔH^{\ddagger} is 21.8 kcal./mole and ΔS^{\ddagger} is -9.8 e. u./mole compared to values of 22.5 and -6.3 , respectively, for *t*-butyl chloride.¹³ The differences are in the same direction as in the case of the secondary system³ previously reported, and smaller. Second, the change from a 48.61% aqueous dioxane solvent to 80% ethanol at 35° increases the solvolysis rate of *t*-butyl chloride by a factor of 19.7 and that of isobutylene iodochloride by a factor half as large, namely, 9.70. The lower sensitivity to solvent change for the latter compound is consistent with mechanism A by analogy with solvent effects in intermolecular cases. Thus the rate of bimolecular reaction of alkyl halides with neutral solvent has been shown to be less sensitive to a change to a more ionizing solvent than the rate of unimolecular solvolysis.⁷

The dependence of k/k_H on solvent in the presence of neighboring iodine indicates that k_{Δ}/k_H and thus k_{Δ}/k_c and L are not quite constant in different solvents. However, the drift with solvent is not extensive, judging by the case of iodine quoted above.

The values of k/k_H for neighboring bromine and iodine derived from the rough rates² of reaction of halohydrins with hydrohalogen acids (Table III) agree fairly well—as in the case of neighboring chlorine—with those derived from solvolysis rates

of sulfonates. Thus values of k_{Δ}/k_c must also agree fairly well.

It is clear that the preceding theoretical considerations regarding the effect of *alpha* and *beta* substitution account qualitatively for the trends in k_{Δ}/k_c observed in Table III. *alpha*-Substitution definitely decreases k_{Δ}/k_c . For example the change from $S_{\beta}S_{\alpha}$ to $S_{\beta}T_{\alpha}$ with neighboring bromine changes k_{Δ}/k_c from 3.9×10^2 to 44. On the other hand *beta* substitution increases k_{Δ}/k_c . For example the change from $P_{\beta}T_{\alpha}$ to $S_{\beta}T_{\alpha}$ to $T_{\beta}T_{\alpha}$ with neighboring Br changes k_{Δ}/k_c from 1.1 to 44 to 4.7×10^2 , respectively.

In classifying the systems as $S_{\beta}S_{\alpha}$, etc., we class methyl and other alkyl groups (as in cyclohexyl) together. Actually, closer inspection will probably show up significant differences. For example, the indications are that k_{Δ}/k_c is larger for 2-butyl² than for cyclohexyl (Table III).

With neighboring bromine and iodine, k_{Δ}/k_c is somewhat larger with the α -phenylethyl than the *t*-butyl halides. Even this detail is predicted by the qualitative considerations advanced. Judging that *alpha* substitution favors k_c more than k_{Δ} , and deducing that two methyl groups are slightly more than equivalent to a phenyl group from the slightly greater solvolysis rates of *t*-butyl^{12,13} over α -phenylethyl halides,^{10,11} one predicts the greater k_{Δ}/k_c for the α -phenylethyl type.

The striking variation of k/k_H with structure constitutes the most convincing single argument for the operation of both mechanisms **A** and **B** in ionization. We considered an alternative interpretation in which mechanism **B** was the sole one, the open carbonium ion always being formed in the rate-determining step. In this interpretation, deviations of k/k_H from the calculated values of k_c/k_H would be due to polarization of the neighboring group. The effect of *alpha* methyl or phenyl groups would be to diffuse the positive charge of C_{α} by hyperconjugation or resonance and thus decrease the polarization of the neighboring group and the corresponding gain in stability of the transition state. To explain the effect of *beta* methyl groups one could conceivably call on a steric effect such as is envisioned by Brown²⁸ and termed B-strain. Due to the postulated strain due to the alkyl groups on C_{β} , the relief afforded in spreading the C-C β -C angles could favor closer approach of the neighboring group to C_{α} with resultant increase in its polarization.

Examination of such an interpretation reveals some difficulties. First, a steric effect of *beta* methyl groups of the kind postulated appears to be too small in other phenomena to be of sufficient importance here. For example, in solvolysis of halides, steric strain might be expected to be rate-enhancing. In practice, rates of solvolysis¹⁴ of $R_1R_2R_3CCl$ from $(CH_3)_3CCl$ to $(C_2H_5)_2CClCH(CH_3)_2$ are within a factor of 3. If strain were al-

ready serious with methyl groups, serious increases in rate would accompany change to the more substituted structures. Furthermore, the k/k_H values with a neighboring group such as Br drop too rapidly to practically the calculated value of k_c/k_H with addition of methyl to C_{α} and removal from C_{β} . Finally, such an interpretation does not predict the contrast between Cl on the one hand and Br and I on the other. With Cl, k/k_H is not sensitive to structure while with Br and I it is. However, estimates of the stabilization due to a dipole²⁹ at the center of the halogen atom induced by half a unit positive charge on C_{α} show that the effect is comparable in magnitude with all three halogens. Besides, the magnitude of the effect is far from sufficient to account for the large value of k/k_H with iodine. Even on the exaggerated basis of a half-charged C_{α} atom (not a transition state C_{α} -Y dipole), using usual distances and angles and halogen polarizabilities derived from atomic refractions one obtains values of the polarization energy in kcal./mole of: Cl, 1.8; Br, 2.3; I, 2.9. Distortion of the C_{α} -C β -S angle (in I or III) from tetrahedral to 90°, for example, increases these values by only approximately 75 per cent., hardly enough to compensate for the work of bond-bending.

Thus on the basis of data so far available the interpretation on the basis of mechanisms **A** and **B** seems preferable. However, it is clear that the previous calculation of k_c/k_H based on neighboring Cl neglecting polarization and treating the effective dielectric constant D_E as an adjustable parameter actually is made on the simplifying assumption that polarization effects of the type mentioned in the transition state for formation of III are of comparable importance throughout. Thus there is still another reason³ for lack of accuracy in k_c/k_H .

Closure of Other Small Rings.—The same theoretical considerations used above in discussing structure and reactivity are useful in interpreting the closure of classical small rings such as epoxide, imine and episulfide rings. In the case of epoxide ring closure, especially, there are available instructive data from the work of Smith¹⁹ on the second-order rate constants k_2 for

TABLE V
RATE CONSTANTS FOR REACTION OF CHLOROHYDRINS WITH SODIUM HYDROXIDE

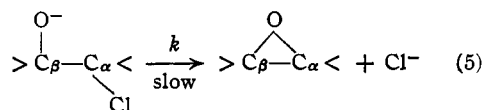
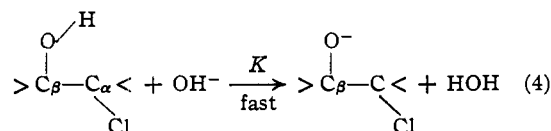
Compound	k_2 (18°) min. ⁻¹	pK_A	k sec. ⁻¹
HOCH ₂ CH ₂ Cl	0.31	16.9	5
CH ₃ CH(OH)CH ₂ Cl	6.5	17.0	1.3×10^2
HOCH ₂ CHClCH ₃	1.7	17.0	34
(CH ₃) ₂ C(OH)CH ₂ Cl	78	17.2	2.5×10^3
HOCH ₂ CCl(CH ₃) ₂	77	17.0	1.5×10^3
(CH ₃) ₂ C(OH)CHClCH ₃	424	17.2	1.3×10^4
CH ₃ CH(OH)CCl(CH ₃) ₂	633	17.1	1.6×10^4
(CH ₃) ₂ C(OH)CCl(CH ₃) ₂	3600	17.3	1.4×10^6

(28) (a) Brown, Bartholomay and Taylor, *THIS JOURNAL*, **66**, 435 (1944); (b) Brown, *Science*, **103**, 385 (1946).

(29) Debye, "Polar Molecules," Dover Publications, New York, N. Y., 1945, p. 18.

reaction with sodium hydroxide of the series of methyl substituted ethylene chlorohydrins. These rate constants are listed in Table V.

The mechanism we have suggested previously for the epoxide ring closure²² involves the unimolecular conversion (specific rate constant k) of the chloroalcoholate ion to oxide (equations 4 and 5). The unimolecular rate constant k is given as a



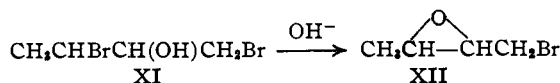
function of the measured second-order constant k_2 by equation 6, where K_A is the acidity constant of the chlorohydrin and K_W is the ion-product of

$$k_2 = kK = kK_A/K_W \quad (6)$$

water. In order to estimate k , rough pK_A values for the chlorohydrins were calculated by the method of Branch and Calvin,^{30a} using their inductive constants for Cl and CH₃ and a pK_A of 18.0 for ethanol.^{30b} These estimated pK_A values are shown in Table V together with the derived values for k . The order of magnitude (5 to 10⁶ sec.⁻¹) of the specific rate of conversion of chloroalcoholate ion to oxide is very large.

Primary and secondary halides ionize at rates no greater than 10⁻⁸ and 10⁻⁴ times, respectively, those of the corresponding tertiary halides.^{7,28} Thus, from Smith's values¹⁹ for the rate of hydrolysis of the tertiary halohydrins, values of the order of 5 × 10⁻¹³ and 5 × 10⁻⁹ sec.⁻¹, respectively, become upper limits for k_c of primary and secondary halohydrins. These estimates are exceeded by the values for k in Table V by factors of 10¹³ to 5 × 10¹⁵ in the case of the primary halohydrins and 7 × 10⁹ to 3 × 10¹² in the case of the secondary halohydrins. These factors are too large to ascribe to a simple electrostatic effect of the O⁻ charge, the ring closure being very predominantly a concerted one ($k = k_\Delta$).

The expected rate-enhancing effect of methyl substitution on either carbon atom of the halohydrin system is observed. While the primary propylene chlorohydrin is more reactive than the secondary, the latter is more reactive than ethylene chlorohydrin. The beneficial effect of alkyl substitution on oxide ring closure is further illustrated by the reported formation³¹ of the most substituted oxide XII from the halohydrin XI



(30) (a) Branch and Calvin, "The Theory of Organic Chemistry," Prentice-Hall, Inc., New York, N. Y., 1941, Chapter VI; (b) McEwen, THIS JOURNAL, **58**, 1124 (1936).

(31) Petrov, J. Gen. Chem. (U. S. S. R.), **11**, 713 (1941).

which carries competing primary and secondary bromine atoms.

Other classical small ring closures show the rate-enhancing effect of an α methyl group. Thus in the case of ethylene imine formation in water at 25° relative reactivities³² are CH₃-CHClCH₂NH₂, 4 > CH₂ClCH₂NH₂, 1. On the other hand, for the closure of a 5-membered imine ring an α methyl group gives the unfavorable effect characteristic of external type bimolecular displacements.³² The rate-enhancing effect of an α methyl group on β -lactone formation³³ is shown by the relative rates in water at 70°: CH₃CHClCH₂CO₂⁻, 5 > ClCH₂CH₂CO₂⁻, 1.

Inspection of the k values for the tertiary halohydrins in Table V reveals effects of methyl substitution which are formally correct for k_Δ . Actually, a calculation by the method of Kirkwood and Westheimer³⁴ of the extra electrostatic energy W due to the interaction of the negative charge on the O⁻ oxygen atom with the transition state C_α-Cl dipole (moment 5.42 D) gives values of k/k_{OH} (where k_{OH} is k_c for neutral halohydrin and k is from Table V) of the observed order of magnitude (Table VI). However, the factor of 10² intro-

TABLE VI
ELECTROSTATIC CALCULATION OF EFFECT W OF NEGATIVE CHARGE IN CHLOROALCOHOLATE ION

Compound	D _E ^a	W ^b kcal./mole	calcd. k/k_{OH} , 18° C.	observed
HOCH ₂ CCl(CH ₃) ₂	2.70	10.85	1.4 × 10 ⁴	2.3 × 10 ⁷
CH ₃ CH(OH)CCl(CH ₃) ₂	2.60	11.28	2.9 × 10 ⁴	4.7 × 10 ⁸
(CH ₃) ₂ C(OH)CCl(CH ₃) ₂	2.51	11.68	5.9 × 10 ⁴	2.3 × 10 ⁹

^a Effective dielectric constant calculated from Kirkwood and Westheimer's equation 11 for a spherical molecule.^{34a} Molecular radii calculated from Kopp's atomic volumes quoted by Leermakers and Weissberger.³⁵ Internal dielectric constant 2.00, external dielectric constant 78. ^b $W = (eM \cos \theta)/r^2 D_E$. Symbols have usual meaning. Previous³ conventions regarding tetrahedral bonds, bond distances, *trans*-arrangement of C-Cl and C-O⁻ bonds employed here. Transition-state C-Cl distance of 2.26 Å.

duced by two β methyl groups is hard to account for electrostatically since the effective dielectric constant D_E is low and relatively constant. This gives calculated values of k/k_{OH} relatively constant to β methyl substitution. On this account, the values of k of at least the β -methyl substituted tertiary halohydrins are believed substantially equal to k_Δ .

Semi-Quantitative Theory of the Effect of α and β Substitution.—It is possible to extend the qualitative considerations with regard to α and β methyl substitution to a semi-quantitative treatment for L and thus k_Δ/k_c , k/k_c and k/k_H . For any one neighboring group, leaving group and solvent, one can approximate

(32) Freundlich and Salomon, Z. physik. Chem., **166**, 161 (1933).

(33) Simpson, THIS JOURNAL, **40**, 874 (1918).

(34) (a) Kirkwood and Westheimer, J. Chem. Phys., **6**, 506 (1938); (b) Westheimer, THIS JOURNAL, **62**, 1892 (1940); (c) Westheimer and Shookhoff, *ibid.*, **61**, 555 (1939).

(35) Leermakers and Weissberger in Gilman, "Organic Chemistry," Vol. II, John Wiley and Sons, New York, N. Y., 1943, p. 1743.

ΔF_c^\ddagger , the free-energy of activation for mechanism **B**, by equation 7. L_c represents the free-

$$\Delta F_c^\ddagger = L_c - C_\alpha N_\alpha \quad (7)$$

energy of activation for step **B** of the *beta*-substituted ethyl compound, N_α the number of *alpha* methyl groups, and C_α is a parameter that would have the value of *ca.* 5.5 kcal./mole from a tentative factor of *ca.* 10^4 per *alpha* methyl group in solvolysis rates.^{7,26} Equation 7 assumes relative insensitivity to *beta* methyl groups of rates of ionization to open carbonium ions III. For solvolysis of $R_3CCCl(CH_3)_2$, Table II shows the lack of effect of *beta* methyl groups.

In approximating ΔF_Δ^\ddagger , the free-energy of activation of step **A**, equation 8 is used. L_Δ rep-

$$\Delta F_\Delta^\ddagger = L_\Delta - d_\alpha N_\alpha - d_\beta N_\beta \quad (8)$$

resents the free-energy of activation for step **A** of the *beta*-substituted ethyl compound, N_β the number of *beta*-methyl groups, and d_α and d_β are parameters. Equation 8 is based on the assumption that the stabilization by *alpha* and *beta* methyl groups of the transition-state leading to intermediate II is proportional to the number of *alpha* and *beta* methyl groups.

From equations 7 and 8, the variation of the driving force L with structure is readily derived. In principle d_α and d_β in equation 8 may vary with structure and neighboring group, depending on the extent of carbonium ion character of C_α . However, one single equation 9 fits the available experimental data quite well. In equation 9, L_0 is

$$L = 1.365 \log (k_\Delta / k_c) = L_0 - 2.27 N_\alpha + 1.79 N_\beta \quad (9)$$

($L_c - L_\Delta$) and is fairly insensitive to the nature of the solvent and leaving group. It varies mainly with the nature of the neighboring group and is termed the standard driving force of the neighboring group.

The values of L_0 for neighboring I, Br and OCH_3 are listed in Table VII. The value for OCH_3 stems from the one borderline value of k_Δ/k_c obtained in the cyclohexyl system.³ In Table III, alongside the experimental values of k_Δ/k_c are given the values calculated from equation 9. It is clear that the crude energy treatment represented by equation 9 fits the data satisfactorily. Also listed in Table III are values of k_Δ/k_c calculated from equation 9 for structures where no direct determinations were possible.

According to equations 7, 8 and 9, $d_\beta = 1.79$ kcal. and $C_\alpha - d_\alpha = 2.27$ kcal. Thus the hyperconjugative stabilization per methyl group in the transition-states is *ca.* 5.5 kcal. at C_α for step **B**, and *ca.* 3.2 kcal. at C_α and 1.8 kcal. at C_β for step **A**. The latter figure speaks for a stabilization energy per methyl group in the three-membered charged heterocyclic rings II in excess of the 2.5 kcal. hyperconjugation energy per methyl²³ in olefins. The sequence $C_\alpha > d_\alpha > d_\beta$ is reasonable because it is also the sequence of decreasing car-

bonium ion character of the corresponding carbon atoms.

The rates of oxide closure (k in Table V) afford a test of the validity of an equation of the type 8 over the entire range of structure of C_α and C_β . Equation 10 with the values of 1.45 for d_α and 1.67 for d_β fits the data in Table V with a mean de-

$$1.332 \log k = 0.94 + 1.45 N_\alpha + 1.67 N_\beta \quad (10)$$

viation of 0.17 in $\log k$.

Driving Force and Nucleophilic Character of Neighboring Groups.—Returning to the L_0 values in Table VII, we notice that we are in effect focusing attention on the relative abilities of the neighboring groups in nucleophilic attack on the adjacent carbon atom. Even for external substitutions, efficiency in nucleophilic attack on carbon is not well understood. In considering the activity of various nucleophilic agents, basicity is a fair guide as long as one remains with one attacking atom (*e. g.*, O in OH, CH_3COO , etc.). However, when one varies the nature of the attacking atom (*e. g.*, O, S), polarizability seems to be an important aspect. For internal substitution the problem is even more complicated because of such factors as strain. The values of L_0 for the neighboring groups represent one measure of nucleophilic character. To the values of L_0 derived from equation 9 and listed in Table VII are added rough minimum estimates of the driving force L for the neighboring groups SCH_2CH_2OH , NH_2 and O^- in the *beta*-substituted ethyl chlorides in water at 25°. The estimated values of k/k_H for these compounds are also listed in Table VII, representing an alternative measure of nucleophilic character of the neighboring groups.

TABLE VII

VALUES OF STANDARD DRIVING FORCE L_0 AND k/k_H FOR VARIOUS NEIGHBORING GROUPS IN β -SUBSTITUTED ETHYL COMPOUNDS

Neighboring group	L_0	k/k_H
SCH_2CH_2OH	13 ^{a,b}	10^7
I	8.71	1.6×10^3
NH_2	8 ^{a,c}	10^4
O^-	6 ^{a,d}	10^{10}
Br	4.55	0.39
OH, OCH_3	1.34	0.1

^a k_H for C_2H_5Cl in water at 25° estimated at 10^{-8} times value²⁰ for *t*- C_4H_9Cl or 3×10^{-10} sec.⁻¹ (upper limit).
^b k_o/k_H estimated at 10^{-2} . k_Δ from data of Bartlett and Swain.²⁶ ^c k_c/k_H estimated at 10^{-1} . k_Δ from Freundlich and Salomon.³² ^d k_o/k_H estimated at 10^6 . k_Δ from Table V.

Neighboring Groups in Primary Systems.—In considering the whole range of structure of compound I with a neighboring group, we expect the greatest driving forces L or highest values of k_Δ/k_o when C_α is primary as shown in Table III. Actually, it is only with some of the classical type neighboring groups such as O^- , NR_2 and SR that

(36) Bartlett and Swain, Report No. 4683, Division 9, N.D.R.C., O.S.R.D.

we have known rates which definitely indicate high values of k_{Δ}/k_c for primary compounds. With other neighboring groups such as Br, OCH_3 , etc., we are in the process of collecting data on further structures, some with C_{α} primary. Because of the care which must be exercised in seeking unimolecular mechanisms with primary compounds, there is little of significance in the literature on these latter cases. Thus, for example, Bennett and Reynolds³⁷ found the reaction of ethylene chlorohydrin with hydrogen bromide in phenol proceeded at a rate negligible compared to that of ethanol. If the unimolecular type interpretation of Bennett and Reynolds were correct, the effect of the chlorine atom would be of direct interest here. However, it is very probable that the mechanism is bimolecular^{3,26} ($\text{ROH}_2^+ + \text{Br}^-$) at least with ethanol.

Also of interest is the reaction of ethylene dihalides with silver salts. Ethylene dibromide has been reported³⁸ to react with alcoholic silver nitrate faster than ethyl bromide. However, Petrenko-Krichenko and Opotsky³⁹ report quantitative work to the contrary, and we have confirmed their findings by comparison of the relative rates of precipitate formation on treatment of pure samples of ethyl and ethylene bromides with alcoholic silver nitrate. From the data of Petrenko-Krichenko and Opotsky³⁹ on the reaction of halides with silver nitrate, it is clear that ethylene chloride is quite inert relative to ethyl chloride, ethylene bromide is roughly one-tenth as reactive as ethyl bromide and ethylene iodide is fully as reactive as ethyl iodide. While the effects of the neighboring Cl, Br, and I atoms are at least in the right order for participation, the reaction of halides with silver nitrate is too much complicated^{40,41} by such things as higher order reactions and adsorption effects to justify any certain deductions and comparisons with values of k_{Δ}/k_c in Table III at the present time.

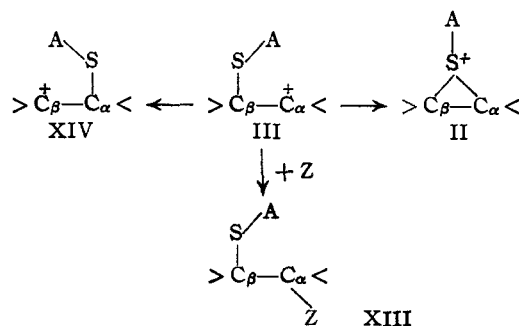
Rates, Stereochemistry and Products.—To control steric results of nucleophilic displacement reactions it is often necessary to assess the relative tendencies for bimolecular displacement with inversion or unimolecular type displacement which can lead to various steric results of which, perhaps, the most interesting is retention of configuration in the presence of a suitable neighboring group. For this purpose, a knowledge of the rates in reactions of the unimolecular type (as well as the bimolecular type) of the substituted compounds is essential, and toward this end the rate work so far reported is already useful.

Correlating the present work on rates of uni-

- (37) Bennett and Reynolds, *J. Chem. Soc.*, 131 (1935).
 (38) Shriner and Fuson, "Identification of Organic Compounds," John Wiley and Sons, Inc., New York, N. Y., 1940, p. 43.
 (39) Petrenko-Krichenko and Opotsky, *Ber.*, **59**, 2131 (1926).
 (40) Roberts, Young and Winstein, *THIS JOURNAL*, **64**, 2157 (1942).
 (41) Dostrovsky and Hughes, *J. Chem. Soc.*, 169 (1946).

molecular solvolyses with the previous⁴² work on the stereochemistry and products of such reactions, it becomes clear that most of the previous work has dealt with cases in which the rate-determining reaction step was the type A. Inversion of configuration in this step, followed by a second inversion in the conversion of cycle II to product, accounts for the clean-cut retentions of configuration.

For the situations where the rate work indicates the ionization is at least partly by mechanism B, there is little information on products and stereochemistry. In this sense, the rate work has helped to select crucial cases for stereochemical scrutiny. It is clear from the work of Lucas and Gould⁴³ that a neighboring chlorine atom gives rise to retention of configuration in the reaction of the 2-butene chlorohydrins with thionyl chloride. The conditions here are, of course, remote from those in the rate measurements. Also, it is evident that in the reactions of stilbene derivatives^{42d} with silver acetate in acetic acid, a β -acetoxy group participates in the displacement reaction for at least one of the diastereomeric acetoxychlorides, whereas, apparently, a neighboring chlorine atom fails to participate in at least one of the diastereomeric dichlorides. In the cases where the rate-determining step is B, the rate constants refer to the rate of formation of open carbonium ion III and do not yield information on the reaction paths III follows. The ion III may close to II, it may coordinate with reagent or solvent Z to give product XIII, or it may rearrange either to new ion XIV or in other ways, to mention some of the possibilities. Also, the stereochemical results



may be controlled by restriction of rotation around the $C_{\beta}-C_{\alpha}$ bond. Further chemical work is being carried on in these directions.

Experimental

Styrene Dibromide.⁴⁴—This compound was prepared by addition of bromine to styrene. Recrystallization from alcohol gave material, m. p. 72.3–72.5°, reported variously⁴⁵ from 72° to 74–75°.

- (42) (a) Winstein, Hess and Buckles, *THIS JOURNAL*, **64**, 2796 (1942); (b) Winstein and Buckles, *ibid.*, **65**, 613 (1943); (c) Winstein and Henderson, *ibid.*, **65**, 2196 (1943); (d) Winstein and Seymour, *ibid.*, **68**, 119 (1946).
 (43) Lucas and Gould, *ibid.*, **68**, 2541 (1941).

(44) We are indebted to Mr. Bruce Garner for the preparation of some of this material and for preliminary work on its alcoholysis.

- (45) (a) V. Braun and Moldanek, *Ber.*, **54**, 619 (1921); (b) Read and Reid, *J. Chem. Soc.*, 1488 (1928).

Styrene Iodochloride.—To a mixture of 13.6 g. (0.050 mole) of mercuric chloride, 10.4 g. (0.10 mole) of freshly distilled styrene and 200 ml. of absolute ether in a 1-liter round-bottom flask equipped with a reflux condenser, a mercury-sealed stirrer, and protected with a calcium chloride tube, was added with stirring 25.4 g. (0.10 mole) of iodine. Stirring was continued for one hour and then, because of illness, the reaction mixture was allowed to stand approximately a month.

The ethereal solution was decanted from the mercuric iodide and concentrated to a volume of 60 ml. with the aid of a water pump. The concentrated solution was washed rapidly with aqueous potassium iodide, then aqueous sodium bisulfite, finally water, and dried over potassium carbonate. Removal of the ether at reduced pressure and recrystallization of the residue from petroleum ether yielded 12.5 g. (47%) of product, m. p. 40.6° unimproved by further recrystallization. Ingle⁴ reported m. p. 46° for the product of addition of iodine monochloride to styrene, but repetition of this preparation yielded material, m. p. 40°. After treatment of 0.1907 g. of material, m. p. 40.6°, in a stoppered Erlenmeyer flask overnight with a solution of 2 g. of sodium iodide in 25 ml. of absolute acetone, titration with thiosulfate required 28.49 ml. of 0.0499 *N* solution. Equivalent weight: 134.1 (calculated 133.3).

Isobutylene Dibromide.—Redistilled Eastman Kodak Co. material, b. p. 76.4–76.8° (74 mm.), n_D^{20} 1.5095 (reported⁴⁶ b. p. 147–148° (742 mm.), n_D^{20} 1.5103) was used for rate measurements.

Isobutylene Iodochloride.—Approximately a 20% excess of liquid isobutylene was distilled into a well-stirred mixture of 81.6 g. (0.300 mole) of mercuric chloride, 152 g. (0.600 mole) of iodine and 400 ml. of ether in a flask equipped with a dry-ice condenser and a mercury-sealed stirrer, and protected with a calcium chloride tube. Stirring was continued for one hour and then the mixture was left overnight. The ethereal solution was decanted, concentrated at reduced pressure and then washed rapidly with aqueous potassium iodide, aqueous sodium bisulfite and then water. It was dried over magnesium sulfate, then over potassium carbonate. The ether was removed at reduced pressure and the residue was distilled at 22.5 mm. through an 18" glass spiral column to yield 88.3 g. (67%) of product, b. p. 55.5–56.2°, n_D^{20} 1.5237, d_4^{25} 1.727, *M*_{RD} 38.69 (calc. 38.34), equivalent weight for iodine chloride elimination as in the case of styrene iodochloride 109.4 (calc. 109.2). Istomin⁵ reported d_4^{25} 1.7502 for the product of addition of iodine chloride to isobutylene.

Solvents.—The absolute alcohol solvent contained less than 0.02% water by the paraffin oil test of Robertson.⁴⁷ Four volumes of alcohol were diluted with one volume of conductivity water at 25° to prepare 80% alcohol.

Aqueous dioxane was prepared by addition of 946 g. of conductivity water to 1000 g. of dioxane, b. p. 100.0° (747 mm.), purified according to the directions of Fieser.⁴⁸

Rate Measurements.—The rates at 55° and 70°, and the rate of solvolysis of isobutylene dibromide at 25°, were measured by the sealed ampoule technique. The other measurements were carried out more conveniently by removing at intervals aliquots of the thermostated reaction mixture from a thin-walled glass-stoppered Erlenmeyer flask. Titrations were carried out on 5-ml. aliquots with 0.05 *N* sodium hydroxide from a 5-ml. microburet to the brom thymol blue end-point. Since in the partly aqueous solvents some halohydrin is produced during the solvolysis, a slightly acid green end-point color was used consistently, and titrations were performed rapidly with vigorous shaking in the cold, essentially by the method of Suter and Zook.¹⁷ In all measurements except those in aqueous dioxane, aqueous base was found satisfactory. In the latter case, 0.05 *N* base in "50%" dioxane was used. The titrations were usually reproducible to within ±0.010 ml. of

base, except in the earlier work on the dibromides where the probable titration error was *ca.* ±0.020 ml. of base.

In the case of the iodochlorides the concentration of halogen was estimated at intervals by rapid titration with 0.05 *N* aqueous thiosulfate. The amount of halogen was less than 1.5 and 7–12 mole % of the acid produced in the case of the isobutylene and styrene derivatives, respectively.

An approximate estimate of the specific rate of α -methylallyl chloride was obtained by a procedure similar to that used by Peters and Walker.⁴⁹ One to three drops of halide, b. p. 64.5–64.8° (752 mm.), n_D^{20} 1.4159, were added to 100 ml. of water containing two drops of brom thymol blue indicator and a known amount of sodium hydroxide. The time, *t*, until the indicator changed color was measured with a stop-watch, and the concentration of acid after at least ten periods of half-change was determined by titration. From these data, a first-order rate constant can be calculated.

Details on Rate Constants.—First-order rate constants, *k*, where $k = (1/t) \ln [a - x]$, *a* being initial concentration in moles/liter of the organic halide, *t* the elapsed time, and *x* the concentration of generated acid or consumed base, were calculated.

In Table VIII are given data on a typical run on the alcoholysis of styrene dibromide. The first-order rate constants are seen to drop during a run due to reaction of the liberated hydrogen bromide with the ethanol solvent.⁹ The decrease in *k* is linear with time, and equation 11, obtained by the method of least squares, fits the data of this

$$k = 6.83 \times 10^{-4} - 0.0127 \times 10^{-4} t \quad (11)$$

and a duplicate run with a mean deviation of 2.3%. Thus the empirical extrapolation gives an initial rate constant of 6.83×10^{-4} hr.⁻¹ or 1.90×10^{-7} sec.⁻¹. With added 0.1369 *M* sodium perchlorate there was no systematic decrease in the calculated first-order constants until the elapsed time was more than 122 hours. This was probably mainly due to the much lower rate of reaction of the generated hydrogen bromide with ethanol solvent⁹ at this high ionic strength.

TABLE VIII

DATA FOR ETHANOLYSIS OF 0.1183 *M* STYRENE DIBROMIDE AT 54.95°

<i>t</i> , hours	$\frac{x}{0.96\text{-ml. aliquot}}$ in ml. 0.0459 <i>N</i> NaOH per	10 ⁴ <i>k</i> (hr. ⁻¹)
22.5	0.382	6.66
49.5	0.750	5.92
72.7	1.068	5.84
116.1	1.54	5.33
142.6	1.80	5.11
172.5	1.93	4.53
214.4	2.19	4.16
236.7	2.22	3.82

In the case of ethanolysis of *ca.* 0.10 *M* styrene iodochloride at 69.95°, first-order rate constants showed a tendency to climb, probably at least partly due to the greater effect of rising ionic strength than that of reaction of hydrogen chloride with solvent. This is illustrated in Table IX. Extrapolation to zero acid production for two such runs gave initial rate constants of 4.6×10^{-8} sec.⁻¹ and 5.2×10^{-8} sec.⁻¹.

For the determination of solvolysis constants in the aqueous ethanol or dioxane solvents, it was not necessary to extrapolate. The first-order rate constants were steady with a mean deviation of less than 3% to the following extents of reaction: 0.065 *M* isobutylene dibromide in 80% ethanol, *ca.* 10%; 0.085 *M* isobutylene iodochloride in 80% ethanol, *ca.* 13%; 0.033 *M* isobutylene iodochloride in the aqueous dioxane, *ca.* 20%; 0.007 *M* and 0.015 *M*

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(47) Robertson, "Laboratory Practice of Organic Chemistry," The Macmillan Co., New York, N. Y., 1937, p. 161.

(48) Fieser, "Experiments in Organic Chemistry," D. C. Heath and Co., Boston, Mass., 1941, p. 368.

(49) Peters and Walker, *Biochem. J.*, **17**, 260 (1923).

TABLE IX
DATA FOR ETHANOLYSIS OF 0.1075 M STYRENE IODO-
CHLORIDE AT 69.95°

<i>t</i> , sec.	10 ³ <i>x</i>	10 ³ <i>k</i> (sec. ⁻¹)
0	1.00	..
180	2.10	5.78
540	4.71	6.56
720	6.20	6.96
900	7.73	7.25
1260	10.96	7.80

t-butyl chloride, b. p. 50.2° (752 mm.), in the aqueous dioxane, 80%. For *t*-butyl chloride the rate constants were $6.14 \pm 0.11 \times 10^{-4}$ sec.⁻¹ at the lower concentration, $6.43 \pm 0.11 \times 10^{-4}$ sec.⁻¹ at the higher concentration, and $6.30 \pm 0.15 \times 10^{-4}$ sec.⁻¹ for the mean of both runs.

In Table X are given the data on the crude estimate of the rate constant for hydrolysis of α -methylallyl chloride in water at 27.2°.

TABLE X
DATA ON HYDROLYSIS OF α -METHYLALLYL CHLORIDE AT
27.2°

10 ³ <i>a</i>	10 ³ <i>x</i> (NaOH)	<i>t</i> (sec.)	10 ³ <i>k</i> (sec. ⁻¹)
0.632	0.252	624	0.82
1.053	.135	107	1.28
2.637	.240	86	1.11
3.48	.249	73	1.02

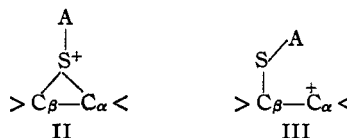
Mean 1.06 ± 0.14

Summary

The rates of solvolysis (*k*) of styrene dibromide, styrene iodochloride, isobutylene dibromide and isobutylene iodochloride have been determined for comparison with reported rates (*k_H*) of the corresponding α -phenylethyl and *t*-butyl halides. The rates of solvolysis are also reported for *t*-butyl chloride in 48.61 wt. per cent. aqueous dioxane at 34.86° and for α -methylallyl chloride in water at 27.2°. The relative reactivities, *k/k_H*, here reported, together with others either previously reported or derived from rate data in the literature, cover the range of structure for both the α and β carbon atoms (*C_α* and *C_β*) which may be primary (P), secondary (S), or tertiary (T).

With neighboring Cl in *S_βS_α*, *P_βT_α*, and *T_βT_α* systems and with neighboring OH in *P_βT_α*, *S_βT_α*, *T_βT_α* systems and in HOCH₂CHClCH=CH₂

values of *k/k_H* are quite constant. In these cases, the rate-determining ionization is predominantly the formation of the carbonium ion III (rate constant *k_c*) rather than the direct formation of cycle II (rate constant *k_Δ*) so that *k/k_H* is essentially



k_c/k_H. The observed insensitivity of *k_c/k_H* to changes in structure, solvent and departing group is rather expected from the electrostatic treatment previously used in discussing the effect of neighboring groups.

For neighboring Br and I, *k/k_H* varies widely with structure. The values of *k_Δ/k_c*, obtained with the aid of estimates of *k_c/k_H* from the electrostatic treatment, range for I from 7.2×10^2 in the *P_βT_α* system to 1.7×10^6 in the *S_βS_α* system and for Br from 1.1 in the *P_βT_α* system to 4.7×10^2 in the *T_βT_α* system. These trends are exactly those predicted by a qualitative theory which recognizes that α substitution stabilizes II and, to a greater extent, III, and that β substitution stabilizes II. Thus β substitution increases *k_Δ* and *k_Δ/k_c* while α substitution increases both *k_Δ* and *k_c* and decreases *k_Δ/k_c*.

The qualitative theory explains the trends observed in rates of closure of the ethylene oxide ring from variously substituted ethylene chlorohydrins. Similarly, it is in accord with the favorable effect of α methyl substitution for closure of the ethylene imine and the β -lactone rings.

For neighboring Br, I and OCH₃ the data on the variation of the driving force *L*, defined as $RT \ln (k_{\Delta}/k_c)$, with the numbers, *N_α* and *N_β*, of α and β methyl groups have been fit by the relation

$$L = L_0 - 2.27 N_{\alpha} + 1.79 N_{\beta}$$

*L*₀, the driving force in the *P_βP_α* system, is tabulated for I, Br, OCH₃, O⁻, NH₂ and SCH₂CH₂OH neighboring groups.

LOS ANGELES 24, CALIF.

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