well be of significance in enzymic catalysis where arginines are present at the active site.[34]

Supplementary Material Available. A listing of structure factor

(34) M. Legg and T. LaCour in this laboratory have obtained preliminary results which indicate that guanidinium ions affect, but decrease, the rate of hydrolysis of p-nitrophenyl phosphate in alkaline ethanol–water solutions. We also have evidence that a two guanidinium–one ester complex forms in these solutions.

amplitudes and Tables VII–IX will appear following these pages in the microfilm edition of this volume of the journal. Photocopies of the supplementary material from this paper only or microfiche (105 × 148 mm, 24× reduction, negatives) containing all of the supplementary material for the papers in this issue may be obtained from the Journals Department, American Chemical Society, 1155 16th St., N.W., Washington, D. C. 20036. Remit check or money order for $3.00 for photocopy or $2.00 for microfiche, referring to code number JACS-74-4471.

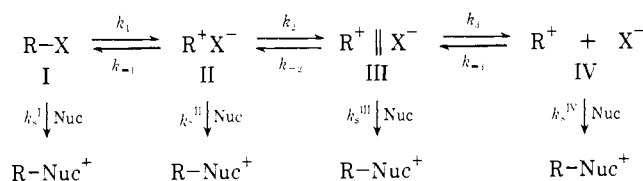# Stability–Selectivity Relationships for Solvolytic Displacement Reactions[1]

J. Milton Harris,[*2] Donald C. Clark, Allyn Becker, and James F. Fagan

Contribution from the Department of Chemistry, California State University— Fullerton, Fullerton, California 92634. Received December 10, 1973

Abstract: A general theory incorporating concepts of ion pairing is presented for the origin of stability–selectivity relationships for solvolytic displacement reactions on alkyl derivatives. It is concluded from a study of alkyl chloride ethanolysis and examination of previous work that these relationships result from a blending of selectivities for attack on neutral substrate (I), tight ion pair (II), solvent-separated ion pair (III), and free cation (IV); the selectivities for attack on all of these species except solvent-separated ion pair are indicated to be constant despite changes in stability. The effect of a change in intermediate stability is to shift the equilibria between I, II, III, and IV and to change the selectivity of III if it is involved. The possibility of solvent sorting about transient carbocation intermediates is also considered and concluded to be unimportant for alkyl chlorides in aqueous ethanol.

It is generally recognized that an increase in stability of an intermediate produces an increase in selectivity of the intermediate.[3–5] Despite the apparent simplicity of this principle, the origin of stability–selectivity relationships for solvolytic reactions of alkyl esters and halides is poorly understood.[6,7] This difficulty is primarily due to the involvement in solvolysis reactions of more than one type of intermediate. Recent works have shown the solvolysis reaction to be best described as in Scheme I.[5,7–14] The various species I, II, III, and IV represent neutral substrate, tight ion pair, solvent-separated ion pair, and free carbocation, respectively. Actually, there is evidence for the importance of even more ion-pair intermediates than those shown in Scheme I (*e.g.*, nucleophilically solvated

(1) A preliminary account of this work has appeared in communication form: J. M. Harris, A. Becker, D. C. Clark, J. F. Fagan, and S. L. Kennan, *Tetrahedron Lett.*, 3813 (1973).
(2) Address correspondence to this author at the Department of Chemistry, University of Alabama–Huntsville, Huntsville, Ala. 35807.
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(4) R. A. Sneen, J. V. Carter, and P. S. Kay, *J. Amer. Chem. Soc.*, 88, 2594 (1966).
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(6) C. D. Ritchie, *J. Amer. Chem. Soc.*, 93, 7324 (1971).
(7) C. D. Ritchie, *Accounts Chem. Res.*, 5, 348 (1972).
(8) S. Winstein, B. Appel, R. Baker, and A. Diaz, *Chem. Soc., Spec. Publ.*, No. 19, 109 (1965).
(9) D. J. Raber, J. M. Harris, and P. v. R. Schleyer in "Ion Pairs," M. Szwarc, Ed., Wiley, New York, N. Y., in press.
(10) R. A. Sneen, *Accounts Chem. Res.*, 6, 46 (1973).
(11) J. M. Harris, *Progr. Phys. Org. Chem.*, 11, 89 (1974).
(12) V. J. Shiner, Jr., and R. D. Fisher, *J. Amer. Chem. Soc.*, 93, 2553 (1971).
(13) H. L. Goering and H. Hopf, *J. Amer. Chem. Soc.*, 93, 1224 (1971).
(14) (a) C. D. Ritchie in "Solute-Solvent Interaction," J. F. Coetzee and C. D. Ritchie, Ed., Marcel Dekker, New York, N. Y., 1969, Chapter 4. (b) F. G. Bordwell, *Accounts Chem. Res.*, 5, 374 (1972).

Scheme I

$$R-X \underset{k_{-1}}{\overset{k_1}{\rightleftharpoons}} R^+X^- \underset{k_{-2}}{\overset{k_2}{\rightleftharpoons}} R^+ \| X^- \underset{k_{-3}}{\overset{k_3}{\rightleftharpoons}} R^+ + X^-$$
$$\text{I} \qquad\qquad \text{II} \qquad\qquad \text{III} \qquad\qquad \text{IV}$$

$$\downarrow k_s^I\,|\,\text{Nuc} \qquad \downarrow k_s^{II}\,|\,\text{Nuc} \qquad \downarrow k_s^{III}\,|\,\text{Nuc} \qquad \downarrow k_s^{IV}\,|\,\text{Nuc}$$

$$\text{R-Nuc}^+ \qquad \text{R-Nuc}^+ \qquad \text{R-Nuc}^+ \qquad \text{R-Nuc}^+$$

ion pairs).[11,14b] Scheme I therefore represents the simplest possible combination. If these intermediates are involved, observed selectivities will be a blend of selectivities for attack on each of the intermediates.

Sneen[4] and Schleyer[5] have demonstrated the occurrence of stability–selectivity relationships for azide and water attack on intermediates from the solvolysis of alkyl halides.[4,5] Sneen[4] considered the intermediates for his series of compounds to be free carbocations; actually, as we will discuss in the following sections, there is extensive evidence that many of these compounds lead to products by nucleophilic attack on solvent-separated ion pairs. Schleyer and his coworkers[5] did not specify the exact nature of the intermediates for their series, but many of the compounds included were also included on Sneen's plot.

Ritchie has recently made the suggestion that stability–selectivity relationships for solvolytic reactions are determined by a blending of selectivities for solvent-separated ion pair (III) and free carbocation (IV) but details of the hypothesis were not given.[6] Ritchie has also shown the selectivity of triarylmethyl, tropylium, and aryldiazonium cations to be independent of stability.[7] This remarkable observation emphasizes the inadequacies of the present ill-defined theories of the relationship between stability and selectivity.

The purpose of this article is to present a theory for

Table I. Rates and Products for the Solvolysis of a Series of Alkyl Chlorides in 70% (v/v) Ethanol

| Chloride	k, sec^{-1} (25°) (80% acetone)[a]	ROEt/ROH[b] (70% ethanol)[a]	Log k_E/k_W[c]
p,p'-Dimethylbenzhydryl[d]	2.70 × 10^{-2}	13.5 ± 2.9 (25°)[e]	1.04
p-Methylbenzhydryl	1.57 × 10^{-3}	5.09 ± 0.62 (25°)	0.84
Benzhydryl[d]	7.25 × 10^{-5}	3.5 ± 0.1 (25°)	0.70
p-Chlorobenzhydryl[d]	2.31 × 10^{-5}	5.8 ± 0.3 (25°)	0.90
p,p'-Dichlorobenzhydryl	1.45 × 10^{-5}	0.550 ± 0.078 (75°)	−0.35
α-Phenylethyl	6.08 × 10^{-7}	1.48 ± 0.02 (50°)	0.31
α-(p-Chlorophenyl)ethyl	1.81 × 10^{-7}	1.47 ± 0.005 (50°)	0.31
exo-2-Norbornyl[d]	7.00 × 10^{-9}	0.60 ± 0.01 (100, 125, 150°)	−0.079
1-Adamantyl[d]	1.10 × 10^{-9}	0.41 ± 0.01 (100, 125, 150°)	−0.25
2-Adamantyl[d]	5.30 × 10^{-13}	0.12 ± 0.01 (200°)	−0.80

[a] Volume per cent in water. [b] Determined by vpc and the result of five or more measurements. Substrate was 0.01 M with 0.012 M pyridine. [c] Derived from $k_E[C_2H_5OH]/k_W[H_2O] = ROEt/ROH$. [d] Rate taken from ref 5. [e] Determined in 80% ethanol.

the relationship between stability and selectivity for solvolysis reactions which is consistent with the ion pair scheme (Scheme I), and also to consider use of this theory for the study of ion pairing. The previously observed stability–selectivity relationships and our own are taken from studies in binary solvents in which solvent sorting (solvent shells about the intermediates of composition other than that of the bulk solvent) may be a complicating factor; this possibility is also considered.

Results and Discussion

Solvent Sorting about Reactive Intermediates. Previous selectivity studies of carbocation intermediates have utilized the azide ion and water as competing nucleophiles.[4–6] Azide ion is a much more effective nucleophile than water[15] and as a consequence the amount of alkyl azide formed can sometimes be much greater than the amount of alcohol formed. We therefore decided to use a solvent system (aqueous ethanol) in which the solvent components themselves act as nucleophiles. This choice introduces difficulties in that it becomes necessary to consider the operation of solvent sorting about the solvolytic intermediates, but it also introduces the prospect that the stability–selectivity relationship in binary nucleophilic solvents may be a useful probe into the solvation process.

Partitioning between the two product forming pathways in eq 1 will be governed by the relative nucleo-

$$R-X \rightleftharpoons [Inter] \begin{array}{c} \xrightarrow{\text{EtOH}} ROEt \\ \xrightarrow{\text{H}_2O} ROH \end{array} \quad (1)$$
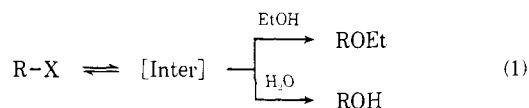
philicities of ethanol and water, by the relative amounts of ethanol and water in the solvent shell about the intermediate, and, as we discuss below, possibly by the stability of the intermediate and the identity of the leaving group. If solvent shell composition about a series of intermediates varies, it will become quite difficult to interpret any effects of substrate variation on product ratios in terms of ion pairing.

In order to test for the operation of solvent sorting about solvolytic intermediates in aqueous ethanol, we have determined the solvolysis rates in aqueous acetone and the substitution products in aqueous ethanol for a series of alkyl chlorides generally recognized[4,5] as solvolyzing without nucleophilic solvent assistance
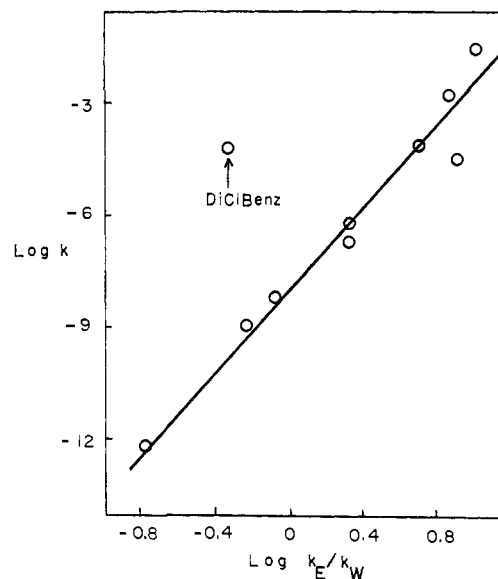

Figure 1. Log k vs. k_E/k_W for alkyl chlorides in 70% (v/v) aqueous ethanol.

(Table I). Solvolysis rates in aqueous acetone were used rather than those in aqueous ethanol because many of the rates in acetone were available from the literature.[4,5] Relative rates in any solvent would be suitable for providing a measure of intermediate stability (below). All products were shown to be stable to the reaction conditions. A plot of log k (80% acetone) against log k_E/k_W (determined from eq 2) yields a fair linear rela-

$$k_E[EtOH]/k_W[H_2O] = ROEt/ROH \quad (2)$$

tionship with only one point (p,p'-dichlorobenzhydryl) deviating significantly (Figure 1). Most of these alkyl chlorides were included in the stability–selectivity plots of Sneen[4] and Schleyer.[5]

Before proceeding, we should point out that the log of solvolysis rate is only a fair measure of intermediate stability. First, ion-pair return may be of variable importance for different substrates, although the use of aqueous ethanol does minimize return.[16,17] Also, it has been noted that a single cation intermediate may be generated at different rates from isomeric alkyl chlorides.[5] Finally, rates and equilibria for carbocation formation and return to neutral substrate (eq

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(16) D. J. Raber, J. M. Harris, and P. v. R. Schleyer, *J. Amer. Chem. Soc.*, **93**, 4829 (1971).

(17) S. Winstein and T. C. Schreiber, *J. Amer. Chem. Soc.*, **74**, 2171 (1952).

3) have been determined for triarylmethyl derivatives,

$$R^+ + H_2O \underset{k_r}{\overset{k_f}{\rightleftharpoons}} ROH + H^+ \qquad (3)$$
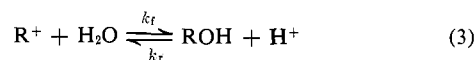
and a direct relationship between rates and equilibria is not observed.[7,18] The rate variation of 10^{11} for the compounds in our study is sufficient to minimize such effects, and we are of the opinion that solvolysis rate is a sufficiently accurate measure of intermediate stability for the present work.

Many years ago, Debye[19] considered the possibility that solvation of a substance in a binary solvent could take place such that the component which best solvates the species will occur in greater than bulk concentration in the solvent shell about this substance. Over the intervening years this phenomenon of solvent sorting or selective solvation has been clearly demonstrated to be important by use of various electrochemical and spectroscopic techniques.[20,21] All of these studies were conducted with stable species which were primarily salts. It is of interest, therefore, to question the importance of solvent sorting about a short-lived intermediate. Some of the unusual aspects of diazonium ion decompositions, for example, have been postulated to be due to reaction of the intermediate carbocation before the solvent shell has had time to "relax" to the most stable state about the cation.[22] Is the usual solvolytic intermediate also so reactive as to react before the solvent molecules about it have had time to reargange completely? Solvent reorganization is estimated to occur with a rate constant of no less than 10^{10} sec^{-1}.[14,22,23] Exchange of solvent molecules between bulk solvent and the solvent shell has been estimated to have a rate constant of 10^9–10^{11} sec^{-1} (for H$_2$O hydrogen bonded to an amine).[24] Winstein, Baker, and Smith have estimated the rate constant for nucleophilic destruction of the solvent-separated ion pair V to be between 10^8 and 10^4 sec^{-1} depending on the solvent involved.[25] Thus it would seem reasonable to expect the lifetime of a solvolytic intermediate to be sufficient to permit solvent shell reorganization and composition changes. However, this prediction is certainly a tenuous one, dependent on both the solvent and substrate involved. Intermediate V is certainly much more stable than that for the 2-adamantyl cation, for example, and the 2-adamantyl cation might then react faster than 10^8 sec^{-1}; that is, at a rate comparable with that postulated for solvent reorganization. Also, rates of changes in solvent shell composition could vary significantly as a function of solute and solvent.

Solvent reorganization is indicated by several research groups to occur upon activation in the solvolysis process; indeed, solvent reorganization may be the major contributor to the free energy of activation for

V, X = p-bromobenzenenesulfonate

these reactions.[7,26–31] Indications of ground-state solvent shell reorganization are at least consistent with possible solvent sorting about a solvolytic intermediate.

Referring to Figure 1, an increase in solvolytic rate (intermediate stability) produces a corresponding increase in the amount of ether product as expected on the basis of the greater nucleophilicity of ethanol compared with water.[15] The observation of a correlation between intermediate stability and selectivity in ethanol–water indicates the composition of the solvent shells about the intermediate (or intermediates—see below) must be either a constant or changing linearly with intermediate stability.

Hyne and his coworkers[32] have proposed that the frequently observed minimum through which solvolytic activation energies pass as binary solvent composition is varied is due to the ability of the polar transition state to select a solvent shell containing a higher composition of water.[33] It was also proposed that the degree of this solvent specificity should be proportional to the extent of charge development in the transition state. For the present work this would mean a linear relationship might be expected between log k (and the corresponding trend in positive charge dispersal) and solvent shell composition. We reject this interpretation for several reasons. First, our substrates vary greatly in size and type (aromatic and saturated) and these factors, particularly size, have been shown to be of major importance in determining solute–solvent interactions.[34,35] It would be difficult to imagine a steady variation in solvent shell composition along a series of compounds differing randomly in size and type. Additionally, thermal energy has been clearly recognized as a randomizing force on solvent shell specificity.[26] Our reactions were carried out at several different temperatures (Table I) with no measurable effect on the product ratios. If solvent sorting is occurring about an intermediate, an increase in temperature should produce a trend toward a solvent shell equal in composition to the bulk solvent and also lead to a change in product ratios. Finally, the Hyne theory predicts that an in-

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(19) P. Debye, Z. Phys. Chem. (Leipzig), 130, 56 (1927).

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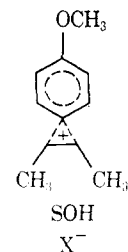
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(26) R. E. Robertson, Progr. Phys. Org. Chem., 4, 213 (1967).

(27) P. M. Laughton and R. E. Robertson in ref 14a, Chapter 7.

(28) C. D. Ritchie, G. A. Skinner, and V. G. Badding, J. Amer. Chem. Soc., 89, 2063 (1967).

(29) D. N. Glew and E. A. Moelwyn-Hughes, Proc. Roy. Soc., Ser. A, 211, 254 (1952).

(30) M. J. S. Dewar, 23rd National Organic Chemistry Symposium, Tallahassee, Fla., June, 1973.

(31) R. C. Dougherty and J. D. Roberts, Org. Mass Spectrom., 8, 81 (1974).

(32) J. B. Hyne, R. Wills, and R. E. Wonka, J. Amer. Chem. Soc., 84, 2914 (1962).

(33) This argument has been opposed by Arnett and his coworkers[34] who have shown the minimum to be due to ground-state destabilization.

(34) (a) E. M. Arnett, W. G. Bentrude, J. J. Burke, and P. McC. Duggleby, J. Amer. Chem. Soc., 87, 1541 (1965); (b) E. M. Arnett, P. McC. Duggleby, and J. J. Burke, ibid., 85, 1350 (1963).

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crease in log k should result in an increased preference for water in the solvent shell. Our results show an increase in log k gives more ether product not more alcohol. These substrate and temperature variations eliminate the possibility of a trend in solvent shell composition, but they do not remove the possibility of nonlinear or random solvent sorting (e.g., all saturated compounds having one solvent shell different from that for all aromatics) which would destroy the stability–selectivity relationship.

The lack of dependence of product ratios on reaction temperature is also inconsistent with the occurrence of one solvent shell different from the bulk solvent composition for all the substrates. Rather, the temperature independence is most consistent with a solvent shell about the intermediates which is identical in composition to the bulk solvent. It also seems probable, therefore, that ethanol–water solvent shells about these neutral substrates are equal in composition to the bulk solvent.[36] The deviation of the p,p-dichlorobenzhydryl substrate may be the result of solvent sorting; future work will be designed to examine this point.

As Schleyer and his coworkers have noted,[5] examination of a series of intermediates which become progressively less stable should reveal a flattening of the stability–selectivity plot at that point at which the intermediates become so reactive as to be unselective; that is the stability–selectivity plot should show a slope of zero (constant selectivity of unity) in the lower reactivity region. Our plot (Figure 1), and Sneen's[4] and Schleyer's,[5] show no indication of approaching a limiting selectivity value. In fact, the selectivities in Figure 1 continue monotonously into the region below unity. Selectivities of less than unity could be explained as due to solvent sorting; however, it is our opinion that this result derives from the nature of the stability–selectivity relationship for carbocation intermediates (next section).

Solvent sorting is known to be important about stable salts (see above). How then can the lack of solvent sorting about ionic intermediates in aqueous ethanol be rationalized? It is possible that our estimates of the times required for solvent composition changes and for reaction of solvolytic intermediates are grossly in error; if there is no solvent sorting about the neutral ground states, then there simply may not be enough time for a change in solvent composition about the intermediates, and all reactions may occur with a solvent shell identical in composition with the bulk solvent. Future research will be directed toward examination of this possibility. Also we plan to investigate solvent systems in which the components differ more than ethanol and water.

In any event, the above considerations indicate that the stability–selectivity relationship for alkyl halides in aqueous ethanol can be explored without interference from solvent sorting.

Ion Pairing and the Stability–Selectivity Relationship. The simplest possible explanation of a stability–selectivity relationship for solvolysis reactions must be

stated in terms of a blend of selectivities for the four species in Scheme I, I–IV. In this section we utilize available experimental data and the ion-pair scheme to derive a theory for the origin of these stability–selectivity relationships.

Any observed selectivity can potentially be composed of four terms, eq 4, where a_i represents the fraction of

$$S_{\text{obsd}} = \sum_i a_i S_i, \qquad i = \text{I–IV} \qquad (4)$$

$$S_i = \log (k_E/k_W)_i \qquad (5)$$

products from attack on species i. A general theory of selectivity can be expressed in terms of eq 4 if it is assumed that each S_i varies according to the stability of i.

As noted earlier, Ritchie has observed constant selectivities, irrespective of stability changes, for certain free carbocations.[7] This observation was rationalized on the basis that desolvation of the involved nucleophile controls reaction with that nucleophile. Since desolvation of the nucleophile should be the same for each nucleophile, regardless of the cation, constant selectivities are observed. Although every cation shows a single selectivity toward any pair of nucleophiles, the different cations do react at significantly different rates with each nucleophile. For example, the ratios of the rate constants for reaction of azide and cyanide anions with tri-(p-anisyl)methyl cation and with trityl cation are essentially constant, yet the trityl cation is by far the most reactive. This difference in cationic reactivity despite constant selectivities remains unexplained.

Nucleophilic displacement reactions on primary alkyl derivatives also show a near constant selectivity independent of leaving-group variation if leaving groups are examined which are bonded to the central carbon by means of the same atom (e.g., esters); the data in Table II are taken from the work of Koskikallio[38] and show

Table II. Relative Rates for Attack of Nucleophiles on Methyl Esters in Water[d]

| Nucleophile | Log $k/k_{\text{H}_2\text{O}}$ | | |
	$CH_3OSO_2C_6H_5$ $(25°)^a$	CH_3ONO_2 $(90°)^b$	CH_3OClO_3 $(0°)^c$
SO_3^{2-}	5.335	4.744	4.737
$S_2O_3^{2-}$	5.165	5.140	5.233
PO_4^{3-}	4.375	4.233	4.226
CO_3^{2-}	3.702	3.637	3.632
SCN^-	3.500	3.819	3.683
NO_2^-	3.271	3.227	3.093
HPO_4^{2-}	2.947	2.945	2.938
Br^-	2.563	2.793	2.786
CH_3COO^-	2.327	2.203	2.296
Cl^-	2.009	1.734	1.727
H_2O	0	0	0

[a] Log $k_{\text{H}_2\text{O}} = -6.69$. [b] Log $k_{\text{H}_2\text{O}} = -6.633$. [c] Log $k_{\text{H}_2\text{O}} = -6.048$. [d] Reference 38.

an almost constant selectivity for methyl esters which differ in reactivity by four powers of ten (nitrate–benzenesulfonate–perchlorate rate ratios for attack by hydroxide at 25° are 1:249:13,000). As discussed earlier, the necessity for solvent reorganization upon activation is indicated to be a major contributor to activation energy for nucleophilic attack on cationic intermediates. Similarly, semiempirical calculations by

(36) Cocivera[37] has reached a similar conclusion concerning the identity of solvent shells for the ground state and transition state of the SN2 solvolysis of 2-propyl tosylate. This conclusion was based on the temperature independence of product composition.

(37) M. Cocivera, Ph.D. Thesis, University of California, Los Angeles, Calif., 1963.

(38) J. Koskikallio, Acta Chem. Scand., 26, 1201 (1972).

Dewar[30] show the pentavalent transition state for chloride ion plus methyl chloride to be more stable than the isolated reactants. Mass spectral studies by Dougherty[31] confirm Dewar's calculations. If the transition state for a displacement reaction is actually more stable than the isolated reactants, the energy required for solvent reorganization must be a major contributor to the activation energy for this reaction type also. If this conclusion is correct, constant selectivities for displacement reactions can be explained in the same manner as Ritchie explained constant selectivities for cation–nucleophile combinations: desolvation of the nucleophile is the controlling factor. Comparisons of protic and dipolar–aprotic solvent effects on S_N2 reactions also illustrate the importance of nucleophile desolvation.[35] Nucleophilic displacement on a neutral substrate or on a tight ion pair differs from cation–nucleophile combination in that a leaving group (usually charged) is expelled in the displacement reaction; this factor accounts for the necessity of considering similar leaving groups (e.g., all esters rather than a series of halides) since solvation of the negative end of the dipolar S_N2 transition state must remain approximately constant.

There is some debate whether nucleophilic displacement reactions take place on neutral substrate (I) or on tight ion pair (II) since the two processes respond almost identically with most mechanistic probes.[9-11] In view of this similarity of processes for nucleophilic attack on I and II, we consider the observation of constant selectivities for nucleophilic displacement on methyl esters to indicate that both S_I and S_{II} are constant. This result, combined with Ritchie's observation of constant S_{IV}, suggests a formulation for the origin of the stability–selectivity relationship in which selectivity for attack on any species is a constant, K_i, irrespective of changes in stability, eq 6–8. If this postulate is correct the stability–selectivity relationship must result

$$S_{obsd} = \sum_i a_i S_i \qquad i = \text{I–IV} \qquad (6)$$

$$S_i = K_i \qquad i = \text{I–IV} \qquad (7)$$

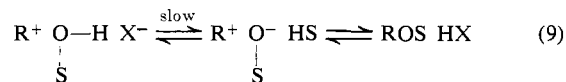$$K_i \neq K_j \qquad i \neq j \qquad (8)$$

because of a shift on the ion-pair spectrum (Scheme I) with stability and a consequent blending of selectivities.

In the following sections we will attempt to determine if these theories for the origin of stability–selectivity relationships can be used to treat our experimental results. But first, we must consider two aspects of the stability–selectivity relationship, first pointed out by Ritchie,[6,7,39] which can make interpretation of these relationships difficult. Ritchie has shown that concentration of trapping agents can affect observed selectivity if products are derived from two species.[6,7] If the steady-state equations are solved for such an equilibrium, the relative steady-state concentrations of the two intermediates are shown to be dependent on concentrations of the nucleophiles. Ritchie has demonstrated this effect for attack by azide ion and water on the solvolytic intermediates of di(p-anisyl)methyl mesitoate in 80% acetone.[6,7] Each of our systems was studied at constant nucleophile concentrations so that relative steady-state concentrations will not be affected.
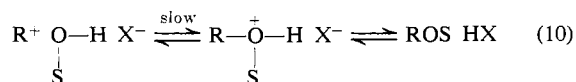
Ritchie has also shown that nucleophilic solvent at-

(39) C. D. Ritchie, J. Amer. Chem. Soc., 94, 3275 (1972).

tack on a triarylmethyl cation is subject to general base catalysis, eq 9.[7,39] If this mechanism also obtains in the systems we have studied, the measured selectivities may be due to relative facilities of proton transfer for ethanol and water rather than to the relative nucleophilicities of ethanol and water. Viewing eq 9 in reverse shows the

$$R^+ \; \underset{\underset{S}{|}}{O}\text{—H} \; X^- \xrightleftharpoons{\text{slow}} R^+ \; \underset{\underset{S}{|}}{O^-} \; HS \rightleftharpoons ROS \; HX \qquad (9)$$

acid-catalyzed heterolysis of an alcohol (S = H) to proceed by rapid cleavage of an O–H bond followed by slow proton transfer. While this mechanism may operate for triarylmethyl species, we question its importance for the relatively poor carbocation precursors of our experiments; for these latter species we suggest that cation–solvent combination is specific based catalyzed, eq 10. In any event, if formation of the

$$R^+ \; \underset{\underset{S}{|}}{O}\text{—H} \; X^- \xrightleftharpoons{\text{slow}} R\text{—}\overset{+}{\underset{\underset{S}{|}}{O}}\text{—H} \; X^- \rightleftharpoons ROS \; HX \qquad (10)$$

intermediate is rate determining, details of the destruction pathway are not important to the present interpretation.

Alkyl Chlorides. The alkyl chlorides in Figure 1 are indicated by many experiments to solvolyze by rate-limiting dissociation to solvent-separated ion pair (III) or free carbocation (IV) followed by rapid nucleophilic attack on one of these species. A summary of these experiments follows: Winstein[8,40] and Goering[13] have studied the solvolysis of benzhydryl derivatives by use of anion-exchange and ^{18}O-scrambling experiments to show that these species are very resistant to nucleophilic attack at the tight ion pair stage; attack occurs on III and on IV, depending on the particular benzhydryl derivative studied. Shiner[41] has studied α-deuterium isotope effects for α-phenylethyl derivative solvolysis, and has concluded that interconversion of tight and solvent-separated ion pairs (k_2, Scheme I) is the rate-limiting step for reaction of these substrates. Nucleophiles cannot approach the backside of the reactive carbon for the norbornyl cation or the 1-adamantyl cation so products must come from attack on III or IV; the relative importance of III and IV is not known. Interconversion of tight and solvent-separated ion pairs is also indicated by studies of α-deuterium isotope effects,[12,42] product stereochemistry,[43] and trends in product composition with leaving-group variation,[44a] to be the rate-determining step for 2-adamantyl derivative solvolysis.

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The stability–selectivity relationship for the alkyl chlorides in Figure 1 can therefore be treated in terms of only two intermediates: solvent-separated ion pair (III) and free carbocation (IV). Equations 3 and 6 for S_{obsd} can then be reduced to

$$S_{obsd} = \sum_i S_i \qquad i = \text{III and IV} \qquad (11)$$

If S_{III} is assumed to be negative, we see that the occurrence of $S_{obsd} < 1$ in Figure 1 can be explained as due to the nature of the stability–selectivity relationship: that is, to a blending of $S_{III} < 1$ and $S_{IV} > 1$ with $a_{III} > a_{IV}$; it is not necessary to include solvent sorting in the explanation (see above).

An increase in solvent ionizing power generally shifts an equilibrium between two ion pairs or between one ion pair and a free carbocation to favor the more dissociated of the two species.[44b] Therefore, a test for product formation from more than one intermediate can be performed by increasing the solvent ionizing power and testing for a change in observed selectivity. To illustrate, if products are formed from one of the alkyl halides of Figure 1 by attack on III and IV, an increase in water percentage should shift the equilibrium to IV and change S_{obsd}. As noted earlier, a change in relative concentrations of the two nucleophiles, ethanol and water, will also give a change in observed selectivity because of a change in relative steady-state concentrations of III and IV; however, Ritchie's results[6] indicate that this influence will be small except when the concentration of one nucleophile is much higher than that of the other. If a change in selectivity with a change in solvent ionizing power is not observed, assumptions regarding steady-state concentrations are not needed; only one intermediate is involved.

We have determined the effect of a large change in ethanol–water concentration on the observed selectivity for solvolysis of *exo*-2-norbornyl chloride (Table III).

Table III. Substitution Products for the Aqueous Ethanolysis of *exo*-2-Norbornyl Chloride as a Function of Solvent Composition at 100°

% ethanol[a]	ROH/ROEt[b]	k_E/k_W[c]	S_{obsd}[d]
90	0.45 ± 0.02	0.79	−0.10
80	0.95 ± 0.03	0.84	−0.08
70	1.69 ± 0.03	0.82	−0.09
65	2.20 ± 0.10	0.78	−0.11
60	2.60 ± 0.03	0.82	−0.09
55	3.10 ± 0.10	0.85	−0.07
50	3.40 ± 0.10	0.94	−0.02
45	4.7 ± 0.3	0.85	−0.07
40	5.1 ± 0.1	0.94	−0.02

[a] Volume per cent in water. [b] Solution were buffered with pyridine and products shown to be stable to reaction conditions. [c] From eq 2. [d] Log k_E/k_W.

The selectivities are seen to be essentially constant, confirming product formation from one intermediate. We concluded earlier that the intermediates giving negative selectivities must react, at least in part, *via* solvent-separated ion pairs (III); thus, *exo*-norbornyl chloride must yield products entirely by III. This conclusion also holds for the solvolysis of 1- and 2-adamantyl chloride since these substrates produce less stable carbocations than does norbornyl, and, therefore, are not expected to react *via* free carbocation (IV).

Schleyer and his coworkers[5] have also observed constant selectivities for attack by azide anion and water on 1- and 2-adamantyl chloride and *exo*-2-norbornyl chloride. These results also provide support for our interpretation.

The increase in selectivities for 2- and 1-adamantyl chloride and *exo*-2-norbornyl chloride (Table I), despite formation of product from only one intermediate (III), must result because of a change in selectivity of the respective solvent-separated ion pairs with changes in stability. Our earlier postulate that selectivities were constant for attack on any of the four species of Scheme I is therefore incorrect. The evidence is now most consistent with selectivities being constant for I, II, and IV but variable for III. The most suitable explanation for the stability–selectivity relationship of Figure 1 can then be expressed as

$$S_{obsd} = a_{III}S_{III} + a_{IV}S_{IV} \qquad (12)$$

$$S_{IV} = K_{IV} \qquad (13)$$

$$S_{III} \propto \text{stability of III} \qquad (14)$$

A general statement for the entire solvolytic reactivity range (Scheme I) is

$$S_{obsd} = \sum_i a_i S_i \qquad i = \text{I–IV} \qquad (15)$$

$$S_i = K_i \qquad i = \text{I, II, and IV} \qquad (16)$$

$$K = \text{constant} \qquad (17)$$

$$S_{III} \propto \text{stability of III} \qquad (18)$$

We conclude that stability–selectivity relationships for solvolysis reactions result from a blending of selectivities for attack on the species involved, potentially I–IV, where selectivities are constant for attack on I, II, and IV and change with stability only for the solvent-separated ion pair III. Thus in certain cases a relationship is observed because of a shift in the ion-pair spectrum (Scheme I) rather than a change in stability and selectivity of a particular intermediate. As pointed out above, constant selectivities for I and II are contingent upon the types of leaving groups considered. We do not know why the selectivity of III varies with stability while that of IV does not, but the behavior differences must be related in some way to the number of solvent molecules separating cation and anion in the two species.

In the following paper,[45] we present experimental evidence from the study of other systems which provides support for the proposed theory of the origin of stability–selectivity relationships for solvolysis reactions.

Experimental Section

Alkyl Chlorides. These compounds were commercially available or were prepared as previously described: 2-adamantyl chloride,[46] 1-adamantyl chloride,[47a] *exo*-2-norbornyl chloride,[47b] α-(*p*-chlorophenyl)ethyl chloride,[48] α-phenylethyl chloride,[48] *p,p'*-dichloro-

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benzhydryl chloride,[49] *p*-chlorobenzhydryl chloride,[49] benzhydryl chloride (Aldrich), *p*-methylbenzhydryl chloride,[49] and *p,p'*-dimethylbenzhydryl chloride.[50]

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Solvents. Ethanol was distilled from magnesium ethoxide and mixed (v/v) with double-distilled water.

Kinetic Procedure. Rates were determined conductimetrically as previously described.[5]

Product Determination. Product ratios were determined by direct gas chromatographic analysis of reaction mixtures. A 6 ft × $^1/_8$ in. column packed with 5% SF96 on 60–70 mesh Anakrom ABS was used.

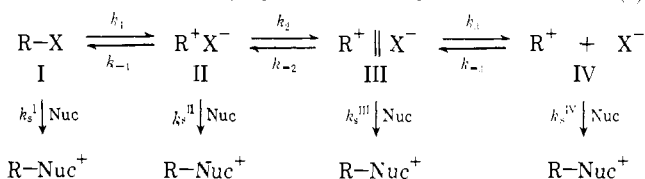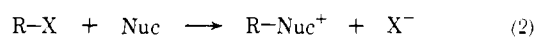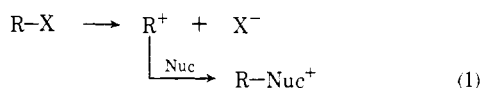# Ion-Pair Identification by Means of a Stability-Selectivity Relationship[1]

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Abstract: Rates and products for the aqueous ethanolysis of 2-adamantyl arenesulfonates are reported and these data used to construct a stability–selectivity plot. A selectivity dependence on leaving group identity is observed as expected for product formation by attack on an ion-pair intermediate. Surprisingly water is found to be more nucleophilic than ethanol for attack on these intermediates and it is concluded that the intermediates can only be solvent-separated ion pairs. Additionally, the aqueous ethanolyses of a series of benzhydryl benzoates are studied. For these derivatives a constant selectivity is observed despite changes in leaving group. Although such a result would seem to implicate product formation only from free carbocation, we conclude that this is not the case; solvent-separated ion pairs also appear to be involved.

According to Hughes and Ingold's original formulation of the S_N1 and S_N2 mechanisms for nucleophilic substitution on saturated carbon, reaction *via* the S_N1 pathway (eq 1), but not the S_N2 pathway (eq 2), should result in product independence of leaving group X.[3] Recent research has shown ion pairs to be involved in the substitution process such that a unimolecular process may also yield II or III in addition to the free carbocation IV (Scheme I).[4–6] Therefore reaction by

Scheme I

$$R-X \longrightarrow R^+ + X^-$$
$$\qquad\qquad \Big\downarrow^{Nuc} R-Nuc^+ \qquad\qquad (1)$$

$$R-X + Nuc \longrightarrow R-Nuc^+ + X^- \qquad (2)$$

$$R-X \underset{k_{-1}}{\overset{k_i}{\rightleftarrows}} R^+X^- \underset{k_{-2}}{\overset{k_2}{\rightleftarrows}} R^+\|X^- \underset{k_{-3}}{\overset{k_3}{\rightleftarrows}} R^+ + X^-$$
$$\quad I \qquad\qquad II \qquad\qquad III \qquad\qquad IV$$

$$k_s^I\Big\downarrow Nuc \quad k_s^{II}\Big\downarrow Nuc \quad k_s^{III}\Big\downarrow Nuc \quad k_s^{IV}\Big\downarrow Nuc$$

$$R-Nuc^+ \qquad R-Nuc^+ \qquad R-Nuc^+ \qquad R-Nuc^+$$

an S_N1 mechanism (k_1, k_2, or k_3 rate limiting) can also show a product dependence on leaving group if tight ion pair (II) or solvent-separated ion pair (III) is

formed in the rate-limiting step and rapidly destroyed by nucleophilic attack or elimination. If the rate-limiting step of a substitution reaction can be demonstrated to be unimolecular, a dependence of products on leaving group provides evidence for involvement of ion pairs II or III in the product-determining step. Cocivera and Winstein[7] have applied this concept to explain their observation of changes in the percentage of isobutylene formed from the solvolysis of *tert*-butyl derivatives. Furthermore, if our previous interpretation[8] of stability–selectivity relationships in solvolytic substitution relations is correct, this product dependence on leaving group should be very definite one, varying according to the extent of dissociation when attack occurs and according to stability of the solvent-separated ion pair if it is involved; this relationship can be expressed in terms of the observed selectivity and the selectivity for attack by ethanol and water (or any other pair of nucleophiles) on intermediates *i*, eq 3–6, where

$$S_i = (\log k_E/k_W)_i \qquad (3)$$

$$S_{obsd} = \sum_i a_i S_i \qquad (4)$$

$$S_i = k_i \qquad i = \text{I, II, and IV} \qquad (5)$$

$$S_{III} \propto \text{stability of III} \qquad (6)$$

a_i represents the fraction of products from attack on *i*, and k_i is a constant for I, II, and IV but not for III.

The purpose of this article is to examine the possibility that stability–selectivity relationships may exist

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