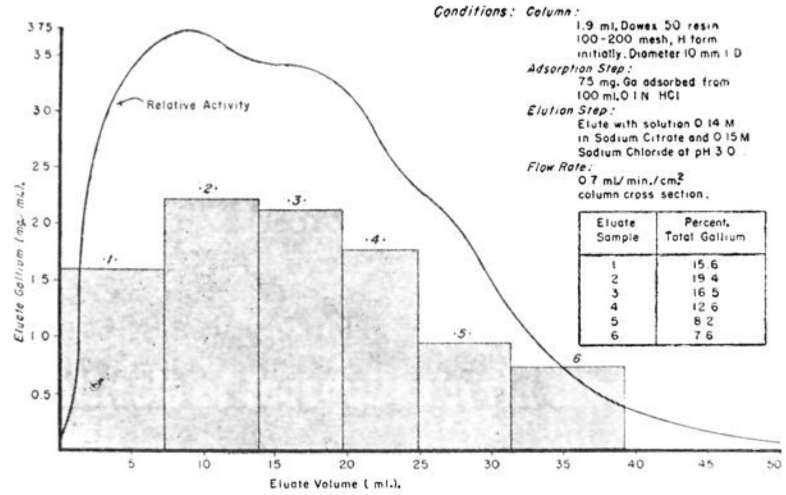
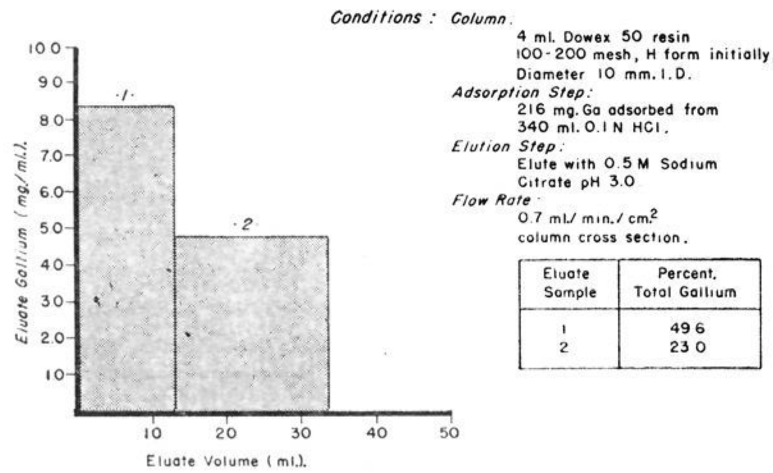


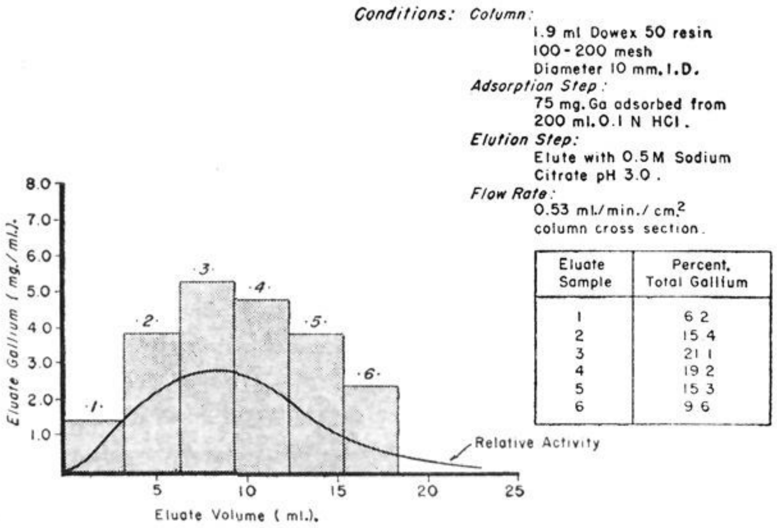
Eluate Sample	Percent. Total Gallium
1	15.6
2	19.4
3	16.5
4	12.6
5	8.2
6	7.6

Fig. 5.—Elution of gallium with 0.14 M sodium citrate, 0.15 M sodium chloride at *p*H 3.0.



Eluate Sample	Percent. Total Gallium
1	49.6
2	23.0

Fig. 6.—Elution of gallium with 0.5 M sodium citrate *p*H 3.0.



Eluate Sample	Percent. Total Gallium
1	6.2
2	15.4
3	21.1
4	19.2
5	15.3
6	9.6

Fig. 7.—Elution of gallium with 0.5 M sodium citrate, *p*H 3.0.

(Fig. 4) and reducing the elution flow rate from 0.7 to 0.53 ml./min./sq. cm. column cross section. Although the elution curve was more symmetrical indicating a closer approximation to equilibrium conditions, the gallium to citrate mole ratio was not changed appreciably (see Fig. 7). Further reductions in flow rate would be impractical as any increase in elution efficiency would be counterbalanced by decay loss of product gallium.

In all cases the *p*H of gallium citrate solution produced by the ion exchange method was approximately 2.3. Thus it was necessary to adjust the *p*H to 7.0 by the addition of 1.0 M sodium hydroxide. For highly radioactive solutions the use of the indicator brom cresol purple is effective.

OAK RIDGE, TENNESSEE RECEIVED DECEMBER 11, 1950

[CONTRIBUTION FROM THE DEPARTMENTS OF CHEMISTRY OF THE UNIVERSITY OF CALIFORNIA, LOS ANGELES, AND COLUMBIA UNIVERSITY]

The Correlation of Solvolysis Rates and the Classification of Solvolysis Reactions into Mechanistic Categories

BY S. WINSTEIN, ERNEST GRUNWALD[1] AND H. WALTER JONES[2]

The modes of classification of solvolysis reactions into mechanistic categories are discussed, and there are introduced the categories **N** (nucleophilic) involving a carbon–solvent interaction with covalent character in the transition state, and **Lim.** (limiting) involving an interaction without covalent character. The variation of solvolysis rate with solvent is scrutinized for a number of primary halides and benzenesulfonates, for a number of so-called borderline substances such as isopropyl bromide and benzyl chloride, and for *trans*-2-bromo- and *trans*-2-methoxycyclohexyl *p*-bromobenzenesulfonate with the aid of a linear free energy relationship. This linear relationship is quite successful when applied to nucleophilic solvents such as the aqueous alcohols, but solvolysis rates are lower than predicted by the relationship in acetic or formic acid except for the cases assigned to the **Lim.** category.

The attempt to describe the solvolysis of so-called borderline substances in a solvent in terms of two different simultaneous processes is not successful, and it is concluded that the description in terms of one process accounts for all known facts. The factors controlling rates of **N** and **Lim.** solvolyses, the conditions which convert solvolytic processes from the **N** to the **Lim.** category, and the assignment of cases to these categories are considered.

Most discussions of nucleophilic substitution on carbon are based on Hughes and Ingold's S_N1–S_N2 classification.[3]

In S_N1, a rapid product-controlling stage is thought to follow a slow rate-determining ionization of RX to a cationic intermediate, the rate determining ionization not requiring a covalent interaction[3e] between R and solvent in the transition state. The unimportance of steric effects in S_N1 substitution in contrast to their role in S_N2 reactions[3d,4,5] has perhaps been overemphasized.[6,7] We have reference not only to facilitation of S_N1

---

[1] Jewett Fellow, Columbia University, 1948–1949; Department of Chemistry, Florida State University, Tallahassee, Fla.

[2] Some of the material reported in this article is from the Ph.D. Thesis of H. Walter Jones, U. C. L. A., 1948; Western Regional Laboratory, Dept. of Agriculture, Albany, Calif.

[3] (a) Gleave, Hughes and Ingold, *J. Chem. Soc.*, 236 (1935); (b) Hughes and Ingold, *ibid.*, 244 (1935); (c) Hughes, *Trans. Faraday Soc.*, **34**, 185 (1938); (d) Hughes, *ibid.*, **37**, 603 (1941); (e) Bateman, Church, Hughes, Ingold and Taher, *J. Chem. Soc.*, 979 (1940).

[4] (a) Day and Ingold, *Trans. Faraday Soc.*, **37**, 686 (1941); (b) Dostrovsky, Hughes and Ingold, *J. Chem. Soc.*, 173 (1946).

[5] Dhar, Hughes, Ingold, Mandour, Maw and Woolf, *J. Chem. Soc.*, 2093 (1948).

[6] Winstein and Buckles, THIS JOURNAL, **64**, 2780 (1942).

[7] A. G. Evans, "The Reactions of Organic Halides in Solution," Manchester University Press, Manchester, Great Britain, 1946.

rate due to steric strain,[8] but especially to steric hindrance to solvation.[7] In highly hindered systems, such steric effects may be obscured by driving forces due to participation[9] of carbon or hydrogen or functional neighboring groups.[10]

While recognizing the important participation of solvent molecules in the S_N1 transition state, Hughes and Ingold have preferred the term unimolecular. Hammett and co-workers have used the term polymolecular.[11] Extrapolating from kinetic studies of the solvolysis of *p*-methoxybenzhydryl chloride[12] or trityl chloride[13a] in solvents such as nitrobenzene or benzene, where it is not yet clear[14] just what is going on, and choosing to emphasize the functions of two solvent molecules, Swain has termed these termolecular.[13]

In S_N2 substitution there is visualized a one-stage displacement process. Here, too, solvation is important. According to Hughes and Ingold,[3a,15] in S_N2 reactions there must be degrees of collaboration by the reagent Z: in the process of expelling the substituent X, and we have for some years felt that this phenomenon is advantageously discussed in terms of the canonical structures I, II and III which contribute[16] to the transition state. Structures I and II are often quoted.[7,17] Structures of the type III have sometimes been mentioned,[17,18] especially by Baker[19] in his discussion of side-chain substitution involving benzyl halides.

$$\underset{\text{I}}{\text{Z: R—X}} \qquad \underset{\text{II}}{\text{Z—R :X}} \qquad \underset{\text{III}}{\text{Z: R}^{+}\text{ :X}}$$

Classification Schemes for Nucleophilic Displacement on Carbon.—We have seen that two features of S_N1 substitution stand out: Evidence for an intermediate and lack of a covalent interaction between R and solvent in the transition state. Either of these alone can be used as a criterion for the classification of individual reaction cases into mechanistic categories. However, the two criteria will not in general classify cases identically. This is illustrated in Fig. 1 where the vertical subdivisions overlap as structure is varied horizontally. Line I shows Hughes and Ingold's S_N1–S_N2 classification. Line II shows a classification on the basis of whether or not there is positive evidence for an intermediate, such as a "mass law" effect[3e] or stereochemical effects. Line III shows a classification on the basis of the kind of interaction of solvent with carbon in the transition state: The limiting (**Lim.**) class where this does not involve covalent character, the nucleophilic (**N**) class where it does. Still another classification, not shown in Fig. 1, is that of Swain.[13] This is based on the criterion that at least one polar molecule is required for the R portion of the transition state regardless of its role and regardless of evidence for an intermediate. Disregarding such phenomena as neighboring group participation, essentially all cases of solvolysis then fall into one mechanistic category, and this causes Swain[13b] to state there is only one mechanism of solvolysis.

<table>
<tr><td>I. Hughes and Ingold</td><td>S_N1</td><td colspan="2">Borderline Cases</td><td>S_N2</td></tr>
<tr><td>II. Evidence for intermediate</td><td colspan="2">positive</td><td colspan="2">negative</td></tr>
<tr><td>III. Covalent character to solvent–R interaction</td><td colspan="2">Lim.(−)</td><td colspan="2">N(+)</td></tr>
</table>

Fig. 1.—Classification of nucleophilic displacements on carbon.

The Problem of Borderline Cases.—Hughes and Ingold's S_N1–S_N2 classification (Fig. 1) leaves room for borderline cases where there is some evidence for an intermediate and also for an interaction with some covalent character between solvent and R in the transition state. While usually discussing these borderline cases in terms of separate S_N1 and S_N2 reactions, Hughes and Ingold have also stated that there is no sharp line of demarcation[20] between S_N1 and S_N2, that the two mechanisms are "the extremes of a graded range"[3a] and merge, and that there must be intermediate mechanisms.[3a,15,21] Despite all discussion, the question remains whether the solvolysis of any such borderline substance in a neutral solvent should be described in terms of two kinds of process or only one kind.

A solution to these questions may be sought in the relation between solvolysis rate and solvent, for the relevant solvent properties which affect the rate, nucleophilic character and ionizing power, vary independently. Nucleophilic character is a complex property, but basicity has long been used as a measure[3a,22] in cases where the nucleophilic atom is constant. A quantitative measure of ionizing power has been made available only recently in our work on the correlation of solvolysis rates.[23] Thus the tools are now available for a more rigorous treatment of the general problem of the solvent dependence of solvolysis rates. As a corollary, the problem of the solvolysis

---

[8] (a) Bartlett, "Recent Studies on Steric Effects," delivered at 10th National Organic Symposium of the American Chemical Society, Boston, Mass., June, 1947, p. 22 of abstracts; (b) Brown and Fletcher, THIS JOURNAL, **71**, 1845 (1949).

[9] (a) Winstein and Trifan, *ibid.*, **71**, 2953 (1949); (b) Winstein, paper presented at 11th National Organic Symposium, Madison, Wisconsin, June 21, 1948, page 65 of abstracts.

[10] Winstein and Grunwald, *ibid.*, **70**, 828 (1948).

[11] (a) Hammett, "Physical Organic Chemistry," McGraw-Hill Book Co., Inc., New York, N. Y., 1940, Chapters V and VI; (b) Steigman and Hammett, THIS JOURNAL, **59**, 2536 (1937); (c) Farinacci and Hammett, *ibid.*, **59**, 2542 (1937).

[12] Bartlett and Nebel, *ibid.*, **62**, 1345 (1940).

[13] (a) Swain, *ibid.*, **70**, 1119 (1948); (b) Swain and Eddy, *ibid.*, **70**, 2989 (1948); (c) Swain, Esteve and Jones, *ibid.*, **71**, 965 (1949).

[14] See ref. 3e and Swain, *ibid.*, **72**, 2794 (1950).

[15] Hughes and Ingold, *Trans. Faraday Soc.*, **37**, 657 (1941).

[16] In suitable cases, such as those involving aromatic compounds, α-haloketones, etc. (Winstein and Jones, unpublished work) or substances with an atom capable of increasing its shell of valence electrons beyond an octet, such as Si (*e.g.*, Hückel, "Theoretische Grundlagen der organischen Chemie," Akademische Verlagsgesellschaft m. b. H., Leipzig, 1940, p. 540; and Swain, Esteve and Jones [13c]) structures of the type Z—R—X need also to be included. Thus the R portion of the transition state may carry a substantial negative charge. Even with structures I–III, R may be less positive in the transition state than in R—X.

[17] (a) Baughan and Polanyi, *Trans. Faraday Soc.*, **37**, 648 (1941); (b) Dostrovsky, Hughes and Ingold, *J. Chem. Soc.*, 1283 (1948).

[18] Waters, *Trans. Faraday Soc.*, **37**, 685 (1941).

[19] (a) Baker and Nathan, *J. Chem. Soc.*, 519, 1840 (1935); (b) Baker, *Trans. Faraday Soc.*, **37**, 632 (1941).

[20] Hughes, Ingold and Shapiro, *J. Chem. Soc.*, 225 (1936).

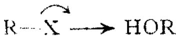
[21] Dhar, Hughes and Ingold, *ibid.*, 2060 (1948).

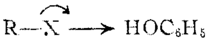
[22] Hughes, Ingold and Patel, *ibid.*, 526 (1933).

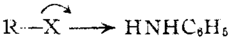
[23] Winstein and Grunwald, THIS JOURNAL, **70**, 846 (1948).

mechanisms for borderline cases can be dealt with more precisely.

In the previous paper[23] whose correlations we now extend, we had considered solvolyses of the limiting class (rate constant k_1) whose rates depend on ionizing power, and solvolyses of the nucleophilic class (rate constant k_x) whose rates depend on both ionizing power and nucleophilic character. Ionizing power included specific electrophilic action of solvent on X, *e.g.*, by hydrogen bonding, as illustrated in IV,[11] V[24] and VI.[25]


IV


V


VI

For a number of cases which it was reasonable to put into or close to the limiting mechanistic category the variation of rate with solvent satisfied the linear free energy relationship represented by equation (1).

$$\log k = \log k_0 + mY \qquad (1)$$

In this equation k and k_0 were the specific solvolysis reaction rate constants in a solvent and in the standard solvent, 80% ethanol, respectively, Y was a measure of the solvent ionizing power and m was a slope characteristic of each substance.

In setting up the Y values, Y was usually set equal to $\log k - \log k_0$ for *t*-butyl chloride, the most convenient standard. For aqueous acetone solvents, it was necessary to use two sets of Y values, one based on *t*-butyl bromide and another based on benzhydryl chloride. This difficulty represented one limitation of the free-energy relationship (1) which must share with linear free energy relationships in general the restriction that there are limitations as to range of structure and conditions over which they apply. In a following article[26] we report more data in aqueous acetone which further emphasize the limitations.

For isopropyl *p*-bromobenzenesulfonate which Hughes and Ingold classify as borderline[3] (Fig. 1), plots of log k *vs.* Y were not linear over the whole solvent range, values of log k in the more nucleophilic solvents ethanol, methanol and aqueous alcohol tending to be high. There was some success in the assumption of two simultaneous processes in these nucleophilic solvents. k_1 was calculated from equation (1) where the parameters log k_0 and m had been estimated from data in the weakly nucleophilic acetic acid–acetic anhydride solvent mixtures, and k_x was the difference between the observed k and k_1. It turned out that k_x in the limited range ethanol→80% ethanol satisfied equation (1) with a low m value nearly identical with that for n-butyl bromide.

Results.—We have now scrutinized more primary compounds and borderline[3] cases. The pertinent first-order rate constants are summarized in Table I. The columns in this table list the compounds, temperatures, initial concentrations, numbers of rate measurements and average values of the first-order rate constants as well as their precision measures. The rate constants are usually based on two kinetic runs in which initial concentrations are varied by a factor of two.

Table I

First-order Specific Solvolysis Rates

Compound temp., °C.	Solvent[a]	Initial concn., M	n[a]	k(sec.$^{-1}$)
trans-2-	EtOH	0.01–0.02	2	$(2.67 \pm 0.04) \times 10^{-7}$
Bromo-	MeOH	.006–0.01	2	$(1.28 \pm 0.02) \times 10^{-6}$
cyclo-	80% EtOH	.01–0.02	2	$(7.02 \pm 0.14) \times 10^{-6}$
hexyl *p*-	50% EtOH	.003	2	$(9.12 \pm 0.10) \times 10^{-5}$
bromo-	AcOH[b]	....	..	5.28×10^{-7}
benzenesulfonate, 50.00				
trans-2-	EtOH	.02–0.04	2	$(3.11 \pm 0.03) \times 10^{-7}$
Methoxy-	MeOH	.01–0.02	2	$(1.12 \pm 0.01) \times 10^{-6}$
cyclo-	80% EtOH	.01–0.02	3	$(3.25 \pm 0.06) \times 10^{-6}$
hexyl *p*-	50% EtOH	.009	2	$(1.61 \times 0.02) \times 10^{-5}$
bromo-	AcOH[b]	....	..	3.46×10^{-7}
benzenesulfonate, 50.00				
Methyl	EtOH	.07–0.16	2	$(3.93 \pm 0.10) \times 10^{-7}$
bromide,	80% EtOH[c]	.05–0.10	2	$(2.19 \pm 0.04) \times 10^{-6}$
50.00	50% EtOH[c]	.04–0.07	2	$(5.66 \pm 0.10) \times 10^{-6}$
	HOH	.018–0.036	2	$(1.05 \pm 0.03) \times 10^{-5}$
Ethyl	EtOH[d]	....	..	2.37×10^{-7}
bromide,	80% EtOH[e]	....	..	1.39×10^{-6}
55.00	50% EtOH[f]	.03–0.05	2	$(5.25 \pm 0.10) \times 10^{-6}$
	HOH	.006–0.012	2	$(1.83 \pm 0.04) \times 10^{-5}$
Ethyl *p*-	EtOH	.02–0.06	3	$(2.46 \pm 0.03) \times 10^{-6}$
toluene-	MeOH	.02–0.05	3	$(4.83 \pm 0.05) \times 10^{-6}$
sulfonate,	80% EtOH	.02–0.06	3	$(9.23 \pm 0.15) \times 10^{-6}$
50.00	50% EtOH	.03–0.05	3	$(2.18 \pm 0.02) \times 10^{-5}$
	AcOH[g]	.02–0.06	3	$(3.83 \pm 0.24) \times 10^{-8}$
Isopropyl	EtOH[h]	.01–0.2	2	$(1.12 \pm 0.02) \times 10^{-7}$
bromide	80% EtOH[h]	.02–0.04	2	$(1.18 \pm 0.02) \times 10^{-6}$
50.00	50% EtOH[h]	.02–0.03	2	$(8.45 \pm 0.10) \times 10^{-6}$
	HOH	.001–0.003	2	$(1.16 \pm 0.05) \times 10^{-4}$
Benzyl	EtOH	.04–0.1	3	$(3.14 \pm 0.06) \times 10^{-7}$
chloride,	MeOH	.04–0.1	3	$(1.23 \pm 0.04) \times 10^{-6}$
50.00	80% EtOH	.03–0.1	3	$(2.22 \pm 0.06) \times 10^{-6}$
	50% EtOH	.04–0.1	3	$(1.22 \pm 0.05) \times 10^{-5}$
Benzyl *p*-	EtOH	.02–0.04	2	$(5.33 \pm 0.25) \times 10^{-5}$
toluene-	MeOH	.12–0.14	2	$(1.67 \pm 0.04) \times 10^{-4}$
sulfonate,	80% EtOH	.05–0.07	2	$(3.24 \pm 0.30) \times 10^{-4}$
25.05	AcOH[g]	.04–0.06	2	$(2.61 \pm 0.03) \times 10^{-5}$

[a] EtOH = ethanol; MeOH = methanol; AcOH = acetic acid; n = number of determinations. [b] Extrapolated from data at higher temperatures (ref. 27). [c] $k = 3.49 \times 10^{-6}$ in 80% EtOH at 55.0° (ref. 28), $E^{\ddagger} = 19.6$ kcal./mole; $k = 2.86 \times 10^{-4}$ in 50% EtOH at 94.85° (ref. 29), $E^{\ddagger} = 20.7$ kcal./mole. [d] Ref. 30. [e] Ref. 28. [f] $k = 1.41 \times 10^{-4}$ in 50% EtOH at 94.85° (ref. 29), $E^{\ddagger} = 19.8$ kcal./mole. [g] Solvent contains 0.20 weight % of acetic anhydride. [h] Data at other temperatures have been obtained in dry, 80%, 60% and 50% ethanol (refs. 20, 21, 31, 32). The agreement between these and our specific rates is satisfactory in view of the stated uncertainties in solvent composition.[21]

In some instances the present results are comparable with published data obtained at other temperatures, and this is indicated in the footnotes of Table I. In the few cases where direct comparisons can be made, the agreement is within the combined experimental errors. It has sometimes been reported that rate constants in mixed solvents cannot be reproduced to better than 10%

---

(24) Bartlett and Dauben, This Journal, **62**, 1339 (1940).

(25) Hückel, Tappe and Legutke, *Ann.*, **543**, 206 (1940).

(26) Winstein, Young Goering and Jones, to be submitted.

(27) Winstein, Grunwald and Ingraham, This Journal, **70**, 821 (1948).

(28) Bateman, Cooper, Hughes and Ingold, *J. Chem. Soc.*, 925 (1940).

(29) Dostrovsky and Hughes, *ibid.*, 164 (1946).

(30) Grunwald and Winstein, This Journal, **69**, 2051 (1947).

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

(32) Crowell and Hammett, This Journal, **70**, 3444 (1948).

by different investigators, even in the same laboratory,[2,28] but this difficulty was not experienced in the present work. Measurements were sometimes repeated in fresh batches of aqueous ethanol and there were no significant changes in specific rate. The high degree of reproducibility of the data is probably due to the care exercised in preparing the mixed solvents. The ethanol component used to prepare the aqueous ethanol solvents was always first analyzed for water, thus eliminating the most likely source of determinate error.

In Figs. 2 and 3 are plotted values of log (k/k_{EtOH}) against Y values previously reported[23] for some of the substances summarized in Table I together with data for other substances for comparison. Data for isopropyl *p*-bromobenzenesulfonate and *t*-butyl bromide are from the previous summary,[23] except that a recent[33] more accurate rate constant for *t*-butyl bromide in ethanol was used. Data for methyl and ethyl benzenesulfonates are from the literature,[34] and specific rates for the alkyl halides in formic acid (Fig. 3) were estimated from data[35] at higher temperatures using values of $E^{\ne}$ observed in aqueous alcohols. The errors due to this assumption are thought to be small compared to the effects on reactivity and are not likely to influence the qualitative relationships.

Primary Compounds.—Figure 2 and Table II show that plots of log k *vs.* Y are satisfactorily linear in the nucleophilic solvent systems methanol, ethanol and water for methyl benzenesulfonate, ethyl benzenesulfonate and ethyl *p*-toluenesulfonate. Least squares values of log k_0 and m, and probable errors r[36] of the fit of equation (1) are summarized in Table II. m is 0.23 for the methyl ester and about 0.27 for the ethyl esters. In the case of ethyl *p*-toluenesulfonate, the rate constant in the weakly-nucleophilic acetic acid solvent is nearly a hundred times lower than in the ethanol–water mixture of equal ionizing power.

Figure 3 indicates the relationship between log k and Y for methyl bromide and ethyl bromide. The plots in the system ethanol–water have significant curvature, but the fit of equation (1) is still fair as summarized in Table II. Values of m in this system are 0.258 for methyl bromide and 0.343 for ethyl bromide. The rate constants are lower in formic acid than in an ethanol–water mixture of equal ionizing power by factors of 200 and 80, respectively, for the methyl and ethyl halides.

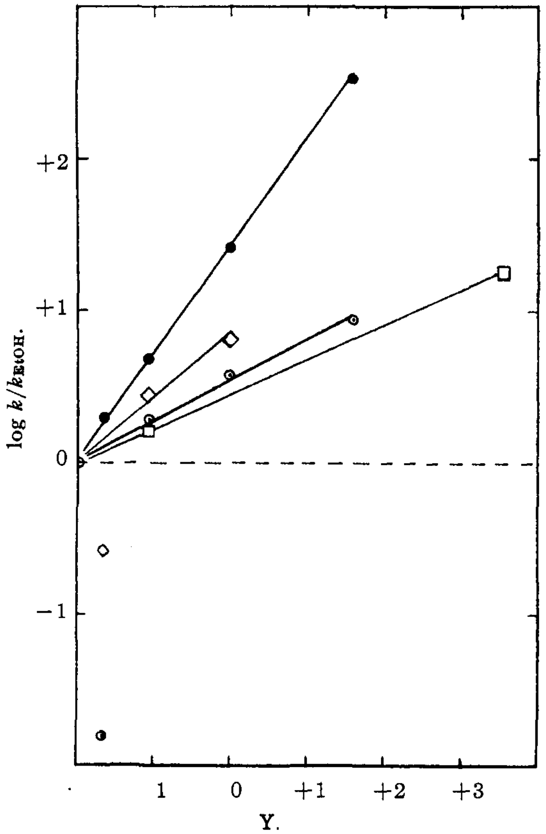


Fig. 2.—Plots of log k/k_{EtOH} *vs.* Y: □, methyl benzenesulfonate, 50.0°; ⊙, ethyl *p*-toluenesulfonate, 50.0°; ◇, isopropyl *p*-bromobenzenesulfonate, 70.0°; ●, *trans*-2-bromocyclohexyl *p*-bromobenzenesulfonate, 50.0°.

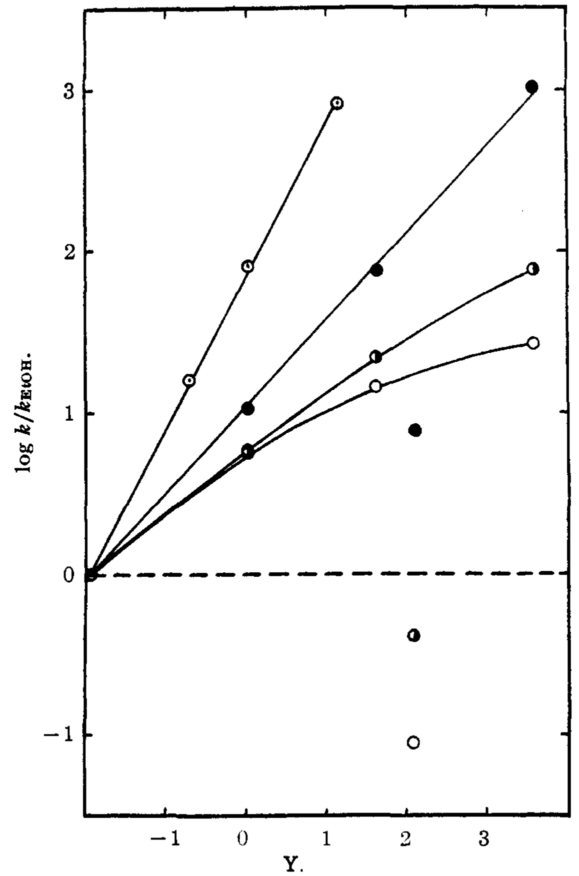


Fig. 3.—Plots of log k/k_{EtOH} *vs.* Y: ○, methyl bromide 50.0°; ◑, ethyl bromide, 55.0°; ●, isopropyl bromide, 50.0°; ⊙, *t*-butyl bromide, 25.0°.

Borderline Cases.[3]—Table I summarizes the data for isopropyl bromide, isopropyl *p*-bromo-

---

[33] Dhar, Hughes and Ingold, *J. Chem. Soc.*, 2065 (1948).

[34] (a) Praetorius, *Monatsh.*, **26**, 1 (1905); **28**, 767 (1907); (b) Karlsson, *Z. anorg. allgem. Chem.*, **145**, 1 (1925); (c) Demeny, *Rec. trav. chim.*, **50**, 60 (1931).

[35] (a) Bateman and Hughes, *J. Chem. Soc.*, 945 (1940); (b) Dostrovsky and Hughes, *ibid.*, 171 (1946).

[36] Margenau and Murphy, "Mathematics of Physics and Chemistry," D. Van Nostrand Co., Inc., New York, N. Y., 1943, p. 502.

TABLE II

CORRELATION OF SOLVOLYSIS RATES

Compound	Temp., °C.	Solvents[a]	log k_0	m	r	$(k_{ROH}/k_{RCOOH})_Y$[b] AcOH	HCOOH
Methyl bromide	50.00	1, 2, 3, 4	−5.779	0.258	0.113		200
Methyl benzenesulfonate	50.00	1, 4, 5	−4.536	.228	.001		
Ethyl bromide	55.00	1, 2, 3, 4	−5.898	.343	.053		80
Ethyl benzenesulfonate	50.00	1, 4, 5, 9	−4.781	.279	.037		
Ethyl *p*-toluenesulfonate	50.00	1, 2, 3, 5	−5.062	.262	.024	80	
Isopropyl bromide	50.00	1, 2, 3, 4	−5.906	.544	.030		20
Isopropyl *p*-bromobenzenesulfonate	70.00	1, 2, 5	−2.750	.408	.036	6	
t-Butyl bromide	25.00	1, 2, 7, 8	−3.472	.940	.021		
Benzyl chloride	50.00	1, 2, 3, 5	−5.594	.425	.076		
Benzyl *p*-Toluenesulfonate	25.05	1, 2, 5	−3.449	.394	.077	30	
trans-2-Bromocyclohexyl *p*-bromobenzenesulfonate	50.00	1, 2, 3, 5, 6	−5.159	.701	.016		
trans-2-Methoxycyclohexyl *p*-bromobenzenesulfonate	50.00	1, 2, 3, 5, 6	−5.539	.493	.067		

[a] Solvents: 1, ethanol; 2, 80% ethanol; 3, 50% ethanol; 4, water; 5, methanol; 6, acetic acid; 7, 90% ethanol; 8, 60% ethanol; 9, 30% ethanol. [b] k_{RCOOH} = specific rate in acetic acid or formic acid; k_{ROH} = specific rate in ethanol–water mixture of equal ionizing power.

benzenesulfonate, benzyl chloride and benzyl *p*-toluenesulfonate. Some of these are plotted in Figs. 2 and 3. It is evident from the figures and Table II that equation (1) fits the data in the nucleophilic solvent systems methanol, ethanol and water to an excellent approximation for the isopropyl compounds, in the case of isopropyl bromide the entire range from ethanol to water being investigated. For the benzyl compounds the fit is fair. Values of m are 0.408 for isopropyl *p*-bromobenzenesulfonate, 0.544 for isopropyl bromide, 0.394 for benzyl *p*-toluenesulfonate, and 0.425 for benzyl chloride. Rate constants in the weakly-nucleophilic solvents acetic acid and formic acid are considerably lower than in ethanol–water mixtures of equal ionizing power, but the decreases in specific rate are not so great as in the cases of the primary compounds (see Figs. 2 and 3 and Table II).

Solvolysis of Isopropyl Bromide: One or Two Simultaneous Processes.—Although the curvature observed in the log k *vs.* **Y** plots for methyl and ethyl bromide somewhat complicates the issue, it can nevertheless be seen that the log k dependence on **Y** for the so-called borderline cases is not well fitted by the k_1, k_x treatment attempted previously.[23] The most crucial case is that of isopropyl bromide for which the entire solvent range from ethanol to pure water was experimentally accessible. Using equations (2), (3) and (4) with the assumption of two simultaneous processes for the solvolysis of this substance in its nucleophilic solvents

$$k = k_1 + k_x \quad (2)$$

$$\log k_1 = m_1\mathbf{Y} + \log k_1^0 \quad (3)$$

$$\log k_x = m_x\mathbf{Y} + \log k_x^0 \quad (4)$$

m_1 was taken equal to 0.940, the value for *t*-butyl bromide, and m_x was taken equal to 0.340, comparable with 0.331 for *n*-butyl bromide and 0.343 for ethyl bromide in aqueous ethanol. Substitution of these m values gave rise to equation (5). The slope and intercept from the least squares fit of the data to equation (5) gave values of k_1^0 and k_x^0 which were used to calculate k_1, k_x and thus k.

$$(10^{-0.340\mathbf{Y}})k = (10^{0.600\mathbf{Y}})\,k_1^0 + k_x^0 \quad (5)$$

These calculations are summarized in Table III which compares observed with calculated values of k. It is evident that in the nucleophilic solvents this type of treatment gives a poor fit of the data, the probable error (r) in log k being 0.193. The fit of the data with a single m value equal to 0.544 gives a much superior fit with a probable error in log k (Table II) of 0.030. Furthermore, the value of k_1 for formic acid predicted by equations (3) and (5) greatly *exceeds* the experimental value (see Table III).

The assumption of two solvolysis processes for the borderline cases in the nucleophilic solvents requires upward curvature in the log k–**Y** plot as k_1/k approaches unity, *i.e.*, as **Y** becomes large. In the case of isopropyl bromide with the assumed m values, the slope d log k/d**Y** is given by equation (6) as a function

$$\frac{\mathrm{d}\log k}{\mathrm{d}\mathbf{Y}} = 0.940 - 0.60\,\frac{k_x}{k} \quad (6)$$

of the ratio k_x/k. The last column in Table III shows that if k is distributed between k_1 and k_x in the indicated way, the slope should rise from 0.34 in ethanol to 0.84 in water. Actually, no significant curvature is apparent.

From this scrutiny of the variation of rate with solvent we see no support for the idea that two kinds of processes occur simultaneously in the solvolysis of borderline cases in any one solvent medium. Also, we know of no reason why such a solvolysis should not be discussed in terms of one process.

General Treatment of Solvolysis.—Since solvolysis rates in general are functions of the solvent properties, nucleophilic character N and ionizing power **Y**, one is led to consider the differential equation (7) where the partial derivatives, ∂ log $k/\partial\mathbf{Y}$ and ∂ log $k/\partial N$ can be thought to measure the contributions of solvation and covalent bond formation to carbon to the total driving force.

$$\mathrm{d}\log k = \left(\frac{\partial \log k}{\partial \mathbf{Y}}\right)_N \mathrm{d}\mathbf{Y} + \left(\frac{\partial \log k}{\partial N}\right)_{\mathbf{Y}} \mathrm{d}N \quad (7)$$

Referring back to the classification of Fig. 1 into categories **N** and **Lim.**, the **N** category, requiring driving forces due to both solvation and

TABLE III

CALCULATION OF k FOR SOLVOLYSIS OF ISOPROPYL BROMIDE ON ASSUMPTION OF 2 PROCESSES: $k_1 = (0.438 \times 10^{-7})(10^{0.940\mathrm{Y}})$; $k_x = (12.05 \times 10^{-7})(10^{0.340\mathrm{Y}})$

Solvent	10^7k(obsd.)	10^7k_x (calcd.)	10^7k_1 (calcd.)	$7 + \log k$ (obsd.)	$7 + \log k$ (calcd.)	Δ	$\frac{d \log k}{d\mathrm{Y}}$ (calcd.)
EtOH	1.12	2.57	0.0061	0.049	0.412	+0.363	0.341
80% EtOH	11.8	12.05	0.44	1.072	1.097	+ .025	.361
50% EtOH	84.5	42.3	14.1	1.927	1.751	− .176	.490
HOH	1160	196	972	3.064	3.068	+ .004	.839
						$r = 0.193$	
HCOOH	8.6		39.5				

bond formation, represents the general case of solvolysis. As reactant structure is varied so as to make $(\partial \log k/\partial N)_\mathrm{Y}$ smaller and smaller, or as the solvent is varied to make N sufficiently low, the driving force due to bond formation becomes negligible and the Lim. case obtains. For a given reactant, the lower $(\partial \log k/\partial N)_\mathrm{Y}$ the easier it is to attain a limiting mechanism by suitable change of solvent. Consequently such a factor as steric hindrance which lowers the importance of bond formation to carbon in the transition state makes easier the attainment of a limiting mechanism.

While it is difficult to obtain absolute values for the two derivatives of equation (7) in a given solvent system, it is possible to obtain relative values. For example, the logarithms of relative rates in two media of equal ionizing power but different nucleophilic character measure $(\partial \log k/\partial N)_\mathrm{Y}$, at least qualitatively. Some values of $k_{\mathrm{ROH}}/k_{\mathrm{RCOOH}}$ at the Y value of either acetic or formic acid are tabulated in Table II. In discussing these quantities it must be remembered that they have little quantitative significance except to establish relative values of $(\partial \log k/\partial N)_\mathrm{Y}$.

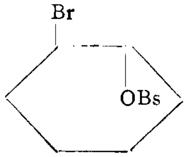
Relative values of the term $(\partial \log k/\partial Y)_N$ are the m values (Table II) in binary solvent systems such as water–ethanol where the components are comparably nucleophilic but differ greatly in ionizing power. The values of m cover the entire range from 0.23 to *ca.* 1 especially if substances such as crotyl chloride are included.[23,26]

The results summarized in Table II conform to an interesting pattern. In general, as structure is varied in the direction more favorable to contribution of valence-bond structure III to the transition state resonance hybrid, the measure of $(\partial \log k/\partial N)_\mathrm{Y}$ logically decreases. At the same time m, the measure of $(\partial \log k/\partial \mathrm{Y})_N$, rises, suggesting that the two kinds of driving force are roughly complementary.

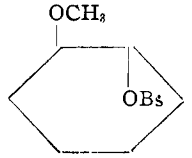
Validity of the Y Function as a Measure of Ionizing Power.—We have so far assumed that some of the cases of solvolysis, especially *t*-butyl chloride, belong in the Lim. category. If this is true, Y is a valid measure of ionizing power. If *t*-butyl chloride is not limiting, $(\partial \log k/\partial N)_\mathrm{Y}$ really measures an excess over *t*-butyl chloride and cases are incorrectly labelled limiting which are in fact not so.

In probing this question further, it is useful to go to cases where the nucleophilic role is assumed by a functional neighboring group. Judging by the rates[10,27] and stereochemistry[6] observed in substitution involving neighboring bromine, the role of supplying a close range nucleophilic backside attack on carbon, which might ordinarily be played by solvent, is here assumed by the neighboring group. Thus the solvolysis rate should depend only on what we have called ionizing power. As a matter of fact, the data for *trans*-2-bromocyclohexyl *p*-bromobenzenesulfonate VII are fitted by equation (1) (including acetic acid solvent) with a probable error in log k of only 0.016. The case of *trans*-2-methoxycyclohexyl *p*-bromobenzenesulfonate (VIII) is similar, the fit being not quite as good.

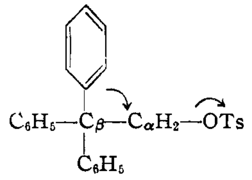
Further supporting evidence for the limiting or near-limiting nature of the solvolysis process with *t*-butyl chloride is derived from solvolysis rates of materials such as 2,2,2-triphenylethyl *p*-toluenesulfonate (IX). As is reported elsewhere,[9b,37] rates of substances such as these are enhanced due to participation of a neighboring group, in this case phenyl, in the rate-determining ionization. In the present example IX, if nucleophilic attack by solvent takes place at all, it is visualized as taking place at the β-carbon atom which, due to the favorable structure of its substituents, could tolerate cationic charge more readily than the central carbon atom in our standard substance, *t*-butyl chloride. We would therefore expect the solvolysis of IX to be a more nearly perfect example of solvolysis of the limiting kind than even that of *t*-butyl chloride, and the rate factor $k_{\mathrm{AcOH}}/k_{\mathrm{EtOH}}$ would increase. Actually, the factor for IX is about equal to that for *t*-butyl chloride. Therefore this evidence, as well as that derived from *trans*-2-bromocyclohexyl *p*-bromobenzenesulfonate, indicates that Y truly measures ionizing power and does not contain terms due to covalent solvent–carbon interaction in the transition state.



VII



VIII



IX

Assignment of Cases to Mechanistic Categories.—The solvolyses of compounds such as *t*-butyl

---

[37] B. Friess, Ph.D Thesis, U. C. L. A., 1949.

halides and α-methylneopentyl *p*-bromobenzenesulfonate are in the limiting category, or very nearly so. The cases of the ethyl, isopropyl and benzyl compounds belong to the **N** category in the aqueous alcohols, but some of these such as isopropyl *p*-bromobenzenesulfonate or bromide may approach the **Lim.** category in acetic acid and more closely in formic acid. The solvolyses of such substances as the ethyl compounds, with large ratios $k_{\text{ROH}}/k_{\text{RCOOH}}$, are far from limiting in acetic acid and probably are not limiting even in formic acid.

Intermediates.—On the present basis, a solvolysis reaction may belong in the **N** category and still give evidence of an intermediate. For example, there is some evidence of a mass-law effect even in the case of isopropyl bromide.[20] Moreover, steric results of solvolysis of substances kinetically similar to isopropyl derivatives, such as 2-octyl bromide or toluenesulfonate, afford evidence for an intermediate. Due to the considerable resonance energy represented by structures I–III, it is possible that substitution should be regarded as proceeding by way of an intermediate even when no kinetic or stereochemical evidence is apparent. It is interesting in this connection that calculations of potential energy surfaces for displacements in general (*e. g.*, reaction of H atom with CH_4 or H atom with H_2), usually indicate metastable intermediates.[38]

Just as there is no sharp boundary between the **N** and **Lim.** mechanistic categories, so there is no sharp distinction between the intermediates from these solvolyses. The first intermediate or ion-pair[6,39] in the solvolysis of the **Lim.** cases may nevertheless have some covalent character to the interaction between a solvent molecule and the central carbon atom, and between the central carbon atom and the leaving group. As the central carbon atom flattens, the approach of a solvent molecule to within the Van der Waals distance[7] can be close enough to give appreciable covalent character to the interaction in question. From the above viewpoint, the stereochemical result of solvolysis is determined by the relative amounts of product formed before and after the first intermediate has become symmetrically solvated. Closely equivalent discussions have been given previously by Hughes and Ingold[40] on the basis of "shielding" of the cation by the leaving group, by Hammett,[11] and more recently by Swain.[13]

Effect of Structure on Solvolysis Rate.—The extensive discussions of Hughes and Ingold in connection with S_N1 apply directly to the question of the effect of structure on rates by the **Lim.** type process. The question of quantitative effect of α-methyl substitution is still difficult. Hughes and Ingold have estimated a factor of 10^4 per methyl group from work in 80% ethanol[3] and we have used a larger tentative figure previously.[41] The factor of 10^4 is too low since the isopropyl case is not in the **Lim.** category in 80% ethanol. We shall not summarize here the data in this connection but merely indicate that the factor is well over 10^4.

It has long been realized that for S_N2 rates the effect of substituents on R is difficult to predict,[11a,19] and that in the S_N2–S_N1 transition region, cases of S_N2 reaction can show the same qualitative effects of structure on rate[19,20,21] as are characteristic of S_N1. In terms of the valence-bond structures I–III, it is clear that as the contribution of structure III to the **N** transition state becomes more important and the R portion of the transition state becomes more positive, the variation of rate with structure (and perhaps solvent) can become qualitatively similar to that of the **Lim.** process. The allyl structure is a favorable one to demonstrate this point.[26]

Small ring closures likewise furnish good examples of the above dependence of **N** rates on structure, partly because steric hindrance has been much demoted in importance.[10,41,42] Similarly, many openings in the so-called "abnormal direction" of ethylene oxides,[43] immonium ions, sulfonium ions, bromonium ions, etc., include examples of **N** processes whose rate is enhanced by α-alkyl or phenyl substitution.

For illustration of the way a change of solvent can bring out this kind of dependence of **N** solvolysis rate on structure, the rate sequence MeBr: EtBr:*i*-PrBr is instructive. At 50.0° the relative solvolysis rates are 1:0.37:0.28 in ethanol, 1:0.39:0.54 in 80% ethanol, and 1:1.08:11 in water. The order changes from a descending one in ethanol to one with a minimum in 80% ethanol and then to an ascending one in water as the ionizing power of the solvent increases.

Experimental

Materials.—Ethyl bromide, b.p. 37.9–38.1° (759 mm.), and isopropyl bromide, b.p. 59.2–59.4° (762 mm.) were Eastman Kodak Co. "white label" reagents and were dried and fractionated before use.

Benzyl chloride, b.p. 37° (1.8 mm.), $n^{20}\text{D}$ 1.5390 was Baker C.P. material and was dried and fractionated before use.

Methyl bromide was obtained from the Matheson Co., East Rutherford, N. J., and was reported to be at least 99.4% pure, the chief impurity being moisture. This material was distilled through a calcium sulfate drying tube into the solvent immediately preceding rate measurement.

Ethyl *p*-toluenesulfonate and benzyl *p*-toluenesulfonate were prepared by the method of Tipson[44] and recrystallized from petroleum ether (b.p. 65–75°). Yields, melting points and equivalent weights were as follows: ethyl *p*-toluenesulfonate, 72%, 33.1°, 200.4 (calcd. 200.3); benzyl *p*-toluenesulfonate, 38%, 57.8°, 264.3 (calcd. 262.3).

trans-2-Bromocyclohexyl *p*-bromobenzenesulfonate, m.p. 92.6–93.2°, and *trans*-2-methoxycyclohexyl *p*-bromobenzenesulfonate, m.p. 65.4–66.2°, have been described previously[27] and were recrystallized before use.

Solvents.—Water was redistilled from alkaline permanganate in an all-glass still protected from carbon dioxide.

Commercial absolute ethanol was dried by the ethyl phthalate method.[45] It was stored in large glass bottles equipped with syphons and protected by soda lime or Ascar-

---

[38] Glasstone, Laidler and Eyring, "The Theory of Rate Processes," McGraw-Hill Book Co., Inc., New York, N. Y., 1941, Chapter 3.

[39] Return of this first intermediate to original R—X is called "internal return"—different from the "mass law effect" or "external return" (see Young, Winstein and Goering, THIS JOURNAL, **73**, 1958 (1951)).

[40] Cowdrey, Hughes, Ingold, Masterman and Scott, *J. Chem. Soc.*, 1252 (1937).

[41] Grunwald and Winstein, THIS JOURNAL, **70**, 841 (1948).

[42] Lindegren, Ph.D. Thesis, U. C. L. A., 1950.

[43] See *e.g.*, Winstein and Henderson, "Ethylene and Trimethylene Oxides," in Elderfield, "Heterocyclic Compounds," Vol. I, John Wiley and Sons, Inc., New York, N. Y., 1949.

[44] Tipson, *J. Org. Chem.*, **9**, 235 (1944).

[45] Fieser, "Experiments in Organic Chemistry," The Macmillan Company, New York, N. Y., 1937, pp. 359, 360, 368.

ite. The water content was checked periodically by Robertson's paraffin oil test[46] and did not increase on storage. One batch of solvent was analyzed for water by the Karl Fischer method[47] one month after preparation and contained less than 0.005% water.

Commercial synthetic methanol was dried with magnesium.[45] The dried solvent contained less than 0.05% water by the miscibility temperature with cyclohexane.[48] In some experiments the commercial product was used without further treatment. This untreated solvent contained 0.12 weight % of water as determined by the Karl Fischer method.[47]

Mixed solvents were prepared from the pure components gravimetrically or volumetrically at 25.0°. X per cent. ethanol is the solvent obtained by adding X volumes of ethanol to 100 − X volumes of water at 25.0°.

Acetic acid containing 0.20 weight % of acetic anhydride was prepared from commercial reagent grade chemicals and analyzed for acetic anhydride by Kilpi's method.[27,49]

Methods of Rate Measurement.—Rates were measured by the usual sealed ampoule technique. Thermostats were of conventional design and maintained the temperature within 0.05°. Thermometers were calibrated by the National Bureau of Standards, and temperature readings were probably accurate to better than ±0.05°.

Reaction mixtures were usually prepared from a known weight of solute and from solvent, either volumetrically or gravimetrically. In the case of the volatile alkyl bromides and of benzyl *p*-toluenesulfonate for which the rate of solution was slow compared to the rate of reaction, initial concentrations were derived from "infinity" titers. For methyl bromide, "infinity" titers were identical within experimental error by treatment with strong alkali followed by argentometric determination of bromide, by treatment with a known excess of alkali and measurement of the decrease in alkali titer, and by addition of more than 50% water and measurement of the acid produced in quantitative solvolysis at 110 and 50°. For the other bromides "infinity" titers were measured by quantitative solvolysis of aliquots of the reaction mixtures to which enough water had been added to produce a medium containing at least 50% water. The addition of water was necessary and sufficient to prevent reaction of the hydrogen bromide produced in the solvolysis with the alcohol component of the solvent.

Reactions were followed to about 75% completion, and initial concentrations were checked by "infinity" titers wherever this was feasible.

In the case of volatile solutes, reaction mixtures were delivered into ampoules from separatory funnels, and the vapor space in the ampoules was kept at less than 5% of the total volume. With these precautions the precision of the rate measurements was satisfactory even when the solvent was water.

Methods of Analysis.—Reactions were followed by withdrawing ampoules from the thermostat at suitable intervals and titrating 5- or 10-ml. aliquots of the reaction mixtures with 0.02–0.05 *N* reagents from 5-ml. microburets.

The reactions of benzyl chloride were followed by mercurometric determination of chloride, using *s*-diphenylcarbazide indicator.[50] The reactions were arrested by dilution with purified[45] dioxane containing nitric acid. A preliminary run enabled estimation of the amount of nitric acid necessary to have the optimum acidity (0.01 *N*) for precision and accuracy at the end-point. Using reprecipitated reagent grade yellow mercuric oxide and correcting for a titration blank we were able to determine chloride by this method with an accuracy of 0.5%. The determination was not affected by the presence of benzyl chloride.

Solvolysis rates for the other compounds were determined acidimetrically. When acetic acid was the solvent, titrations were done with standard sodium acetate in acetic acid using brom phenol blue as indicator.[27] In the solvent system ethanol–methanol–water, the titrating reagent was standard carbonate-free alkali in partly aqueous ethanol (the solvent composition of the alkali reagent varied during the course of the work but was not critical), and the indicators were methyl red, brom thymol blue and phenolphthalein.

Details of Reaction Kinetics.—With the exception of the cases discussed below the kinetics of solvolysis were first order within experimental error over the ranges investigated. There was some indication that the first-order specific rates dropped slightly as the initial concentration of reagent was increased—in agreement with previous observation[51]—but the changes were within experimental error for the concentration ranges employed.

The kinetics of solvolysis of the halides in ethanol and methanol were complicated by the reaction with solvent of the hydrogen halide product.[30] First-order rate constants drifted downward as the reaction progressed, and it was necessary to evaluate initial rates. It was observed, as previously,[30] that a plot of rate constant *vs.* the square of the hydrogen halide concentration was approximately linear during the early stages of reaction; a least squares extrapolation gave the initial rate. The effect and the extrapolation method have been illustrated for the ethanolysis of ethyl bromide.[30]

The solvolysis of *trans*-2-bromocyclohexyl *p*-bromobenzenesulfonate proceeds to yield *p*-bromobenzenesulfonic acid and bromine-containing products which may solvolyze further. In ethanol, methanol, acetic acid and 50% ethanol this second reaction was slow enough to be negligible. In these solvents the acid titers after 9 half-lives were at most 8% high, and deviations from first-order kinetics during the first 50% reaction were not detectable. In 80% ethanol, the acid titer after 19 half-lives was 32% high, and first-order rate constants drifted upward by 10% during the first 50% reaction. The upward drift of the rate constants was independent of the initial concentration of reagent, indicating the consecutive reactions were of the first order. Initial specific rates were obtained by extrapolation to zero time.

Acknowledgment.—It is a pleasure to acknowledge helpful discussion of the material of this paper with Drs. L. P. Hammett, P. D. Bartlett and C. Gardner Swain.

LOS ANGELES 24, CALIF. RECEIVED OCTOBER 26, 1950

---

(46) Robertson, "Laboratory Practice of Organic Chemistry," The Macmillan Co., New York, N. Y., 1943, p. 177.

(47) (a) Fischer, *Angew. Chem.*, **48**, 394 (1935); (b) Smith, Bryant and Mitchell, THIS JOURNAL, **61**, 2407 (1939).

(48) Jones and Amstell, *J. Chem. Soc.*, 1321 (1930).

(49) Kilpi, *Suomen Kemistilehti*, **13B**, 19 (1940); *C. A.*, **35**, 2445 (1941).

(50) (a) Roberts, *Ind. Eng. Chem., Anal. Ed.*, **8**, 365 (1936); (b) McCleary, *ibid.*, **14**, 31 (1942).

(51) (a) Beste and Hammett, THIS JOURNAL, **62**, 2481 (1940); (b) McCleary and Hammett, *ibid.*, **63**, 2254 (1941).