Chem. Soc. Rev., 1990, **19**, 83–105

The Mechanisms of Nucleophilic Substitution in Aliphatic Compounds*

By Alan R. Katritzky, F.R.S.
DEPARTMENT OF CHEMISTRY, UNIVERSITY OF FLORIDA,
GAINESVILLE, FL 32601, USA
Bogumil E. Brycki
DEPARTMENT OF CHEMISTRY, ADAM MICKIEWICZ UNIVERSITY,
60780 POZNAN, POLAND

1 Introduction

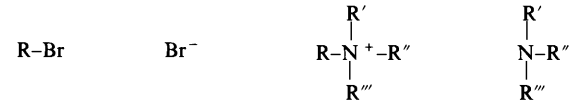
The following article reviews the insight into nucleophilic substitution mechanism that has been made available from studies conducted in non-polar solvents and in the gas phase. It argues for the existence of discrete alternative mechanisms often acting in competition.

2 Nucleophilic Substitution and Charge

In the whole of organic chemistry there is no reaction more important than the replacement by a nucleophile of a leaving group attached to an aliphatic carbon atom.[1] In its most general form this reaction involves the conversion of a nucleophile and a substrate into a product and a leaving group (equation 1).

$$\text{Nucleophile} + \text{R–X*} \longrightarrow \text{Nucleophile–R} + \text{X*} \qquad (1)\dagger$$

In neutral substrates, such as alkyl halides (1), the leaving group is negatively charged [*e.g.*, halide anion (2) or arylsulphonate anion].



neutral substrate (1)	anionic leaving group (2)	cationic substrate (3)	neutral leaving group (4)

In cationic substrates, the leaving group is neutral: *e.g.*, a tertiary amine from a quaternary ammonium cation [*cf.* (3), (4)], a sulphide from a sulphonium salt, an ether from an oxonium salt. Furthermore, acid catalysis can convert a neutral substrate into a cationic substrate: many reactions of alcohols are of this type (equation 2), and the leaving group is effectively a neutral water molecule.

* For more detailed accounts of our own work in this area see reference 31.

† Throughout this article, when there are various possibilities of charge signs, as for X here, charges are omitted and asterisk is used instead.

[1] J. March, 'Advanced Organic Chemistry', 3rd edn.; Wiley, New York, 1985; (*a*) pp. 265–268; (*b*) pp. 259–265.

$$\underset{\text{alcohol}}{\underset{(5)}{R\text{–}OH}} \xrightarrow{H^+} \underset{\text{protonated alcohol}}{\underset{(6)}{R\text{–}\overset{+}{O}H_2}} \longrightarrow \underset{}{R^+} + \underset{\text{neutral water}}{\underset{(7)}{OH_2}} \qquad (2)$$

Nucleophiles are either anionic (*e.g.*, OH^-, OR^-, halide anion, RS^-, RSO_2^-, *etc.*) or neutral (*e.g.*, H_2O, ROH, amines of all types). Thus, from the point of view of charge type, there are four main classes of nucleophilic substitutions, as first depicted by Ingold[2] in equations 3—6:

$$Nu^- + RX \longrightarrow R\text{–}Nu + X^- \qquad (3)$$

$$Nu + RX \longrightarrow R\text{–}Nu^+ + X^- \qquad (4)$$

$$Nu^- + RX^+ \longrightarrow R\text{–}Nu + X \qquad (5)$$

$$Nu + RX^+ \longrightarrow R\text{–}Nu^+ + X \qquad (6)$$

It can be seen that in equations 3 and 6 charge is conserved, while in equation 4 charge is created, and in equation 5 charge is destroyed. These distinctions are of fundamental importance, as will become apparent.

3 Unimolecular and Bimolecular Modes of Nucleophilic Substitution

Ingold first saw clearly[3] that not all nucleophilic substitutions occur by the same mechanism. He distinguished between the bimolecular mode of reaction, where the rate is first order both in the nucleophile and in the substrate concentration, and the unimolecular mode, where the rate depends only on the concentration of the substrate and is independent of that of the nucleophile. Ingold interpreted[2] these two alternative types of kinetic behaviour, respectively, as the S_N2 direct displacement (equation 7), and as the S_N1 type mechanism, where the first, effectively irreversible step is followed by fast reaction of the resulting carbocation with nucleophile (equation 8).

$$Y^* + R\text{–}X^* \longrightarrow [Y \cdots R \cdots X]^{\ddagger} \longrightarrow R\text{–}Y^* + X^* \qquad (7)$$

$$R\text{–}X^* \xrightarrow{\text{slow}} R^+ + X^*, \text{ followed by } R^+ + Y^* \xrightarrow{\text{fast}} R\text{–}Y^* \qquad (8)$$

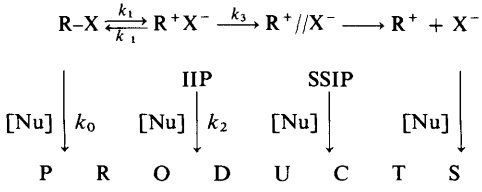
In the 1950s Winstein showed[4] convincingly that the S_N1 mechanism was more complex than had been postulated by Ingold. Working with neutral

[2] C K Ingold, 'Structure and Mechanism in Organic Chemistry', (*a*) 1st edn, Cornell University Press, New York, 1953, pp 306—418, (*b*) 2nd edn, Cornell University Press, New York, 1969, pp 418—610

[3] C K Ingold and E Rothstein, *J Chem Soc*, 1928, 1217—1221

[4] (*a*) S Winstein and D Trifan, *J Am Chem Soc*, 1952, **74**, 1154—1160, (*b*) S Winstein and G C Robinson, *J Am Chem Soc*, 1958, **80**, 169—181, (*c*) S Winstein, P E Klinedinst, Jr, and G C Robinson, *J Am Chem Soc*, 1961, **83**, 885—895

substrates, he obtained evidence that the ionization took place in several stages and he distinguished between 'intimate ion pairs' (IIP) and 'solvent-separated ion pairs' (SSIP) as two distinct types of discrete intermediate before the stage of a free carbocation was reached (Scheme 1).



Scheme 1

In the 1960s, Sneen pointed out[5] that these intimate ion pairs should also be able to react in the bimolecular mode with a nucleophile (equation 10). Although Sneen's postulate that *all* S_N2 reactions involve intimate ion pairs was later shown to be untrue,[6] the mechanism must be considered as a possible alternative in favourable cases.

Sneen mechanism

$$\underset{\text{intimate ion pair}}{R\text{–}X \xrightarrow{\text{fast}} R^+ \cdots X^-} \xrightarrow[\text{rate determining}]{\text{Nu}} R\text{–}Nu \qquad (10)$$

Another potential complication is the participation in the substrate of an adjacent substituent in the unimolecular bond-breaking phase of the S_N1 reaction.[7] Carbocations readily undergo rearrangement (equation 11), and the postulate is that such rearrangement could begin before the bond-breaking was complete, and might accelerate it.[7] As shown in Scheme 2, the substrate (9) can undergo direct S_N2 reaction to give (8), or form the intimate ion pair (11) which in turn could form unrearranged product (8) or rearrange to carbonium ion (12). In the participation hypothesis, carbonium ion (12) would be formed directly from (9).

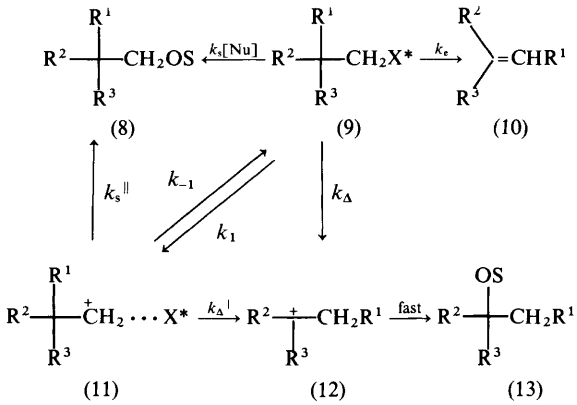
$$RR'CH\overset{+}{C}HR'' \longrightarrow R\overset{+}{C}HCHR'R'' \qquad (11)$$

Use of available experimental evidence to distinguish between these alternative possible pathways of Scheme 2 has been controversial. Direct S_N2 displacement [(9) ⟶ (8), Scheme 2] by solvent as nucleophile to yield unrearranged product,

[5] (*a*) R A Sneen, *Acc Chem Res*, 1973, **6**, 46—53, (*b*) R A Sneen and J W Larsen, *J Am Chem Soc*, 1969, **91**, 362—366, (*c*) R A Sneen and J W Larsen, *J Am Chem Soc*, 1969, **91**, 6031—6035

[6] (*a*) T W Bentley and P v R Schleyer, *J Am Chem Soc*, 1976, **98**, 7658—7666, (*b*) F L Schadt, T W Bentley, and P v R Schleyer, *J Am Chem Soc*, 1976, **98**, 7667—7674, (*c*) T W Bentley and P v R Schleyer, *Adv Phys Org Chem*, 1977, **14**, 1—67

[7] (*a*) S Winstein and H Marshall, *J Am Chem Soc*, 1952, **74**, 1120—1126, (*b*) A Streitwieser, 'Solvolytic Displacement Reactions', McGraw-Hill, New York, 1962



Scheme 2 *Solvolysis processes for primary systems*
(Reproduced from reference 39 with permission)

was believed by Winstein[7a] to dominate normally, with occasional competitive first-order anchimerically assisted heterolysis [(9) ⟶ (12)], that could be rate-determining and was followed by fast formation of rearranged product [(12) ⟶ (13), Scheme 2]. Anchimeric assistance by H or Me transfer, was rejected by later workers and the results interpreted in terms of path (9) ⟶ (8), path (9) ⟶ (11) ⟶ (12) ⟶ (13), and path (9) ⟶ (11) ⟶ (8) of Scheme 2.[8–10] However, controversy remains[11] and, in particular, evidence from secondary kinetic isotope effects favours participation.[12–14]

More recently, it has been shown that electron transfer processes can also be involved in nucleophilic substitution in general,[15] and substitution reactions on charged substrates in particular.[16]

4 Symbolic Representation of Nucleophilic Substitution Reaction Mechanisms

The use of poorly defined terms has caused confusion about reaction mechanisms in chemistry. The system introduced by Ingold suffers from having to serve both as a phenomenological description of the observed features of reactions (substitution, elimination) and as a statement of the mechanism of the reaction

[8] V J Shiner, Jr, 'Isotope Effects in Chemical Reactions', ed C J Collins and N S Bowman, Van Nostrand, Reinhold, New York, 1970, p 90
[9] J E Nordlander, S P Jindal, P v R Schleyer, R C Fort, Jr, J J Harper, and R D Nicholas, *J Am Chem Soc*, 1966, **88**, 4475–4484
[10] W M Schubert and W L Henson, *J Am Chem Soc*, 1971, **93**, 6299–6301
[11] J M Harris, *Prog Phys Org Chem*, 1974, **11**, 89–173
[12] T Ando, H Yamataka, H Morisaki, J Yamawaki, J Kuramochi, and Y Yukawa, *J Am Chem Soc*, 1981, **103**, 430–434
[13] V J Shiner, Jr and R C Seib, *Tetrahedron Lett*, 1979, **20**, 123 126
[14] V J Shiner, Jr and J J Tai, *J Am Chem Soc*, 1981, **103**, 436–442
[15] (*a*) I P Beletskaya and V N Drozd, *Russ Chem Rev* (*Eng Transl*), 1979, **48**, 431–448, (*b*) M Chanon and M L Tobe, *Angew Chem, Int Ed Engl*, 1982, **21**, 1–23
[16] A R Katritzky, in 'Substituent Effects in Radical Chemistry', ed H G Viehe, Reidel Publishing Co, 1986, pp 347–360

(molecularity, concertedness, electronic characteristics). The Ingold nomenclature is also sometimes ambiguous in its interpretations of mechanisms, perhaps most noticeably for S_N2–S_N1 reactions in solvolysis and bimolecular substitutions; some quite different mechanisms fall under the same designation. Moreover, the original Ingold system has been overburdened with non-systematic modification for 30 years.

A new, clear descriptive nomenclature of reaction mechanism is that recommended by IUPAC which deals directly with the basic currency of molecular change: bond making and bond breaking.[17] This system describes the most important properties of reaction mechanisms, *e.g.* the number of steps in the reaction, the sequence of these steps and their nature, including significant diffusion steps.

The formation of a new bond during the transformation of one molecular structure to another is symbolized by '*A*' (association or attachment) and, conversely, the bond breaking components are symbolized by '*D*' (dissociation or detachment). These '*A*' and '*D*' symbols are referred to as 'primitive changes'. When the changes take place in separate reaction steps, they are punctuated by a '+'. A symbol '✱' is used instead of the '+' to designate an intermediate which is of such a short lifetime that it reacts in a step faster than diffusion but slower than a molecular vibration. Sets of non-punctuated '*A*' and '*D*' symbols correspond to 'elementary reactions'. The subscript 'N' is used to designate bond formation to a nucleophile or bond scission with loss of a nucleofuge (*i.e.* leaving group). There is also provision for describing homolytic and cyclic mechanisms and for extra-mechanistic information, including the class of transformation, the nature of the substitution, and the occurrence of catalysis, using easily pronounced terms.

According to the above rules, the mechanisms of nucleophilic substitution at saturated carbon atoms can be described as follows:

A_ND_N Concerted; one step.

$D_N{}^*A_N$ Stepwise; short-lived intermediate, *e.g.* ion pair. Components are not diffusionally equilibrated with the bulk solvent.

$D_N + A_N$ Stepwise; the intermediate can diffuse thorough the solvent.

These correspond to the Ingold S_N2, the ion-pair, and the S_N1 mechanisms, respectively.

5 Why Are Different Mechanisms Followed

Much of the experimental work on reaction mechanisms has been concerned with fitting reactions into the Ingold scheme, or other schemes, such as Winstein's classification of ion-pair intermediates in solvolysis reactions. In comparison there has been comparatively little inquiry into the questions of why a reaction should follow one mechanism rather than another under a particular

[17] (*a*) R. D. Guthrie, *Pure. App. Chem.*, 1989, **61**, 23—56; (*b*) R. Guthrie and W. P. Jencks, *Acc. Chem. Res.*, 1989, **22**, 343—349.

set of experimental conditions and what is the nature of the transition from one mechanism to another as reactants or conditions are changed The answers to these questions are determined in large part by the reaction intermediates whether intermediates are formed at all, what are their structures, and what are their properties Many of the controversies regarding mechanisms come from uncertainty or disagreement about the existence and behaviour of intermediates An intermediate can be defined as a species with a lifetime that is longer than that of a molecular vibration of $\sim 10^{-13}$ s, *i e* a species that has barriers to breakdown both to reactants and to products [18]

Since the distinction between mechanisms of chemical reactions in solution are mainly concerned with the sequence in which reactants are assembled and dispersed in relation to the bond-making and bond-breaking steps, the choice of reaction mechanism is dictated by the lifetimes of intermediates that may be formed in a reaction

A reaction can proceed through a stepwise, monomolecular reaction mechanism when the intermediate has a significantly long lifetime in the solvent, but no lifetime when it is in direct contact with a stronger nucleophilic reagent in the solution and this reagent is favourably oriented Conversely, a concerted, bimolecular reaction mechanism, will take place only when such an intermediate does not exist, *i e* this species is not stable for a few vibration frequencies and there is no barrier for its collapse Concerted reactions with a solute and stepwise reactions with solvent can coexist in the same solution The existence of a solvent-equilibrated intermediate can be diagnosed in several ways (a) by trapping the intermediate, (b) by demonstrating a constant partitioning ratio to products of a common intermediate that is derived from different reactants, (c) by observing a change in rate-limiting step with increasing concentration of reactant or catalyst, (d) by demonstrating a diffusion-controlled reaction with the intermediate [18]

When the lifetime of the intermediate becomes shorter, the reaction may proceed through an enforced preassociation mechanism in which a molecule that will react in a second step (or process) forms an encounter complex with the other reactant (or reactants) before the first step (or process) takes place A concerted mechanism also requires preassociation of the reactants and can be considered as a special case of a preassociation mechanism [18 19]

The reaction coordinate–energy diagram of Figure 1 provides a convenient way to illustrate the above points The diagram, which has wings added to describe diffusional steps, is drawn with the carbon-nucleophile bond order along the abscissa, the carbon-leaving group bond order on the ordinate, and Gibbs energy indicated in the third dimension by the contour lines, in accordance with the usual convention for such diagrams, most of the energy contour lines are omitted for clarity The fully stepwise mechanism with a solvent-equilibrated carbocation intermediate proceeds through the pathway on the outside of the

[18] W P Jencks, *Acc Chem Res*, 1980, **13**, 161—169
[19] W P Jencks, *Chem Soc Rev* 1981 **10**, 345 375

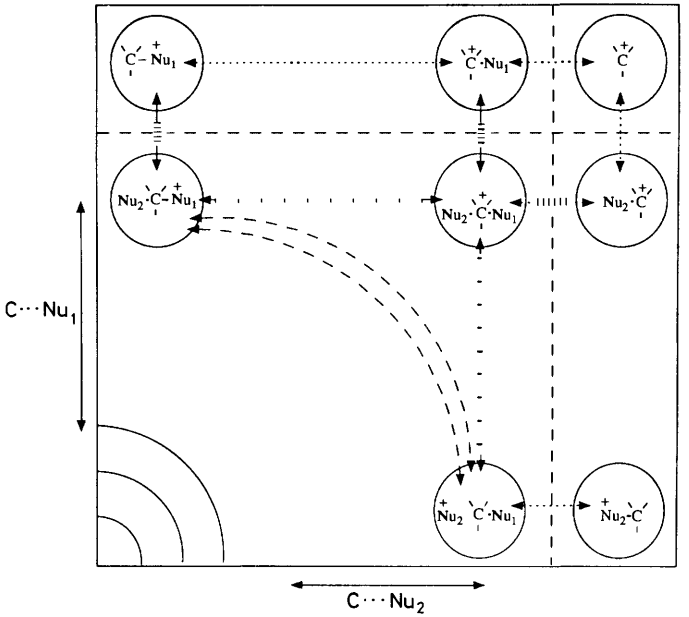


Figure 1 *Reaction coordinate diagram for nucleophilic substitution on carbon with wings for the transport steps. The contour lines are omitted except for the lower left corner*
(Reproduced from reference 18 with permission)

diagram (dotted lines), a reaction with an ion-pair in a weakly nucleophilic solvent enters the centre of the diagram at the upper right, and a preassociation mechanism can proceed through the intermediate in the central box, if it exists, or through concerted pathways 2 and 3 with varying amounts of cationic character in the transition state.

The above discussion may be illustrated by a study of 1-phenylethyl systems.[20–22] The lifetimes of carbocation intermediates were estimated by diffusion-controlled trapping with azide, extrapolating these lifetimes to less stable cations and taking account of the nucleophilic reactivity of added nucleophiles. It was shown that the appearance of concerted bimolecular reactions occurs only when the cation is predicted to have no lifetime in the presence of the nucleophile and the change from stepwise to a concerted mechanism occurs when the intermediate ceases to have a lifetime in the presence of nucleophile.

6 Behaviour at Mechanistic Borderlines

A longtime source of controversy has been the interpretation of behaviour at mechanistic borderlines. Although data is available for many 'borderline'

[20] J. P. Richard and W. P. Jencks, *J. Am. Chem. Soc.*, 1984, **106**, 1383—1396.
[21] J. P. Richard and W. P. Jencks, *J. Am. Chem. Soc.*, 1982, **104**, 5689—4691.
[22] J. P. Richard and W. P. Jencks, *J. Am. Chem. Soc.*, 1982, **104**, 4691 ··4692.

reactions, the interpretation of the results is often made uncertain by the assumptions and corrections that have to be applied when treating the experimental observations For example, in reactions involving anionic nucleophiles, corrections have to be applied for salt effects and, in some cases, for incomplete dissociation of the salt used to supply the nucleophile

An important aspect of the controversy has been whether borderline behaviour represents simply the availability of two alternative reaction paths in competition, or a gradual transition from one pathway to another In the first interpretation,[23] the dominant path under one set of conditions becomes less important as another mechanism becomes more important In the second interpretation,[5] there exists a 'spectrum of merging mechanisms', with a character that is intermediate between S_N1 and S_N2 modes

It has frequently been suggested that a clear-cut distinction between reaction mechanisms is impossible because, for example, there is a gradual transformation of an S_N2 into an S_N1 mechanism with no sharp borderline as the transition state develops more carbocation character [24] Uncertainty on this point complicates the teaching of this important subject [1] and is the source of much confusion at all levels However, a clear distinction can be made if the classification of mechanism is based upon the lifetime of intermediates rather than the character of the transition state The lifetime of intermediates permits a fairly sharp *qualitative* distinction between mechanisms, whereas the character of the transition state or the degree of assistance by the solvent in a reaction gives only a *quantitative* description with no sharp boundaries [18]

The term 'spectrum of merging mechanisms' is widely used in the literature This implies that there is no clear distinction between mechanisms But an intermediate either exists or does not exist, with a fairly sharp distinction between these possibilities, so that a reaction either proceeds in one step, or two steps, or more steps It cannot proceed in one and a half steps Use of terms such as 'merging mechanism' has contributed to much of the confusion in this field and should be discouraged

7 Gas Phase Investigations

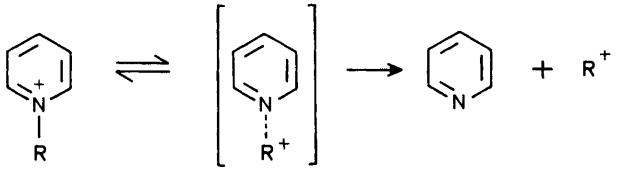
In addition to the structure of the substrate, and the nature of the nucleophile and leaving group, the overall rates of S_N1 ($D_N + A_N$) and S_N2 (A_ND_N) reactions are strongly medium-dependent Sometimes, solvent effects can completely change relative nucleophilicities, as has been shown for halide anions in protic and aprotic solvents [25] Reaction in the gas phase, in the absence of the complicating solvent effects, can shed light on nucleophilicities, leaving group abilities, and steric effects

S_N2 (A_ND_N) type reactions have been extensively studied in the gas phase

[23] (*a*) P Caspieri and E R Swart, *J Chem Soc*, 1961, 4342—4347 (*b*) A Fava, A Iliceto, and A Ceccon, *Tetrahedron Lett*, 1963, **4**, 685—692

[24] S Winstein, E Grunwald, and H W Jones, *J Am Chem Soc*, 1951, **73**, 2700—2705

[25] S Winstein, L G Savedoff, S Smith, I D R Stevens, and J S Gall, *Tetrahedron Lett*, 1960, **1**(9), 24—30



(14) (15) (16) (17)

Scheme 3 *Fragmentation of alkyl-pyridinium cations to pyridine and carbocation*

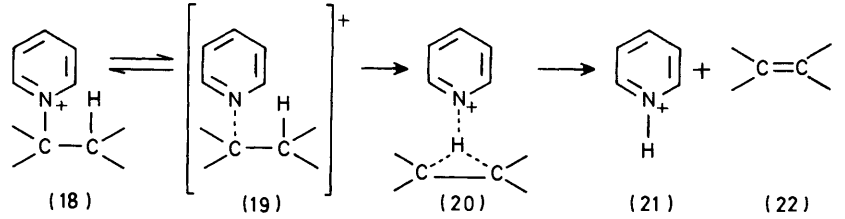
where S_N2 (A_ND_N) reactions of anionic nucleophiles with neutral substrates can be faster than in solution due to preferential solvation of reactants compared to the transition state.[26] The experimental results were interpreted by a model in which the collision complex and a complex of the leaving entities were separated by an energy barrier. Such reactions proceed in the gas phase with inversion of configuration at the carbon atom, just as in solution.[26]

Anions with a localized charge are better gas-phase nucleophiles than those with a delocalized charge: thus benzyl anions are poor nucleophiles despite their large methyl cation affinities.[27] In solution, polarizable nucleophiles are better than non-polarizable ones because they can respond better to demand for charge reorganization. The gas-phase studies[26] show just the opposite behaviour and indicate that the higher nucleophilicity of polarizable anions in solution is a consequence of stronger solvation of the anions with more concentrated charge. Relative nucleophilicities are similar in the gas phase and in dipolar aprotic solvents but very different from those found in protic solvents. However, leaving group abilities are similar for all three media.[26]

Interestingly, gas-phase studies of *N*-alkylpyridinium cations showed that they do indeed undergo fragmentation to neutral pyridine and the carbocation in the gas phase, similarly to their reactions in non-polar solvents (Scheme 3).[28] In addition, many compounds which by beta-elimination can form a strain-free olefin, choose a second pathway to yield protonated pyridine and this olefin (Scheme 4).[29]

The kinetic energy required for dissociation (the 'appearance energy') was determined by measuring the percentage of collisionally activated dissociation (CAD) as a function of the relative kinetic energy. Since reliable thermochemical data are not available for comparison with experimentally derived appearance energies, theoretically calculated energies of pyridine$^+$–R bond cleavage were applied. Heats of formation were calculated for the pyridinium ions Py$^+$–R, for

[26] W. N. Olmstead and J. I. Brauman, *J. Am. Chem. Soc.*, 1977, **99**, 4219—4228.
[27] D. K. Bohme and L. B. Young, *J. Am. Chem. Soc.*, 1970, **92**, 7354—7358.
[28] (*a*) C. H. Watson, G. Baykut, Z. Mowafy, A. R. Katritzky, and J. P. Eyler, *Anal. Instrument.*, 1988, **17**, 155—162; (*b*) A. R. Katritzky, C. H. Watson, Z. Dega-Szafran, and J. R. Eyler, *J. Am. Chem. Soc.*, 1990, **112**, 2471—2478.
[29] A. R. Katritzky, C. H. Watson, Z. Dega-Szafran, and J. R. Eyler, *J. Am. Chem. Soc.*, 1990, **112**, 2479—2484.



(18) (19) (20) (21) (22)

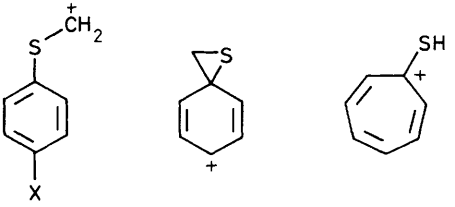
Scheme 4 *Fragmentation of alkyl-pyridinium cations to protonated pyridine and alkene*

pyridine, and for the alkyl cations R^+ using the *AM*1 method.[30] From these ΔH_f values the theoretical heats of dissociation $\Delta\Delta H_f$ for the process of Schemes 3 and 4 were calculated using equation 12:

$$\Delta\Delta H_f = [\Delta H_f(\text{Py}) + \Delta H_f(R^+)] - \Delta H_f(\text{Py}^+\text{–R}) \qquad (12)$$

For those alkyl-pyridinium cations where the carbocation cannot, or is unlikely to, undergo any rearrangement to a more stable system the appearance potentials are either higher or within 3 kcal mol^{-1} of the calculated $\Delta\Delta H_f$ values from equation 12 (methyl, allyl, adamantyl, 1-benzotriazolylmethyl, cinnamyl, diphenylmethyl, or triphenylmethyl pyridinium cations: see Figure 2).

By contrast, for many other *N*-substituted pyridinium cations, the appearance potentials were found to be considerably less than those that would be required to produce an unrearranged carbocation. However, in all such cases it was found that rearrangement pathways were available to the carbocation that would reduce its heat of formation so that the appearance potential would provide enough energy. Thus the low appearance potential found for phenylthiomethyl cation (23) (Figure 2) indicates that rearrangement of (23) occurs through (24) almost all the way to (25) with this $\Delta\Delta H_f$ of 22 kcal mol^{-1} closest to the appearance potential of 32 kcal mol^{-1}.



(23) (24) (25)

Comparison of the calculated $\Delta\Delta H_f$ values with the appearance potentials indicates that for β-phenylethyl cations not only is their dissociation to unrearranged carbocations precluded, but also that rearrangement of (26) to

[30] M. J. S. Dewar, E. G. Zoebisch, E. F. Healy, and J. J. P. Stewart, *J. Am. Chem. Soc.*, 1985, **107**, 3902–3910.

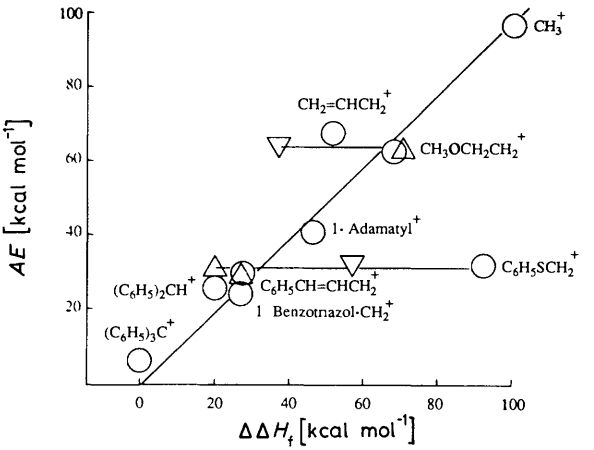
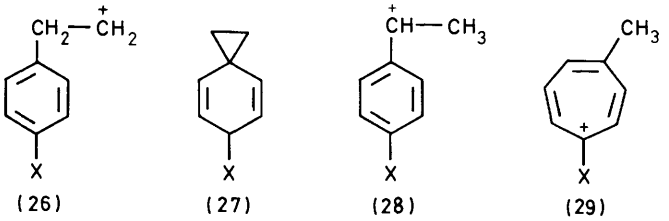


Figure 2 *Plot of experimentally estimated appearance energies (AE) against calculated heats of formation* ($\Delta\Delta H_f$) *of* R^+ *from* N-*substituted pyridinium salts: unrearranged cations* (○)*; cations with successively more extensive rearrangement* (△). [*Values from ref.* 28(*b*)]



spiro (27) during the dissociation process by anchimeric assistance does not provide enough energy. The low appearance potentials suggest that alternative rearrangement of (26) to (28) must occur to a significant extent during the dissociation and possibly that further rearrangement of (28) to (29) occurs.

The dissociation processes of *N*-alkylpyridinium cations in the gas phase invoke the Py • • • R^+ ion–molecule pair as an important intermediate in which non-stabilized R^+ can rearrange to a more stable structure.

8 The Role of the Solvent

The investigation of the detailed mechanism of nucleophilic substitutions of neutral substrates in solution is particularly difficult because of the charge that is created in the transition state of an S_N1 ($D_N + A_N$) type reaction (equation 13). Because of this charge creation, the S_N1 ($D_N + A_N$) reaction mode is neither expected nor found for neutral substrates in non-polar solvents. Moreover, in polar media, the solvent is invariably a potential nucleophile and it may be difficult to disentangle whether such a solvent is behaving simply as a medium of dielectric constant sufficiently high to allow the charge creation in an S_N1 (D_N +

A_N) type process (equation 13), or whether it is behaving as a nucleophile in a S_N2 (A_ND_N) type mechanism.

$$R\text{–}X \longrightarrow R^{\delta+} \cdots X^{\delta-} \text{ (transition state)} \quad (13)$$

$$R\text{–}X^{+} \longrightarrow R^{\delta+} \cdots X^{\delta+} \text{ (transition state)} \quad (14)$$

Such difficulties of interpretation are far less for cationic substrates, because charge is *spread* in the transition state rather than created: contrast equation 14 with equation 13. Thus S_N1 ($D_N + A_N$) type reactions of cationic substrates are expected to, and do, occur in non-nucleophilic solvents of low dielectric constant.[31] Their behaviour in such solvents can be followed and extrapolated through media of increasingly greater polarity.

9 Investigation of Cationic Substrates

Surprisingly, until quite recently very little mechanistic work has appeared on the use of cationic substrates to investigate the mechanisms of nucleophilic substitution at sp^3 carbon centres, the most notable exception being the t-butyldimethylsulphonium cation.[32]

A study of the mechanistic aspects of nucleophilic substitution at saturated carbon atoms where a neutral heterocyclic species was the leaving group commenced in one of our research groups in 1978. Originally this work was motivated by the need for understanding a reaction of considerable synthetic potential,[33] but it soon became evident that it could lead to a deeper understanding of the mechanism of nucleophilic substitution in general. The second part of this review summarizes the conclusions from this work.

The first fundamental question to be resolved was whether the different mechanisms remained distinct at borderlines or whether they merged into each other. Positive evidence will first be presented for the occurrence of distinct mechanisms in competition and the detailed behaviour of primary, secondary, and tertiary substrates will then be reviewed.

10 Positive Evidence for the Occurrence of Distinct S_N1 ($D_N + A_N$) and S_N2 (A_ND_N) Reactions

Plots of substrate rates *vs.* nucleophile concentration, under pseudo-first-order conditions, gave straight lines for a variety of primary and secondary alkyl substrates with a range of nucleophiles in several non-polar and non-nucleophilic solvents.[31,34] However, there was a highly significant difference in the behaviour

[31] (*a*) A R Katritzky and G Musumarra, *Chem Soc Rev*, 1984, **13**, 47—68, (*b*) A R Katritzky, K Sakizadeh, and G Musumarra, *Heterocycles*, 1985, **23**, 1765—1813, (*c*) A R Katritzky and B E Brycki, *J Phys Org Chem*, 1988, **1**, 1—20

[32] (*a*) C G Swain, L E Kaiser, and T E C Knee, *J Am Chem Soc*, 1958, **80**, 4092—4094, (*b*) D N Kevill, W A Kamil, and S W Anderson, *Tetrahedron Lett*, 1982, **23**, 4635—4638

[33] (*a*) A R Katritzky, *Tetrahedron*, 1980, **36**, 679—699, (*b*) A R Katritzky and C M Marson, *Angew Chem, Int Ed Engl*, 1984, **23**, 420—429

[34] A R Katritzky, G Musumarra, K Sakizadeh, S M M El-Shafie, and B Jovanovic, *Tetrahedron Lett*, 1980, **21**, 2697—2699

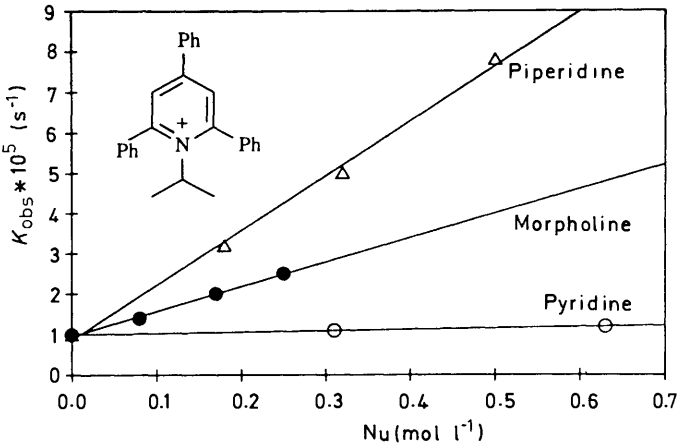


Figure 3 *Nucleophilic substitutions by simultaneous* S_N1 ($D_N + A_N$) *and* S_N2 (A_ND_N) *reactions:* k_{obs} *for* 1-*isopropyl*-2,4,6-*triphenylpyridinium cation* (30) (1.6×10^{-3} M) *plotted* vs. *nucleophilic concentration* (*chlorobenzene solution*, 100 °C)
(Reproduced from reference 34 with permission)

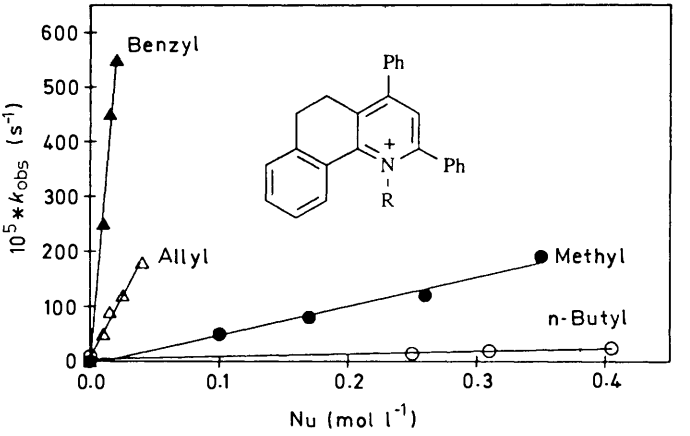


Figure 4 *Rate variation with* N-*substituent:* k_{obs} *for reactions of* N-*substituted* 2,4-*diphenyl*-5,6-*dihydrobenzo*[h]*quinolinum cations* (36), (38), (40), (41) (6.4×10^{-5} M) *with piperidine in chlorobenzene at* 100 °C
(Reproduced from reference 31 with permission)

of the two types of alkyl substrates. The plots for secondary alkyl groups showed a positive intercept which was invariant with the nature of the nucleophile, as seen for example in Figure 3 for the 1-isopropyl-2,4,6-triphenylpyridinium cation (30).[34] By contrast, the lines for primary alkyl substrates generally did not show such intercepts: in Figure 4 this contrasting behaviour is illustrated for a series of benzo[*h*]quinolinum cations (36), (38), (40), and (41).

Positive intercepts, which are invariant with the nature of the nucleophile, have also been found for many reactions in aqueous solution, including the reactions of methoxymethoxy-2,4-dinitrobenzene with neutral nucleophiles,[35] the reactions of *N*-(methoxymethyl)-*N*,*N*-dimethyl-*m*-nitroanilinium cation with anionic nucleophiles and *N*-(methoxymethyl)-*N*,*N*-dimethyl-*p*-bromoanilinium cation with neutral nucleophiles[36] as well as reactions of 1-(4-nitrophenyl)ethyl chloride with anionic nucleophiles.[19] In these cases, the positive intercepts could be caused by concerted reactions of substrates with water.

However, the positive intercepts in the non-polar, non-nucleophilic solvents clearly indicate that unimolecular ($D_N + A_N$)* and bimolecular reactions (A_ND_N) proceed simultaneously and independently for the secondary alkyl substrates. Much further evidence, part of which is summarized in the following sections, supports this conclusion.

11 Nucleophilic Substitution with primary-Alkyl Substrates

Primary-alkyl substrates have a variety of reaction pathways open to them as seen in Scheme 1. We shall see that they normally react by a bimolecular S_N2 (A_ND_N) mode although S_N1 ($D_N + A_N$) type reactions can occur under some conditions favouring such behaviour.

In addition to the evidence of Figure 4, where no intercepts were found for various substrates reacting with the same nucleophile (piperidine) further evidence for the bimolecular S_N2 (A_ND_N) mode is given in Figure 5. This shows separate plots of k_{obs} for three different nucleophiles (piperidine, morpholine, and pyridine) at various concentrations reacting with 1-benzyl-2,4,6-triphenylpyridinium (31) at 100 °C in chlorobenzene solution.[34] Rates for each nucleophile plot as a straight line which passes through the origin, showing that the reaction is first order in nucleophile. The second-order rate constant is proportional to the slope of the line in the plot, and as expected is greatest for piperidine, less for morpholine, and by comparison very much smaller for pyridine, a much less powerful nucleophile.[34]

A distinction between the two possible alternative types of S_N2 reactions, *i.e.*, classical on the substrate and Sneen-type on the intimate ion–molecule pair, was reached from pressure experiments. The classical S_N2 (A_ND_N) reaction rate is enhanced by pressure (*i.e.*, the $\Delta V^{\ddagger}$ is negative), because the two reactants will be pushed closer together.[37] However, for a Sneen-type S_N2 ($D_N{}^*A_N$) reaction on an intimate ion–molecule pair, a large positive $\Delta V^{\ddagger}$ is expected because the pre-equilibrium (equation 10) will be pushed to the left by increasing pressure. The

* The products of solvolysis reactions in non-nucleophilic solvents in the absence of nucleophile have been elucidated (see ref 47) *N*-Alkylpyridinium tetrafluoroborates solvolyse in the absence of nucleophiles in chlorobenzene to give products of alkylation both of the solvent and of the pyridine leaving group In nitrobenzene, only the leaving group is alkylated

[35] G A. Craze, A J Kirby, and R J Osborne, *J Chem Soc*, *Perkin Trans 2*, 1973, 357—363

[36] B L Knier and W P Jencks, *J Am Chem Soc*, 1980, **102**, 6789—6798

[37] (*a*) T Asano and W J Le Noble, *Chem Rev*, 1978, **78**, 407—489, (*b*) M Okamoto, M Sasaki, and J Osugi, *Rev Phys Chem Jpn*, 1977, **47**, 33—43

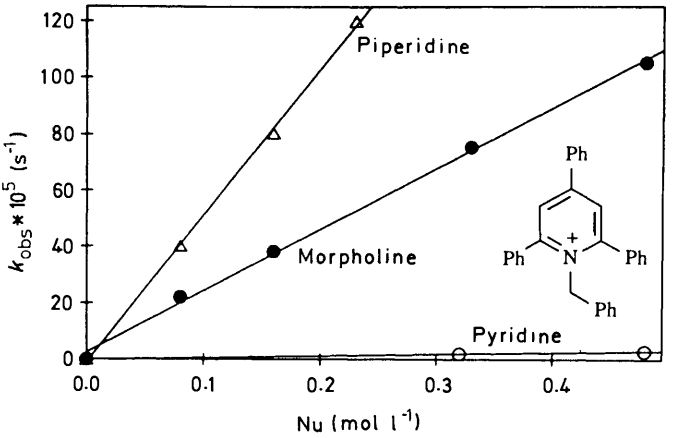
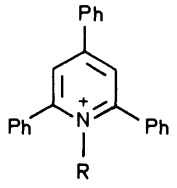
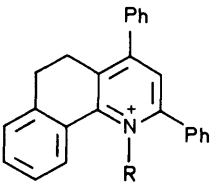
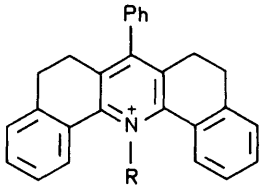


Figure 5 *Nucleophilic substitution by* S_N2 (A_ND_N) *reaction only;* k_{obs} *for* 1-*benzyl*-2,4,6-*triphenylpyridinium cation* (31) (1.6×10^{-3} M) *plotted* vs. *nucleophilic concentration* (*chlorobenzene solution*, 100 °C)
(Reproduced from reference 34 with permission)







(30) R = isopropyl
(31) R = benzyl
(32) R = *p*-methoxybenzyl
(33) R = s-butyl
(34) R = cyclopentyl
(35) R = cyclohexyl

(36) R = methyl
(37) R = isopropyl
(38) R = n-butyl
(39) R = s-butyl
(40) R = allyl
(41) R = benzyl

(42) R = benzyl
(43) R = n-propyl
(44) R = n-pentyl
(45) R = n-octyl
(46) R = isobutyl
(47) R = neopentyl

second stage of the reaction (see equation 10) will possess a negative $\Delta V^{\ddagger}$, but its magnitude should be smaller than that for the pre-equilibrium; thus overall the reaction rate is expected to decrease with increasing pressure. The rate of the reaction of 1-*p*-methoxybenzyl-2,4,6-triphenylpyridinium perchlorate (32) with piperidine clearly decreases with pressure indicating the intimate ion–molecule pair mechanism (Figure 6). Most interestingly, the reaction rate of the *N*-benzylpentacyclic derivative (42) with piperidine initially decreases with increasing pressure, but then passes through a minimum and starts to increase (Figure 7). This indicates that the reaction at normal and fairly low pressures is *via* the intimate ion–molecule pair ($D_N{}^*A_N$) but as the pressure increases, a competing

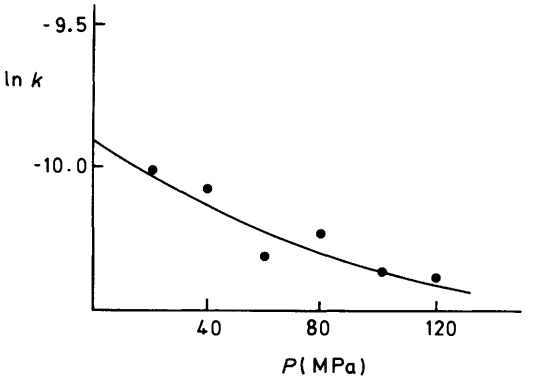


Figure 6 *Reaction via intimate ion-molecule pairs reaction of* 1-p-*methoxybenzyl*-2,4,6-*triphenylpyridinium perchlorate* (32) (2·0 × 10^{-5} M) *with piperidine* (0·1 M) *at* 30 °C *in chlorobenzene solution at varying pressures*
(Reproduced from reference 38 with permission)

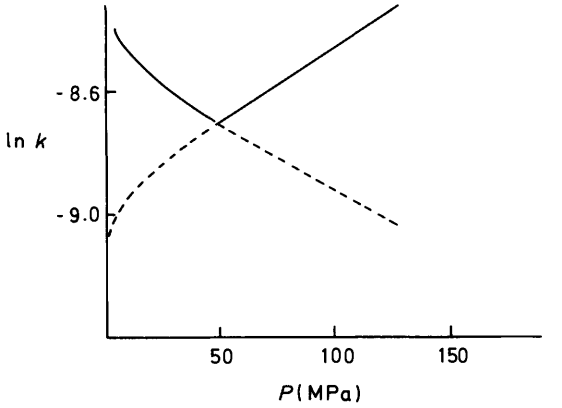


Figure 7 *Competing reactions at high pressure the pseudo-first-order rate constant for the reaction of* N-*benzyl*-5,6,8,9-*tetrahydro*-7-*phenyl*-*bis*-*benzo*[a,h]*acridinumtetrafluoroborate* (42) (2·0 × 10^{-5} M) *with piperidine* (2·0 × 10^{-3} M) *at* 30 °C *in chlorobenzene as a function of pressure*
(Reproduced from reference 38 with permission)

reaction by the classical S_N2 (A_ND_N) process gradually takes over[38] We conclude that both the alternative modes of S_N2-type behaviour can occur

For primary alkyl substrates, S_N1 ($D_N + A_N$) behaviour should be favoured by the most active leaving groups and by multiple β-branching of the alkyl group which hinders S_N2 We therefore studied the series of *N*-primary-alkyl acridinium

[38] A R Katritzky, K Sakizadeh, B Gabrielson, and W J Le Noble, *J Am Chem Soc* 1984, **106** 1879—1880

ions (43)—(45). Compounds (43)—(45), with a straight chain alkyl group, solvolyse in deuteriated methanol (CH_3OD) and in deuteriated acetic acid (CH_3CO_2D) to give mixtures of normal [(9) ⟶ (8)] and rearranged [(9) ⟶ (13)] methyl ethers and acetate esters, respectively.[39] None of the solvolysis products contain deuterium and hence none are formed *via* olefin intermediates [(10), Scheme 2]. The rearranged products [(13), Scheme 2] must arise by an S_N1 type mechanism, either by route (9) ⟶ (11) ⟶ (12) ⟶ (13) (Scheme 2) or by the anchimerically assisted path (9) ⟶ (12) ⟶ (13). Supporting the former route is the fact that the absolute rates disclose no evidence for rate-enhancing anchimeric assistance when β-phenyl or β-methoxy groups are present.

The unrearranged products are likely to be formed by an S_N2 (A_ND_N) type mechanism. In methanol the individual rates for the production of unrearranged products from the *N*-alkylacridinium ions decrease dramatically in the order:

$$\text{n-alkyl} \gg \text{i-butyl} \gg \text{neopentyl}$$

This parallels the behaviour of the corresponding tosylates, and is in agreement with the classical S_N2 (A_ND_N) path (9) ⟶ (8) of Scheme 2.

Acetolysis of the *N*-isobutylacridinium ion (46) involves an important non-olefinic pathway yielding both isobutyl and sec-butyl acetate, and acetolysis in CH_3CO_2D of the neopentyl derivative (47) yields undeuterated neopentyl acetate [*cf.* (8)] as well as deuterated tert-pentyl acetate [*cf.* (13), Scheme 2]. The rates for the formation of unrearranged products for all the alkyl groups (n-alkyl, isobutyl, and neopentyl) are constant within a factor of ~4; this cannot be reconciled with path (9) ⟶ (8), but is just what is expected for the ionization path (9) ⟶ (11) ⟶ (8), *i.e.*, predissociation to an ion–molecule pair (*cf.* equation 10).

For the solvolysis of the *N*-alkylacridinium cations in acetic acid, the rates for the formation of rearranged products (other than by way of an elimination reaction) show that the ratio of migration to direct substitution is nearly constant over the series for hydrogen migration (n-Pr, n-Pent, n-Oct), and again nearly constant over the series for methyl migration (i-Bu, neo-Pent). As the ion–molecule pair (11) is an intermediate in the formation of the unrearranged products by path (9) ⟶ (11) ⟶ (8), this supports path (9) ⟶ (11) ⟶ (12) ⟶ (13), with the intimate ion pair (or ion–molecule pair) (11) a common intermediate for the formation of both the unrearranged and the rearranged products. By contrast, where the direct substitution occurs by path (9) ⟶ (8), *i.e.*, as deduced for the *N*-alkylacridinium ions in MeOH and for the tosylates in EtOH and AcOH, such constancy of ratios is neither expected nor observed.[39]

The similarity between the ratios of the rate of hydrogen or methyl migration in an alkyl tosylate in CF_3COOH (at 75 °C) with those for the corresponding

[39] A. R. Katritzky, Z. Dega-Szafran, M. L. Lopez-Rodriguez, and R. W. King, *J. Am. Chem. Soc.*, 1984, **106**, 5577—5585.

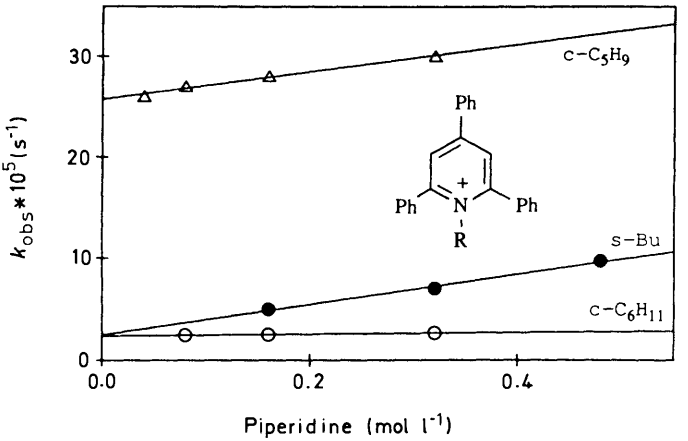


Figure 8 *Rate variation with* N-*substituent:* k_{obs} *for reactions of* N-*substituted*-2,4,6-*triphenylpyridinium cations* (33), (34), (35) (1.6×10^{-3} M) *with piperidine in chlorobenzenes at* 100 °C
(Reproduced from reference 40 with permission)

N-alkylpyridinium ion in AcOH (at 150 °C) suggests that a similar mechanism by path (9) ⟶ (11) ⟶ (12) ⟶ (13) operates for the tosylates.[2b]

12 Nucleophilic Substitution with secondary-Alkyl Substrates

s-Alkyl substrates usually react by a combination of S_N1 ($D_N + A_N$) and S_N2 (A_ND_N) modes. Plots for the reactions of 1-isopropyl-2,4,6-triphenylpyridinium cation (30) with piperidine, morpholine, and pyridine as nucleophiles in chlorobenzene were shown in Figure 3. The straight lines do not pass through the origin, but give the same significant intercept at zero nucleophile concentration. Alongside the second order S_N2 (A_ND_N) component there is thus a first order S_N1 ($D_N + A_N$) component, which is independent both of the amount and of the nature of the added nucleophile.[34]

Similar behaviour is shown for other secondary alkyl substrates. In Figure 8 (monocyclic series) and Figure 9 (tricyclic series) the nucleophile is kept constant, as piperidine, but the *N*-substituent is varied (isopropyl, secondary butyl, cyclopentyl, and cyclohexyl.)[40]

The activation entropies for the S_N1 ($D_N + A_N$) reaction mode are less negative than those for S_N2 (A_ND_N) reactions,[41] and this pattern is found[40] for the individual components of several reactions depicted in Figures 8 and 9.

The S_N1 component can be either classical ($D_N + A_N$), involving free carbonium ions, or take place by fast capture of ion–molecule pairs formed in the

[40] A. R. Katritzky, K. Sakizadeh, Y. X. Ou, B. Jovanovic, G. Musumarra, F. P. Ballistreri, and R. Crupi, *J. Chem. Soc., Perkin Trans.* 2, 1983, 1427—1434.
[41] S. R. Hartshorn, 'Aliphatic Nucleophilic Substitution,' Cambridge University Press, London, 1973, p. 81.

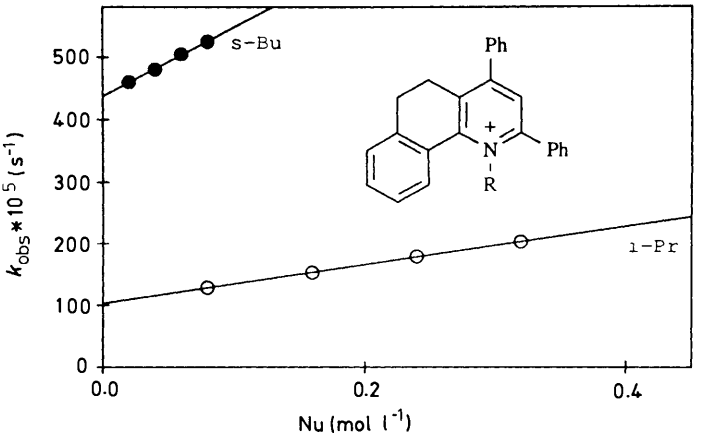


Figure 9 *Rate variation with* N-*substituent:* k_{obs} *for reactions of* N-*substituted*-2,4-*diphenyl*-5,6-*dihydrobenzo*[h]*quinolinum cations* (37), (39) (6.4×10^{-5} M) *with piperidine in chlorobenzene at* 100 °C
(Reproduced from reference 40 with permission)

rate-determining step ($D_N{}^*A_N$). These modes are distinguished by the sensitivity of rates and products to the solvent type and to added nucleophile:[40]

(i) In non-nucleophilic solvents (chlorobenzene, acetonitrile, chloroform), with added nucleophile (piperidine) there is no rate dependence on nucleophile concentration and the products show no rearrangement of the carbon skeleton, *i.e.*, Winstein S_N1 (ion–molecule pair) mechanism applies.

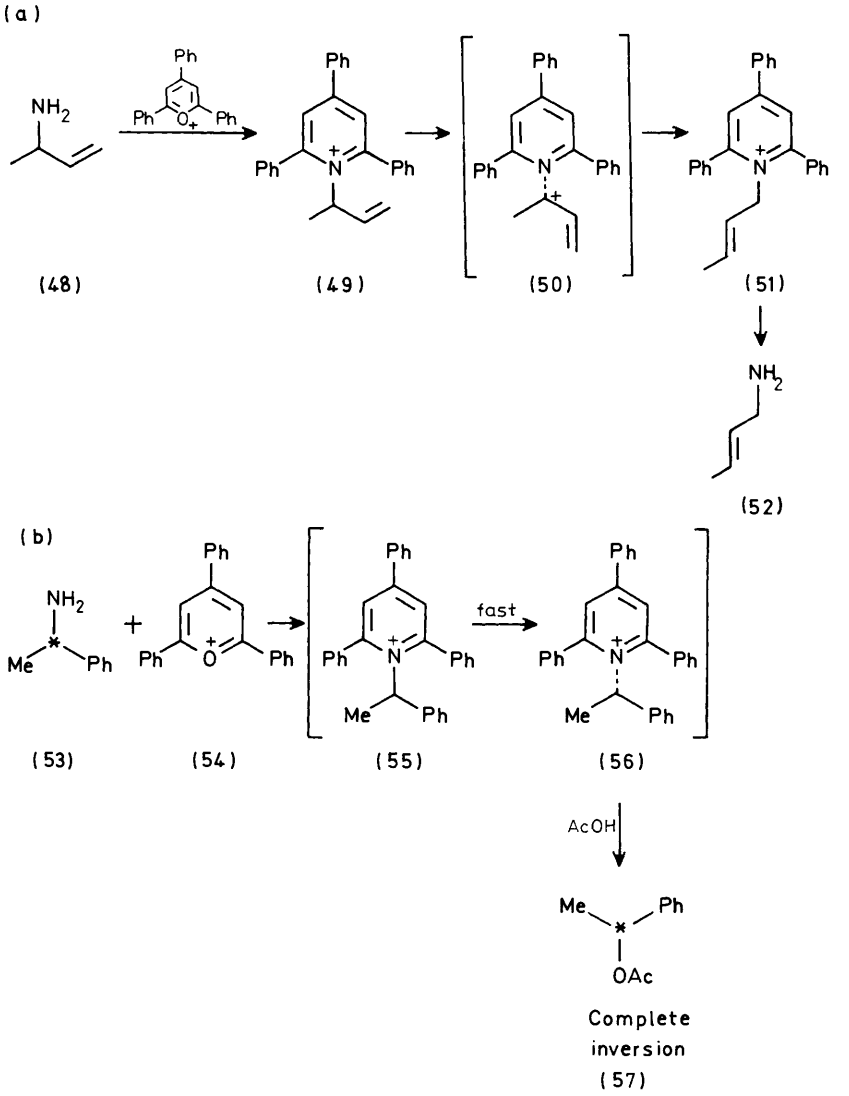
(ii) Solvolysis in weakly nucleophilic solvents (1,1,1,3,3,3-hexafluoropropan-2-ol, trifluoroacetic acid, 2,2,2-trifluoroethanol) gives partially rearranged products in the absence of added nucleophile, *i.e.*, a classical S_N1 ($D_N + A_N$) mechanism.

(iii) In the presence of nucleophile (morpholine) the products of solvolysis in 1,1,1,3,3,3-hexafluoropropan-2-ol are not rearranged although the rates are unaffected by the nucleophile concentration. This proves that rearrangement occurs after the formation of the carbocation, and is prevented by trapping an intermediate after the transition state by the added nucleophile. A Winstein S_N1 mechanism must apply as no free carbocations are involved and the reaction is first order.

(iv) Solvolysis in nucleophilic solvents (pentanol, acetic acid) gives unrearranged products, *i.e.*, classical S_N1 is excluded by analogy and a Winstein S_N1 (ion–molecule pair) mechanism is implied.

Clearly under all these conditions an S_N1 type mechanism is involved. In (i) and (iii) the added nucleophile is able to intercept the incipient carbocation before rearrangement. This indicates the formation of an intimate molecular-ion pair in a rate determining stage.

Arguments related to the variation of rates with solvent polarity parameters



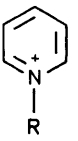
Scheme 5 *Evidence for intimate ion–molecule pair*
(Reproduced from reference 43 with permission)

indicate[42] that in nucleophilic solvents (pentanol or acetic acid), in addition to the S_N1 mechanism, a competitive S_N2 mechanism occurs, where the acetic

[42] A. R. Katritzky, M. L. Lopez-Rodriguez, and J. Marquet, *J. Chem. Soc., Perkin Trans. 2*, 1984, 349–354.

acid or pentanol molecules are acting not simply as solvent but also as nucleophiles.

Additional evidence is available for the formation of intimate ion–molecule pairs from secondary alkyl substrates. *N*-α-Methylallyl-2,4,6-triphenylpyridinium cation (49) rearranges in solution to the γ-methylallyl isomer (51) *via* an intimate ion–molecule pair (50) (Scheme 5a) because the 2,4,6-triphenylpyridine-free molecule is stable and unreactive and if formed from (49) could not give (51).[43] Furthermore, optically active α-phenylethylamine and 2,4,6-triphenylpyrylium cation in acetic acid solvent give a reactive pyridinium ion which immediately forms the corresponding acetate with complete inversion (Scheme 5b); this demonstrates that no free carbocation $PhCH(Me)^+$ is formed which would result in racemization.[43]



(58) R = adamantyl
(59) R = t-butyl
(60) R = 1-methyl-1-phenylethyl

The above evidence shows that secondary alkyl substrates can undergo nucleophilic substitution by the S_N2 (A_ND_N) and by both of the two types of S_N1 reaction; that *via* the free carbonium ion ($D_N + A_N$), and that involving an intimate ion–molecule pair ($D_N{}^*A_N$) as intermediate.

13 Nucleophilic Substitution with tertiary-Alkyl Substrates

Here the pattern is much more simple: S_N1 ($D_N + A_N$) type mechanism only.

1-(1-Adamantyl)-(58), 1-t-butyl-(59), and 1-(1-methyl-1-phenylethyl) pyridinium cations (60) solvolyse at rates independent of solvent polarity, of solvent electrophilicity, or of solvent nucleophilicity.[44] In Figure 10, the solvent polarity parameter of Dimroth, E_T,[45] measures the overall solvation ability. The E_T scale corresponds to a linear combination of solvent dipolarity, π*, and hydrogen bond donor acidity, α (α in turn corresponds to solvent electrophilicity[46]). These cationic substrates (solid points) give rates which vary less with the substrate structure than do those of the corresponding compounds with anionic leaving groups (open points), as clearly illustrated in Figure 9. This is due to the fact that charge is created in the transition state of the latter class of compounds, but not

[43] A. R. Katritzky, Y. X. Ou, and G. Musumarra, *J. Chem. Soc., Perkin Trans 2*, 1983, 1449—1454.
[44] A. R. Katritzky and B. Brycki, *J. Am. Chem. Soc.*, 1986, **108**, 7295—7299.
[45] C. Reichardt, *Angew. Chem., Int. Ed. Engl.*, 1979, **18**, 98—110.
[46] R. W. Taft and M. J. Kamlet, *J. Chem. Soc., Perkin Trans. 2*, 1979, 1723—1729.
[47] A. R. Katritzky, C. M. Marson, J. L. Chen, F. Saczewski, and R. W. King, *J. Chem. Soc., Perkin Trans. 2*, 1986, 1331—1337.

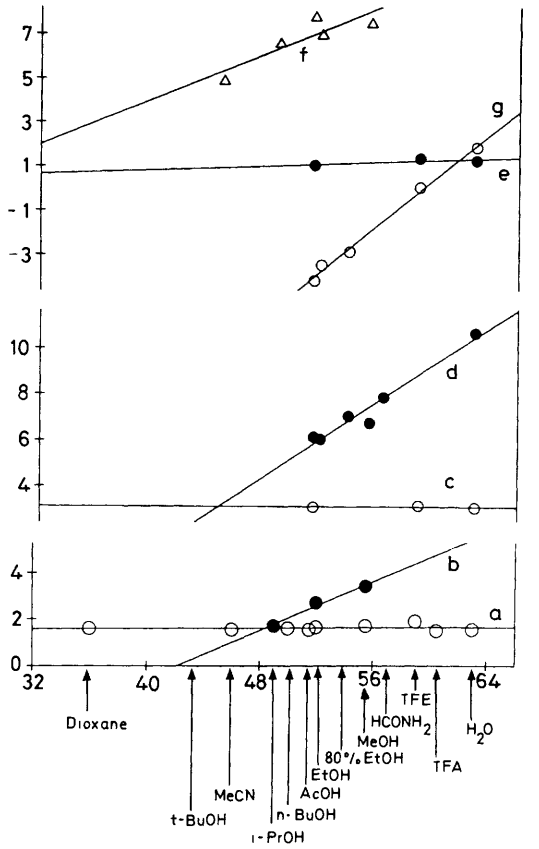


Figure 10 *Plots against E_T of logarithms of observed rate constants for the solvolysis in various solvents of* (*a*) 1-(1-*methyl*-1-*phenylethyl*)*pyridinium perchlorate* (60) *at* 80 °C, (*b*) *cumyl chloride at* 25 °C, (*c*) 1-*t-butylpyridinium perchlorate* (59) *at* 180 °C, (*d*) *t-butyl chloride at* 180 °C, (*e*) 1-(1-*adamantyl*)*pyridinium perchlorate* (58) *at* 190 °C, (*f*) 1-*adamantyl tosylate at* 190 °C, *and* (*g*) 1-*adamantyl chloride at* 50 °C
(Reproduced from reference 45 with permission)

in the former, where charge is only dispersed. Thus, halide solvolysis rates show a large sensitivity to solvent polarity. The rates for the cationic substrates (58)—(60) are unaffected by pH change, and by the presence of nucleophiles. Hence, these t-alkylpyridinium cations solvolyse by an S_N1 ($D_N + A_N$) type mechanism. There is no evidence for any participation of the solvent.

14 General Conclusions

We have presented evidence for the occurrence or non-occurrence of four mechanisms of nucleophilic substitution in solution (Table).

Table *Mechanisms found for different classes of substrate*

Mechanism	*Substrate*		
	primary-alkyl	*s-alkyl*	*t-alkyl*
Classical S_N1	yes	yes	one or both
Winstein S_N1	yes	yes	one or both
Classical S_N2	yes	one or both	no
Sneen S_N2	yes	one or both	no

These mechanism types remain distinct without merging at mechanistic borderlines. We find no evidence for rate enhancing anchimeric assistance in β-branched n-alkyl groups in solution. In the present review, we have not included evidence for electron transfer mechanisms; this can occur with certain substrates and nucleophiles, and has been summarized in part elsewhere.[16]

These conclusions apply to cationic substrates; for neutral substrates direct evidence is much more difficult to obtain, but it is tempting to extrapolate all these conclusions to all substrate types.

Acknowledgements. We thank many friends and colleagues for discussions (at times quite vigorous), particularly Drs. M. A. Battiste, J. A. Deyrup, W. P. Jencks, and J. A. Zoltewicz.