**Figure 5.** Bronsted plot for the reaction of semicarbazide with *p*-chlorobenzaldehyde.[25]

stant of 5×10^{10} M^{-1} sec^{-1} for hydronium ion catalyzed protonation of **8**,[10] the value for several carboxylic acids is about 3×10^9 M^{-1} sec^{-1}. This may be compared to values of 2–3×10^9 M^{-1} sec^{-1} for carboxylic acid catalyzed protonation of **9**, the intermediate formed in intramolecular thiol ester aminolysis.[6] The rate constant for direct conversion of **8** to **7** catalyzed by water, 1.5×10^7 sec^{-1}, is similar to the rate constant of 9×10^6 sec^{-1} for the direct conversion of **9** to **10** in thiol ester aminolysis.[6] It must
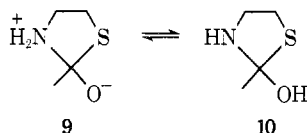

be concluded that the mechanism of eq 10 cannot be ruled out from the existing data.

The methoxyaminolysis of *p*-nitrophenyl acetate is general acid catalyzed with $\alpha \approx 0$ for several carbox-

ylic acids.[26] For less acidic ammonium ion catalysts α increases with the transition occurring for catalysts with pK_s's near 5.5. The authors proposed that the difference in the value of α for carboxylic acids and ammonium ions may be due to bifunctional catalysis on the part of the carboxylic acids.

However, another explanation is consistent with the experimental observations. This is illustrated by the mechanism of eq 11, which is virtually identical
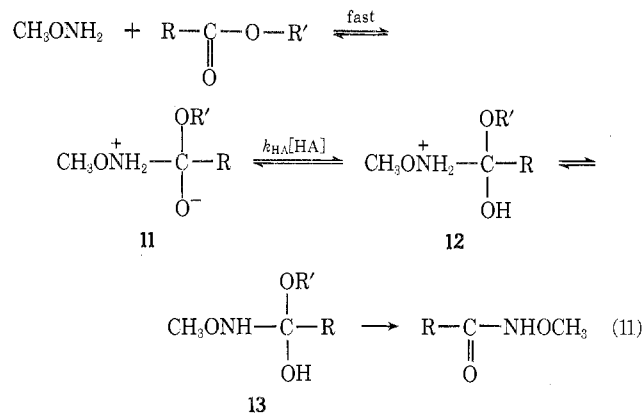
with the proposed mechanism for thiol ester aminolysis.[6,7] The rate-determining step would then be conversion of **11** to **12**. The transition from $\alpha = 0$ to $\alpha = 1$ should occur for catalysts with pK_a's near the pK_a of the OH group of **12**. Using a $\Sigma \sigma_I$-pK_a correlation for alcohols[23] the predicted pK_a of **18** is 5.3 to 7.5. The observed transition at 5.5 is consistent with this prediction, and so the mechanism of eq 11 cannot be ruled out as a possibility.

(26) L. do Amaral, K. Koehler, D. Barlenbach, T. Pletcher, and E. H. Cordes, *J. Amer. Chem. Soc.*, **89**, 3537 (1967).

Organic Ion Pairs as Intermediates in Nucleophilic Substitution and Elimination Reactions[1]

Richard A. Sneen

Department of Chemistry, Purdue University, Lafayette, Indiana 47907

Received August 2, 1971

A particularly unfortunate, although perhaps inevitable, consequence of the recognition of carbonium ions as reaction intermediates in certain substitutions at saturated carbon was the tendency to assume that they are more universal than is in fact the case. Very soon after their recognition disquieting experimental data were forthcoming that could be forced into the carbonium ion picture only by making certain *ad hoc* assumptions about their behavior. Thus the partial inversion of configuration accompanying solvolysis of optically active 2-octyl halides in various solvents was ascribed to partial shielding of

Richard A. Sneen is a native of Wisconsin and attended St. Olaf College and then the University of Illinois (Ph.D., 1955, E. J. Corey). He was then a research associate at UCLA in the laboratory of the late Saul Winstein. Since 1956 he has been on the staff at Purdue University where he is now Professor. His research interests are concentrated in the field of organic reaction mechanisms with special emphasis on the roles of ion pairs in substitution and elimination reactions.

the carbonium ion by the leaving group;[2] product spreads on solvolysis of allylic halides were ascribed to the operation of simultaneous S_N1 (carbonium ion) and S_N2 reactions,[3] and borderline behavior was attributed to a new mechanism intermediate between S_N1 and S_N2.[4]

That these and other related phenomena might have their origin in something less vague than "shielding" or "borderline behavior" was suggested by Hammett, who very early used the term ion pair in connection with organic reactions.[5] It was left to Winstein, however, to provide the first definitive experimental evidence for the existence of such species —ion pairs—as organic intermediates. His brilliant investigations, dating from the early 1950's, established that ion pairs of two distinct types (intimate and solvent separated) are in fact discrete intermediates in selected organic reactions, intermediates with finite life times, whose presence can be established by trapping experiments.[6] These experiments should have awakened us immediately to a realization that many organic reactions, which had generally been assumed to be those of carbonium ions, were in fact reactions of ion pairs. In large part they did not.

A measure of the hold which dissociated carbonium ion theory had on the minds of organic chemists, even as late as 1965, can be gleaned from our statement of that year[7] that "it would seem that caution should be advised about the representation of reactions of *simple* secondary systems as proceeding through free carbonium ion intermediates. Although ion pairs are definitely implicated as intermediates in reactions of these systems, free carbonium ions have not been established."

In the intervening few years the ubiquity of ion-paired species and the relative infrequency of dissociated carbonium ions under solvolytic conditions seem to have become fairly generally recognized. Yet little has been written in the way of a general reinterpretation provided by the recognition of the intermediacy of ion pairs in nucleophilic displacement and elimination reactions. It is the purpose of this Account to begin this organization.

It will be our thesis that recognition of the ability of ion-paired intermediates to serve as substrates for nucleophilic attack has consequences profound and far-reaching. This concept can bring a great deal of order to the kinetics and stereochemistry of substitution reactions and to their structural and reactivity relationships. It suggests a new mechanism of anchimeric assistance and makes intelligible the diversity of products resulting from the various types of ion-pair precursors. Above all, it provides the unifying feature to link together the classically defined mechanisms, S_N1, S_N2, E1, E2, and S_N2'.

The Unifying Ion-Pair Mechanism of Nucleophilic Substitution at a Saturated Carbon Atom
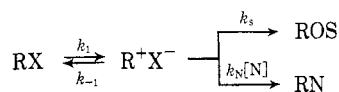
Perhaps the beginnings of our present involvement in ion-pair chemistry can be most realistically traced to the work of Weiner. He established that, when the act of substitution by solvent water into 2-octyl sulfonates in various aqueous dioxane mixtures was isolated from artifactual, complicating side reactions, it was found to take place entirely with inversion of configuration.[7-9] Furthermore, kinetic experiments, coupled with these stereochemical findings, led us to suggest that an asymmetric intermediate intervened in this overall displacement.[10] We tentatively suggested that this intermediate was an ion pair.
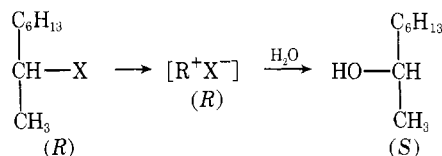
It remained for Larsen[11,12] to provide more convincing evidence for this proposal. This he achieved by finding conditions under which the competitive reactions with 2-octyl mesylate of water and added inorganic azide ion, N_3^-, brought about the destruction of starting material at a rate intermediate between zeroth and first order in $[N_3^-]$. This situation obtained in the rather aqueous 30% (v/v) aqueous dioxane (70% water).

The presumed generalized reaction scheme (Scheme I) can be written

Scheme I

$$RX \underset{k_{-1}}{\overset{k_1}{\rightleftharpoons}} R^+X^- \begin{array}{c} \overset{k_s}{\longrightarrow} ROS \\ \underset{k_N[N]}{\longrightarrow} RN \end{array}$$

and leads to the following product distribution and kinetic relations as a function of nucleophile concentration

$$\frac{[RN]}{[ROS]} = \frac{k_N[N]}{k_s} = m[N] \qquad (1)$$

$$\frac{k_{exptl}}{k_{NA}} = \frac{((k_{-1}/k_s) + 1)(1 + (k_N[N])/k_s)}{((k_{-1}/k_s) + 1 + (k_N[N])/k_s)} =$$

$$\frac{(x+1)(1+m[N])}{(x+1+m[N])} \qquad (2)$$

where $k_N/k_s = m$ and is available from product data (eq 1), $x = k_{-1}/k_s$, and k_{NA} is the solvolytic rate constant in the absence of azide ion but corrected for normal salt effects.

The ability of eq 1 and 2 to correlate the data for the competitive reactions of azide ion and water with 2-octyl mesylate in 30% (v/v) aqueous dioxane is evident in Table I. The inability of alternate mecha-

(2) C. K. Ingold, "Structure and Mechanism in Organic Chemistry," Cornell University Press, Ithaca, N. Y., 1953, p 381 ff.

(3) A. G. Catchpole and E. D. Hughes, *J. Chem. Soc.*, 4 (1948).

(4) S. Winstein, E. Grunwald, and R. W. Jones, *J. Amer. Chem. Soc.*, 73, 2700 (1951).

(5) L. P. Hammett, "Physical Organic Chemistry," McGraw-Hill, New York, N. Y. 1940, p 171 ff.

(6) S. Winstein, B. Appel, R. Baker, and A. Diaz, *Chem. Soc., Spec. Publ.*, 19, 1 (1965), and references cited therein.

(7) H. Weiner and R. A. Sneen, *J. Amer. Chem. Soc.*, 87, 287 (1965).

(8) H. Weiner and R. A. Sneen, *Tetrahedron Lett.*, 1309 (1963).

(9) Paralleling these reports from our laboratories were reports by Streitwieser and his coworkers that acetolyses of these same substrates, 2-octyl sulfonates, when complicating side reactions are recognized, take place with complete inversion of configuration. See A. Streitwieser, Jr., *et al., J. Amer. Chem. Soc.*, 87, 3682, 3686 (1965), and references cited therein.

(10) H. Weiner and R. A. Sneen, *J. Amer. Chem. Soc.*, 87, 292 (1965).

(11) R. A. Sneen and J. W. Larsen, *J. Amer. Chem. Soc.* 88, 2593 (1966).

(12) R. A. Sneen and J. W. Larsen, *J. Amer. Chem. Soc.* 91, 362 (1969).

Table I
Comparison of Observed and Predicted Product Distributions and Rate Constants for the Reactions of 2-Octyl Mesylate with Solvent Water and Sodium Azide in 30% Aqueous Dioxane at 36.2° [12]

[NaN$_3$], M	% RN$_3$, exptl	% RN$_3$, calcd^a	k_{exptl} × 10^4, sec^{-1}	k_{ip}^b × 10^4, sec^{-1}	k_{SN2}^c × 10^4, sec^{-1}
			1.74 ± 0.04		
0.054	38.4	32.3	2.43 ± 0.08	2.41	2.74
0.057	39.3	34.1	2.26 ± 0.11	2.43	2.80
0.098	52.5	47.0	2.67 ± 0.14	2.90	3.61
0.152	54.5	57.8	3.65 ± 0.14	3.50	4.84
0.199	64.0	64.3	3.73 ± 0.12	3.92	5.88
0.258	69.3	70.0	4.71 ± 0.08	4.47	7.36
0.311	74.6	73.8	4.91 ± 0.15	4.92	8.77

^{a} Calculated from eq 1 with $m = 9.04$. ^{b} Calculated from eq 2 with $m = 9.04$, $x = 2.59$, $k_{NA} = 1.74 × 10^{-4}(1 + 1.04[N_3^-])$. ^{c} Calculated from eq 1 with $m = 9.04$, $x = \infty$, $k_{NA} = 1.74 × 10^{-4}(1 + 1.04[N_3^-])$.

nisms and combinations of mechanism to correlate the data have been argued elsewhere.[12,13,16,17]

This successful identification of a 2-octyl mesylate ion pair in substitution reactions of the corresponding covalent substrate provides a ready reconciliation of the problems associated with the borderline region defined long ago by Ingold. Much more exciting is its ability—at least in theory—to accommodate both traditional S$_N$1 and S$_N$2 behavior.

The situation described by the data of Table I, that of a nonintegral and decreasing kinetic order with increasing nucleophile concentration, is the result expected for the ion-pair mechanism where neither the rate of formation of ion pair nor its rate of destruction is solely rate determining; *i.e.*, where k_{-1} and k_s are comparable in magnitude. If the destruction of ion pair becomes rate determining, *i.e.*, if $k_{-1} \gg k_s$, eq 2 reduces to

$$\lim(x \to \infty) \, k_{exptl}/k_{NA} = 1 + m[N]$$

and traditional S$_N$2 behavior is expected. If on the other hand the formation of ion pair becomes rate determining, *i.e.*, if $k_s \gg k_{-1}$, eq 2 reduces to

$$\lim(x \to 0) \, k_{exptl}/k_{NA} = 1$$

and traditional S$_N$1 behavior is predicted.

(13) Since the publication[12] in 1969 of the details of our study of the "borderline" behavior of 2-octyl mesylate toward solvent and azide ion, in 25 and 30% aqueous dioxane, and of our interpretation of these reactions as proceeding *via* the ion-pair mechanism, two alternative attempts to reconcile these data with traditional mechanisms (competitive, simultaneous S$_N$1 and S$_N$2[14] or simple S$_N$2[15]) have appeared in print from two independent laboratories. We have discussed each of these publications in detail in the Appendix to a recent publication.[16] We shall not repeat that discussion here, but the interested reader is referred to it.

(14) B. J. Gregory, G. Kohnstam, M. Paddon-Row, and A. Queen, *Chem. Commun.*, 1032 (1970).

(15) D. J. Raber, J. M. Harris, R. E. Hall, and P. v. R. Schleyer, *J. Amer. Chem. Soc.*, **93**, 4821 (1971).

(16) R. A. Sneen and H. M. Robbins, *J. Amer. Chem. Soc.*, **94**, 7868 (1972).

(17) It should be realized that the reaction of ion pair with N$^-$ to furnish RN, with rate constant, k_N, of Scheme I, is probably at least a two-stage reaction. Microscopic reversibility suggests strongly that an ion pair, N$^-$R$^+$, must intervene. Its subsequent collapse to RN, however, is probably sufficiently fast (especially at low concentrations of common ion, X$^-$) to ensure that its formation is effectively irreversible.

$$R^+X^- \underset{X^-}{\overset{N^-}{\rightleftarrows}} N^-R^+ \xrightarrow{fast} NR$$
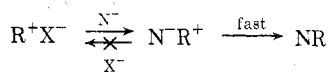
Thus, a *single, basic mechanism*, the ion-pair mechanism, is able, at least in theory, to accommodate the entire spectrum of mechanistic types: S$_N$1, borderline, S$_N$2. It remains to establish if *only* this basic mechanism functions.

From what has been said above it will be apparent that the ion-pair mechanism can be differentiated from traditional S$_N$1 and S$_N$2 mechanisms, using the techniques described here, only under borderline conditions—conditions in which the rate constants, k_{-1} and k_s, are comparable in magnitude. Even with this severe limitation a rather impressive array of substrates have now been shown to react according to the predictions of the ion-pair mechanism. The systems and conditions investigated to date are summarized in Table II.[18] Efforts are currently under way to add to this list simple primary and even methyl substrates.[19]

The Unification of Substitution and Elimination Mechanisms

It has for some time been our belief that the very general concurrence of competitive substitution and elimination reactions observed in organic chemistry must have its origin in something more fundamental than a casual—if too frequent—coincidence; this concurrence, observed over a wide spectrum of substrate types, solvents, and base–nucleophiles, strongly suggests that the competitive product-forming steps of these reactions must be quite unselective, a conclusion at variance with the traditional view that rates and products are determined in the same steps of the reaction, the fundamental postulate of classical mechanisms S$_N$2 and E2.

It seemed to us highly probable, in view of our demonstration of the existence of ion-pair intermediates in substitution reactions, that these intermediates might also be common to competitive eliminations. Accordingly, Howard Robbins investigated the competitive elimination and substitution reactions of α-phenylethyl bromide in solvent ethanol, catalyzed by added ethoxide ion and/or solvent, with a view toward implicating a common ion-pair intermediate.[20] This system was particularly attractive since it had been shown by Ingold[21] that, at high concentra-

(18) The α-arylethyl halides of Table II, α-phenylethyl bromide ($x = 8.5$, $m(N_3^-) = 131$)[16] and α-p-tolylethyl chloride ($x = 3.30$, $m(N_3^-) = 11.1$),[16] together with the experiments conducted with the related α-p-tolylethyl bromide (in ethanol) ($x \simeq 0$, $m(N_3^-) = 22.7$)[16] provide an interesting series of substrates which reinforce the ion-pair hypothesis. Within this series of three related compounds we have a substrate, α-phenylethyl bromide, which approaches "S$_N$2" behavior ($x = 8.5$) and one which is experimentally indistinguishable from "S$_N$1" ($x \simeq 0$). Yet their *selectivity ratios toward azide ion*, $k_N/k_s = m$, *are within a factor of 6*. Truly if fundamentally different types of substrates (largely covalent (S$_N$2) from α-phenylethyl bromide and largely carbonium ion (S$_N$1) from α-p-tolylethyl bromide) were involved, these similar k_N/k_s ratios would be surprising.

We have here found, in effect, a mechanism to extend the criterion established in the Appendix of ref 12, that linear product plots are indicative of a common precursor of ROS and RN over a considerable range of nucleophile concentration without the experimental complications which would ensue if the experiments had been conducted on a single substrate.

(19) In an interesting paper that utilizes some novel linear free energy relationships, Professor John M. W. Scott has provided evidence that bimolecular nucleophilic substitutions into the methyl halides may take place *via* the ion-pair mechanism: J. M. W. Scott, *Can. J. Chem.*, **48**, 3807 (1970).

(20) R. A. Sneen and H. M. Robbins, *J. Amer. Chem. Soc.*, **91**, 3100 (1969).

(21) E. D. Hughes, C. K. Ingold, S. Masterman, and B. J. McNulty, *J. Chem. Soc.*, 899 (1940).

Table II
Substrates and Conditions Conforming to the Predictions of the Ion-Pair Mechanism (Scheme I)

Substrate	Solvent,[a] Temp, °C	Nucleophile	m^c	x^d	Ref
2-Octyl mesylate	30% D:W, 36.2°	N_3^-	9.04	2.59	12
2-Octyl mesylate	25% D:W, 36.2°	N_3^-	8.22	2.33	12
p-Methoxy-benzyl chloride	70% A:W, 20°	N_3^-	21.6	1.98	35, e
Benzoyl chloride ethyl chloride	50% A:W,[b] 0.0°	o-Nitroaniline	4.42	1.10	35, f
α-Phenylethyl bromide	EtOH, 50°	SCN⁻	27.0	8.5	16
	EtOH, 50°	N_3^-	131	8.5	16
α-p-Tolyl-ethyl bromide	EtOH, 50°	SCN⁻	4.40	3.3	16
	EtOH, 50°	N_3^-	11.1	3.3	16
α,γ-Dimethyl-allyl chloride	EtOH, 36.0°	SCN⁻	6.6	4.0	27
	EtOH, 36.0°	N_3^-	33.0	4.0	27
	90% E:W, 27.0°	N_3^-	12.0	2.3	27

[a] D:W = dioxane–water; A:W = acetone–water; E:W = ethanol–water. [b] Weight per cent. [c] $m = k_N/k_s$ determined from product data and eq 1. [d] $x = k_{-1}/k_s$ defined by eq 2. [e] G. Kohnstam, A. Queen, and B. Shillaker, *Proc. Chem. Soc. London*, 157 (1959). [f] V. Gold, J. Hilton, and E. G. Jefferson, *J. Chem. Soc.*, 2756 (1954).

tions of added ethoxide, a constant ratio of elimination:substitution (~1:2) is obtained.

Preliminary experiments by Robbins[16] established that the competitive substitutions of solvent ethanol and added azide ion or thiocyanate ion into the substrate proceeded *via* an ion-pair mechanism with $x = k_{-1}/k_s = 8.5$ (Table II). The substitution–elimination reactions were assumed to compete as in Scheme II, for which one can write the following relations:

Scheme II
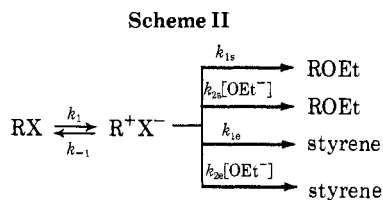
$$\frac{[\text{styrene}]}{[\alpha\text{-phenylethyl ethyl ether}]} =$$

$$R = \frac{k_{1e} + k_{2e}[\text{OEt}^-]}{k_{1s} + k_{2s}[\text{OEt}^-]} \quad (3)$$

In the absence of base, R_{NB}, this reduces to eq 4, and at infinite base, $R_{\infty B}$, it becomes eq 5.

$$R_{NB} = a = k_{1e}/k_{1s} \quad (4)$$

$$R_{\infty B} = b = k_{2e}/k_{2s} \quad (5)$$

Defining

$$y = k_{2s}/k_{1s} \quad (6)$$

one obtains relation 7.

$$k_{2e}/k_{1s} = by \quad (7)$$

Equation 3 can now be written

$$y = (R - a)/\{[\text{OEt}^-](b - R)\} \quad (8)$$

The constants a and b can be evaluated from ex-

perimental data with the aid of eq 4 and 5, respectively ($a = 0.018$ and $b = 0.500$), and the constant $y = k_{2s}/k_{1s}$ can then be evaluated from the remaining product data ($y = 12.5$).[20,21]

A steady-state treatment of the data leads to the kinetic expression

$$\frac{k_{\text{exptl}}}{k_{NB}} = \frac{(x + 1 + a)(1 + a + (1 + b)y[\text{OEt}^-])}{(1 + a)(x + 1 + a + (1 + b)y[\text{OEt}^-])} \quad (9)$$

where k_{exptl} and k_{NB} are the observed pseudo-first-order rate constants in the presence and absence of base, respectively, $x = k_{-1}/k_{1s}$ and is available from substitution studies[16] ($x = 8.5$; also *vide supra*), and a, b, and y are obtained from eq 4, 5, and 8, respectively.

The ability of this equation, with no adjustable parameters, to correlate the data is made evident by the data of Table III.[22]

Again one wonders about the generality of the ion-pair mechanism of elimination, and, of course, the task of establishing it experimentally belongs to the future. Yet we at least cannot view the rather satisfying order that a common ion-pair intermediate brings into the formerly chaotic picture of four, fundamentally different and separate, mechanisms, S_N1, S_N2, E1, and E2, without a measure of confidence that a concept so unifying and simplifying in nature will have a rather extended range of operation.[23]

The Identification of Distinct, Discrete, Allylically Related Ion Pairs

It is our belief that the concept of selectivity has been a very badly underused mechanistic criterion in organic chemistry. If one accepts the extrathermodynamic premise (really a corollary of the Hammond

(22) See, however, D. J. McLennan, *Tetrahedron Lett.*, 2317 (1971).

(23) Professor F. G. Bordwell has presented evidence of a quite independent nature that the competitive bimolecular substitutions and eliminations which he has observed from p-CH₃C₆H₄SO₂CH=CH(CH₃)₂CX proceed *via* a common ion-pair intermediate: F. G. Bordwell, Fourteenth Conference on Reaction Mechanisms, Burlington, Vt., June 14, 1972, and private communications.

Table III
Comparison of Observed and Predicted Rate Constants for the Reactions of α-Phenylethyl Bromide with Solvent and Sodium Ethoxide in Absolute Ethanol at 50° [20]

[NaOEt], M	$k_{\text{exptl}}{}^{a} \times 10^5$, sec^{-1}	$k_{\text{ip}}{}^{b} \times 10^5$, sec^{-1}	$k_{\text{SN2}}{}^{c} \times 10^5$, sec^{-1}
	11.3 ± 0.3		
0.114	35.4 ± 1.0	28.8	36.2
0.121	35.7 ± 1.1	29.6	36.7
0.533	65.7 ± 1.9	59.6	123
0.686	74.8 ± 0.7	65.0	150
1.07^{d}	98 ± 7	75.6	236
∞		(106)	(∞)

^{a} Experimentally observed pseudo-first-order rate constant. ^{b} Calculated from eq 9 with $a = 0.018$, $b = 0.500$, $y = 12.5$, and $x = 8.5$. ^{c} Calculated from eq 9 with $a = 0.018$, $b = 0.500$, $y = 12.5$, and $x = \infty$. ^{d} Average of three separate runs.

Table IV
Comparison of Observed and Predicted Product Distributions and Rate Constants of the Reactions of α,γ-Dimethylallyl Chloride ($ca.$ 0.01 M) with Ethanol and Tetra-n-propylammonium Azide in Ethanol at 36.0°[27]

$[(\text{Pr})_4\text{NN}_3]$, $M \times 10^2$	% RN_3, exptl	% RN_3,^{a} calcd	$k_{\text{exptl}} \times 10^4$, sec^{-1}	$k_{\text{ip}}{}^{b} \times 10^4$, sec^{-1}	$k_{\text{SN2}}{}^{c} \times 10^4$, sec^{-1}
			1.33 ± 0.01		
1.90	38.4	38.6	2.29 ± 0.05	2.06	2.32
3.86	58.6	56.2	2.97 ± 0.10	2.72	3.41
5.90	67.7	67.2	3.78 ± 0.17	3.41	4.72
11.20	79.2	78.8	4.70 ± 0.20	4.94	8.61

^{a} Calculated from eq 1 with $m = 33.0$. ^{b} Calculated from eq 2 with $m = 33.0$ and $x = 4.0$. ^{c} Calculated from eq 2 with $m = 33.0$ and $x = \infty$.

postulate) that a diversity of competitively formed products, especially when formed under widely varying experimental conditions, is to be associated with low-energy, nonselective, product-forming steps, he is led to the conclusion that these products must be formed from a high-energy intermediate. This theme, with variations, recurs time and again in this Account.

The immediate case in point is the long-recognized, very general phenomenon of product spreads observed on solvolysis of isomeric, allylically related halides; thus a pair of such halides does not, in general, give rise to the same mixture of allylic solvolysis products.[24] Using this fact as a guideline we were encouraged to look (and successfully so) for evidence that allylic ion-pair intermediates can serve as substrates for nucleophilic attack in the reactions of α,γ-dimethylallyl chloride.[25]

Both kinetic and stereochemical techniques were used in this investigation, which was carried out by Bradley.[27] The kinetic technique paralleled that originally utilized by Larsen:[12] the competitive reactions in solvent ethanol (36°) of α,γ-dimethylallyl chloride with solvent and either tetra-n-propylammonium azide or sodium thiocyanate were found to occur at a rate less than first but greater than zeroth order in nucleophile. Products were formed in accordance with eq 1 [$m(\text{N}_3{}^-) = 33.0$; $m(\text{SCN}^-) = 6.6$], while rates were correlated by eq 2 [$x(\text{N}_3{}^-) = x(\text{SCN}^-) = 4.0$].[28] The azide data are summarized in Table IV. Thus one concludes that an ion pair must intervene in these reactions of α,γ-dimethylallyl chloride as the common precursor of both solvoly-

sis product and substitution product (azide or thiocyanate).[29]

However, when one adds stereochemical information to these kinetic conclusions he finds that Scheme I is altogether too simple to accommodate all of the facts. Bradley[27] made the following stereochemical observations: (1) solvolysis of optically active α,γ-dimethylallyl chloride in absolute ethanol at 27.0° furnishes racemic α,γ-dimethylallyl ethyl ether ($k_\alpha = (1.15 \pm 0.03) \times 10^{-4}$ sec^{-1} and $k_{\text{t}} = (4.95 \pm 0.12) \times 10^{-5}$ sec^{-1}, the ratio $k_\alpha/k_{\text{t}} = 2.32$ and is invariant with added common ion Cl$^-$); (2) reaction of levorotatory α,γ-dimethylallyl chloride at 27.0° in absolute ethanol in the presence of tetra-n-propylammonium azide (0.11 M) furnishes racemic ether and dextrorotatory α,γ-dimethylallyl azide (presumably inverted).

Thus the substitution products are formed in processes with fundamentally different stereochemistries, alkyl azide with maintained asymmetry and the ethyl ether with racemization. Nonetheless their competitive formation in accordance with eq 1 establishes that they share a common intermediate. These data are most simply rationalized by a scheme (Scheme III) which includes an asymmetric (intimate) ion pair which can either serve as substrate for azide attack, racemize via a suprafacial 1,3-allylic shift, or, alternatively, react further to furnish a solvent-separated ion pair (either symmetric or a rapid equilibrium between two mirror-image structures) which collapses to racemic solvolysis product.

Several features of this study are deserving of comment: (1) the initially formed ion pair, presumably intimate, is able to preserve its stereochemical integ-

(24) R. H. DeWolfe and W. G. Young, *Chem. Rev.*, 56, 794 (1956).

(25) This allylic substrate is of the type used so advantageously by Goering and his coworkers in their extensive investigations of ion-pair phenomena.[26] It has the property that a suprafacial 1,3-allylic rearrangement converts a molecule into its enantiomer, thus providing a facile route for racemization.

(26) See, for example, H. L. Goering, M. M. Pombo, and K. D. McMichael, *J. Amer. Chem. Soc.*, 85, 965 (1963).

(27) R. A. Sneen and W. A. Bradley, *J. Amer. Chem. Soc.*, 94, 6975 (1972).

(28) Note that data for both nucleophiles are correlated by the *same* value of x. (This has also been observed by Robbins for substitutions into α-phenylethyl bromide and α-p-tolylethyl chloride, Table II and ref 16). This provides independent confirmation of the ion-pair scheme as the quantity $x = k_{-1}/k_{\text{s}}$ should be independent of the nature of the nucleophile. Note also that when the value of x has been assessed from the data for either nucleophile, no arbitrary parameters exist in the correlation of rate data for the second nucleophile; there remain no degrees of freedom.
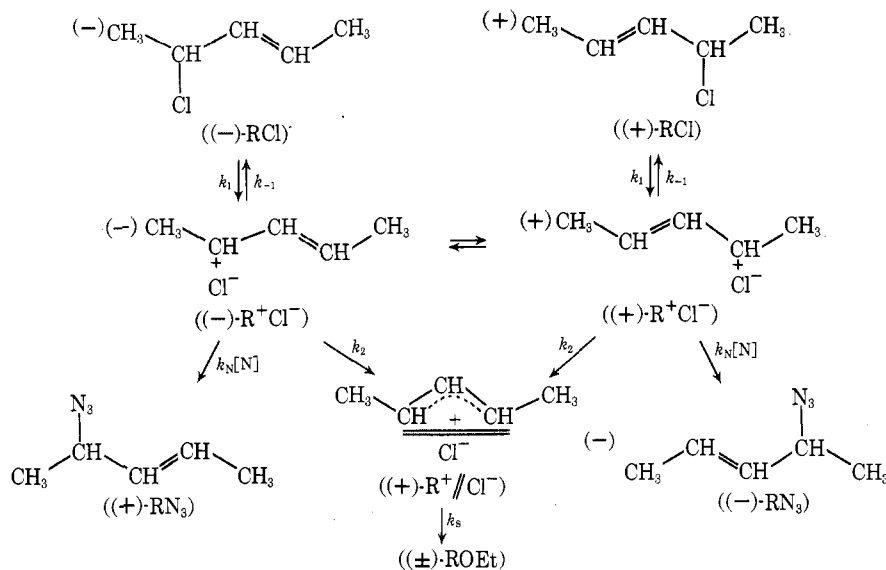
(29) We have also attempted to fit these data to a scheme of competitive $\text{S}_\text{N}2$ (RN) and ($\text{S}_\text{N}1$ (ROS + RN) reactions with limited success. A telling argument against this alternative rationalization is provided by experiments in which certain of these reactions were repeated, this time in 90% aqueous ethanol.[27] As the solvolysis rate increases by a factor of 19 (EtOH → 90% EtOH) the *bimolecular component* of the rate (in the presence of azide ion) *increases by a factor of 9.4*. In terms of the Grunwald–Winstein[30] relationship this corresponds to a *solvent sensitivity* (m^{31} of the bimolecular reaction of α,γ-dimethylallyl chloride with azide ion of $m(\text{N}_3{}^-) = +0.76$ ($m = 1 =$ limiting). Truly if this be an $\text{S}_\text{N}2$ reaction it must have a great deal of carbonium ion character.

The rationalization of these data, in terms of nonselective reactions of high-energy intermediates, ion pairs, will be apparent.

(30) E. Grunwald and S. Winstein, *J. Amer. Chem. Soc.*, 70, 841 (1948).

(31) The quantity, m, referred to here, the substrate constant of the Grunwald-Winstein mY relationship,[30] is to be distinguished from the more usual m of this Account, the selectivity constant of eq 1 and 2.

Scheme III

$$
\begin{array}{c}
((-)\text{-RCl}) \xrightleftharpoons[k_{-1}]{k_1} ((-)\text{-R}^+\text{Cl}^-) \rightleftharpoons ((+)\text{-R}^+\text{Cl}^-) \xrightleftharpoons[k_{-1}]{k_1} ((+)\text{-RCl}) \\
((+)\text{-RN}_3) \xleftarrow{k_N[N]} \quad \xrightarrow{k_2} ((+)\text{-R}^+/\!/\text{Cl}^-) \xleftarrow{k_2} \quad \xrightarrow{k_N[N]} ((-)\text{-RN}_3) \\
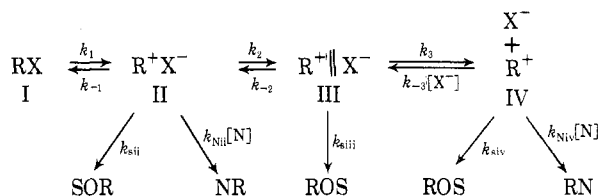((\pm)\text{-ROEt}) \xleftarrow{k_s}
\end{array}
$$

rity; this must mean that the counteranion is closely associated in space with the allylic carbon atom to which it was originally covalently bonded;[32] (2) two types of ion pairs, differing presumably as Winstein's[33] intimate and solvent-separated types, have been identified; obviously the process labeled k_s of the generalized basic ion-pair scheme (Scheme I) can take different forms, depending on circumstances;[34] (3) the identification of configuration-holding intimate ion-pair intermediates derived from allylic halides suggests a very attractive new mechanism of the S_N2' reaction.[32,35,36] Presumably the initially

$$
\begin{array}{c}
\xrightleftharpoons[k_{-1}]{k_1} \\
\xrightarrow[\text{(S}_N2)]{k_N[N]} \\
\xrightarrow[\text{(S}_N2')]{k_N'[N]}
\end{array}
$$
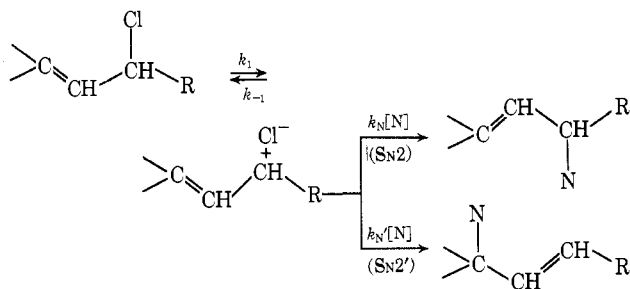
formed ion pair has distributed some of its positive charge to the γ position; a balance between charge density and steric factors must then determine the proportions of S_N2 and S_N2' products. At all events the unification of these two mechanisms is thus conceptually achieved.

General Observations and Comments

It seems desirable to adopt a standardized framework for the description of ion-pair reactions. An expanded form of the original Winstein formulation[33] is recommended. The covalent substrate (RX), the
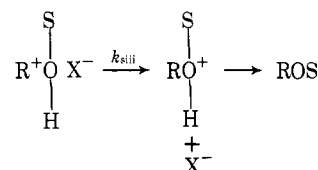
$$
RX \underset{k_{-1}}{\overset{k_1}{\rightleftharpoons}} R^+X^- \underset{k_{-2}}{\overset{k_2}{\rightleftharpoons}} R^+\|X^- \underset{k_{-3}[X^-]}{\overset{k_3}{\rightleftharpoons}} \begin{array}{c} X^- \\ + \\ R^+ \end{array}
$$

$$
\begin{array}{ccccc}
\text{I} & & \text{II} & \text{III} & \text{IV} \\
\swarrow k_{sii} \searrow k_{Nii}[N] & & \downarrow k_{siii} & \swarrow k_{siv} \searrow k_{Niv}[N] \\
\text{SOR} \quad \text{NR} & & \text{ROS} & \text{ROS} \quad \text{RN}
\end{array}
$$

intimate ion pair (R^+X^-), the solvent-separated ion pair ($R^+\|X^-$) and the dissociated ion (R^+) are identified with roman numerals I, II, III, and IV, respectively. Substitution by solvent (k_s) and external nucleophile (k_N) is identified with a particular precursor by a subscript, e.g., k_{siii}. Eliminations can also be identified with subscripts, e.g., k_{eii}. Rearrangements can be indicated as

$$
R^+X^- \underset{k_{-r}}{\overset{k_r}{\rightleftharpoons}} R'^+X^-
$$
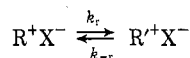
Other symbolisms can be developed and added to this basic framework as their prototypes are identified.

It will be noted that we have omitted processes k_{si} and k_{Ni}; this is deliberate and follows from our conviction that traditional S_N2 reactions, involving direct attack on covalent carbon, have not been established.[35] The absence of the step k_{Niii} will also be noted; it seems probable to us, in the light of several findings,[27,32,37] that this process is unable to compete, at least generally, with the process k_{siii}.[38] We suggest that this process, k_{siii}, takes place by a collapse mechanism,[35] an intervening solvent molecule of the solvent-separated ion pair simply collapsing onto the cationic carbon

$$
R^+\underset{H}{\overset{S}{O}}\ X^- \xrightarrow{k_{siii}} R\underset{H}{\overset{S}{O^+}} \longrightarrow ROS
$$
$$
\begin{array}{c} + \\ X^- \end{array}
$$

(32) R. A. Sneen and J. V. Carter, *J. Amer. Chem. Soc.*, **94**, 6990 (1972).

(33) S. Winstein, E. Clippinger, A. H. Fainberg, R. Heck, and G. C. Robinson, *J. Amer. Chem. Soc.*, **78**, 328 (1956).

(34) In terms of Scheme III, the x and m of eq 1 and 2 become $x = k_{-1}/k_2$ and $m = k_N/k_2$.

(35) R. A. Sneen and J. W. Larsen, *J. Amer. Chem. Soc.*, **91**, 6031 (1969).

(36) For a recent review of the current status of the classical S_N2' mechanism, see F. G. Bordwell, *Accounts Chem. Res.*, **3**, 281 (1970).

(37) Unpublished work, D. M. Roscher, Ph.D. Thesis, Purdue University, 1966, and J. R. Ellis, Ph.D. Thesis, Purdue University, 1969.

This leads to an interesting, if as yet rather speculative, hypothesis to account for some of the diverse stereochemical results reported for nucleophilic substitutions and, in particular, solvolyses. The collapse mechanism for solvolysis from the solvent-separated ion pair might reasonably be expected to take place with retention of configuration.[35,40]

Following Ingold, one can reasonably expect complete racemization in the substitution products resulting from dissociated carbonium ion,[41] and Weiner's stereochemical studies with simple 2-octyl substrates[7] suggest that processes k_{sii} and k_{Nii} proceed with inversion. Thus one has every variety of substitution stereochemistry potentially available, inversion from the intimate ion pair, retention from the solvent-separated ion pair and racemization from the dissociated ion.
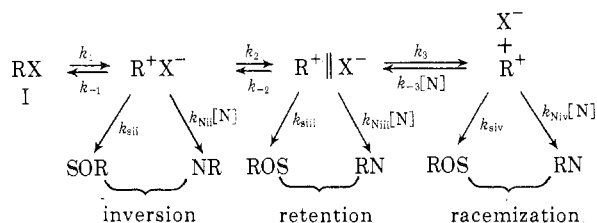

Presumably a relatively unhindered backside coupled with a relatively unstable incipient carbonium ion, R^+ (2-octyl, isopropyl), will favor reaction at the intimate ion-pair stage. Conversely a more hindered backside and/or a more stable incipient carbonium ion center will result in reaction at the solvent-separated or dissociated stage. These ideas are currently being subjected to experimental test.

A readily available experimental quantity in many of the experiments described in this article is the slope of a plot of the product ratio, [RN]/[ROS] *vs.* [N]. Often (but not always) a plot of these quantities is linear and its slope may have mechanistic significance. In the simplest cases, for example the competitive reactions of azide ion and solvent with 2-octyl sulfonates in aqueous dioxane,[7] the slope of a product plot, with some confidence, measures k_{Nii}/k_{sii}, while for triphenylmethyl chloride[42] the slope of

such a plot undoubtedly measures k_{Niv}/k_{siv}. Current indications are that, depending on the nature of the substrate, the k_N/k_s value (for a given nucleophile) will have characteristic ranges, and in fact it has been shown that a quantitative free-energy relationship exists between log k_t and log (k_N/k_s) for reactions thought to take place at a dissociated ion stage.[42] The ratio k_N/k_s promises to be useful as a diagnostic test of mechanism.

The quantity k_N/k_s will be recognized as a measure of the selectivity of the reacting species, a measure of the substrate's ability to distinguish between different nucleophiles, and thus it is a potential measure of the instability of the species. It is hoped that selectivities may ultimately provide us with an estimate of the energies of various ion pairs.

We have elsewhere[35] summarized the reactions of ion pairs which have been experimentally documented; these include substitutions,[12,16,27,35] eliminations,[20] racemization,[43] scrambling of O atoms in leaving groups (sulfonates, benzoates, etc.),[44] and anion exchange.[33] In general, then, ion pairs do the things which had historically been ascribed to dissociated carbonium ions. In addition, we suggested[35] that the many rearrangements, which give evidence of anchimeric assistance, may proceed by an initially unassisted (and potentially reversible) formation of an ion pair whose return to covalent starting material, however, is circumvented by a facile rearrangement. This two-stage process we believe to be a reasonable and very probable alternative to the traditional view of a synchronous one-stage reaction. Experiments are under way to document it.[45]

$$RX \; \underset{\longleftarrow}{\longrightarrow} \; R^+X^- \; \xrightarrow{fast} \; R'^+X^- \; \longrightarrow \; products$$

Finally, we comment briefly on the nature of ion-pair intermediates. We are frequently asked to describe them in some detail; thus people are curious about the distance between counterions, the hybridization and geometry of the cationic portion, the nature of the energy barrier between intimate and solvent-separated ion pairs, the reasons for the ability of certain ion pairs to preserve asymmetry, the charge distribution and geometry in the transition state derived from nucleophilic attack, and so forth. We too find these questions of interest—of considerably interest, in fact. But for most of them we have at present no definitive answers. Time and future experiments will undoubtedly provide some answers, but for now we are forced to think of ion pairs operationally in terms of their reactions which we can measure.

We wish to make only one further point: an ion pair is *not* simply a pair of ions, a pair of point charges.[46] Considerable polarization of the electron density of the anionic component toward the cationic

(38) When it does compete, it may well be of a fundamentally different mechanism. There are suggestions implicit in Winstein's work[39] and suggestive evidence from some of our studies[37] that such a reaction, when it occurs, does so *via* an initial exchange mechanism to give a new solvent-separated ion pair—and probably with retention of configuration.

$$R^+ \| X^- + Y^- \longrightarrow R^+ \| Y^- + X^-$$
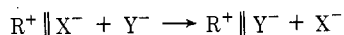
Microscopic reversibility suggests that the new solvent-separated ion pair should revert to covalent product *via* the intimate ion pair.

$$R^+ \| Y^- \longrightarrow R^+Y^- \longrightarrow RY$$
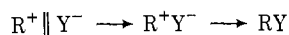
The overall reaction, which accomplishes the act of substitution, is, however, of a type fundamentally different from more normal substitutions. Perhaps this explains the otherwise strange order of efficiencies (LiClO$_4$ > LiOAc), unrelated to nucleophilicities, observed by Winstein[39] in his studies of the special salt effect.

(39) S. Winstein and E. Clippinger, *J. Amer. Chem. Soc.*, **78**, 2784 (1956).
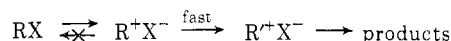
(40) Providing, incidentally, a very satisfactory alternative to backside nonclassical bonding to rationalize the frequently observed examples of retention.

(41) Again it should be emphasized that dissociated carbonium ions derived from secondary—and even many tertiary—substrates are rare, at least under the usual solvolytic conditions.[35]

(42) R. A. Sneen, J. V. Carter, and P. S. Kay, *J. Amer. Chem. Soc.*, **88**, 2594 (1966).

(43) S. Winstein, M. Hojo, and S. Smith, *Tetrahedron Lett.*, 12 (1960).

(44) H. L. Goering and R. W. Thies, *J. Amer. Chem. Soc.*, **90**, 2967, 2968 (1968).

(45) See also V. J. Shiner, Jr., R. D. Fisher, and W. Dowd, *J. Amer. Chem. Soc.*, **91**, 7748 (1969).

(46) See, for example, J. L. Kurz and J. C. Harris, *J. Amer. Chem. Soc.*, **92**, 4117 (1970).

component must exist; this will be recognized as the essence of the covalent bond. An alternative to the name, "ion pair," might be "extended covalent bond." But this would tend to deemphasize too strongly the charge separation which undoubtedly exists.

We will continue to use the term ion pair, but we would hope that the organic chemical public would recognize that the situation is perhaps better described as "an extended bond with considerable ionic character."

Evidence for Protonated Cyclopropane Intermediates from Studies of Stable Solutions of Carbonium Ions

Martin Saunders,* Pierre Vogel, Edward L. Hagen, and Jerrold Rosenfeld

Department of Chemistry, Yale University, New Haven, Connecticut 06520

Most organic processes occur *via* one or more reaction intermediates. These intermediate species can be of any structural type. However, in order to *be* intermediates, they must rapidly undergo further reaction under experimental conditions.

The necessary high reactivity often results from some unusual structural feature. Anions, radicals, and cations are quite common as intermediates. Carbenes, triplet states, excited singlet states, and highly strained systems have often been proposed as reaction intermediates in recent years. The significance of the intermediates involved is so great that the study of organic reaction mechanisms is usually organized in accord with the types of intermediate proposed. There are, of course, many interesting reactions which occur *via* single-step processes without intermediates.

Many important reactions occur through intermediate cations. Some require ionic catalysts or reactants, and others occur through ionization of neutral precursors. In some of the cations the positive charge resides on carbon and in some on other elements. Cations in which the major part of the charge resides on carbon have long been called carbonium ions.

Reactions in which carbonium ion intermediates rearrange are common and have long been studied. Nevertheless, the detailed mechanisms of these rearrangements are still the subject of controversy. Among the possible intermediates and transition states considered for these rearrangements are cations containing three-membered rings with seven substituent atoms or groups, thus having structures which might arise from the addition of a proton to a cyclopropane ring. Such structures are logically invoked in considering the common Wagner–Meerwein 1,2 shift of an alkyl group in carbonium ions (Figure 1). Indeed, one is virtually required to invoke structures of this sort as either transition states or intermediates for these reactions.

There has been considerable argument concerning the bond character of the ring bonds, the possible mode of attachment of the substituents, and the charge distribution in such species, since they are electron deficient and cannot have electron-pair bonds between all connected atoms. However, the most important, and vexing, chemical question is whether these structures are only transition states in rearrangements or whether they can be intermediates in some or all cases. To discuss them without prejudging the structural and energetic uncertainties, we will use, to describe them, the name protonated cyclopropane as a neutral, catch-all term. We will draw them using solid lines for bonds indicating an apparently pentavalent carbon atom in a three-membered ring (Figure 1) even though, because of the electron deficiency, some of the bonds must be partial. Of course, many analogies to these fractional bonds may be found in the structures of electron-deficient boron and aluminum compounds as well as in CH_5^+.

Protonated cyclopropane intermediates have been proposed many times to interpret kinetic and product studies of solvolytic reactions.[1] However, the cations themselves are not stable in these reactions, and evidence for their existence and properties has only been inferred from a study of the products of reac-

Martin Saunders received his Ph.D. at Harvard in 1956 and has been teaching at Yale University ever since. His research interests concern the preparation and properties of carbonium ions and also the application of nmr spectroscopy to the study of fast reactions and the measurement of equilibrium isotope effects.

Pierre Vogel received his Ph.D. from the University of Lausanne in 1969 and spent 2 years of postdoctoral research at Yale. Edward L. Hagen and Jerrold Rosenfeld obtained their Ph.D. degrees with Professor Saunders in 1968 and 1969, respectively.