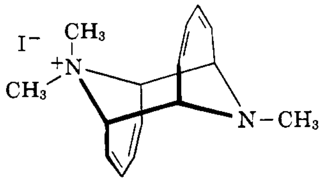

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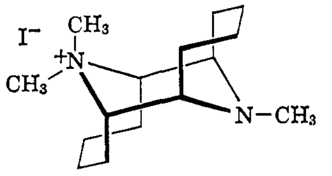

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formation of only monoquaternary derivatives has been observed in other bridged piperazines.[12]

A full account of the chemistry of these compounds is in preparation.

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(12) M. V. Rubtsov and E. S. Nikitskaya, *Usp. Khim. USSR*, **34**, 1040 (1965).

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Contribution No. 1208
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Received April 14, 1966

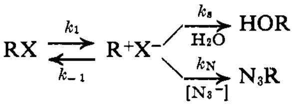
Identification of an Ion-Pair Intermediate in an SN2 Reaction[1]

Sir:

On the basis of rather indirect evidence we recently suggested[2] that a bimolecular displacement reaction, having all of the defining characteristics of an SN2 reaction, actually had as its mechanism the reversible formation of an ion pair whose subsequent attack by nucleophile was rate determining. Direct confirmatory evidence that this is the case is now available and constitutes the subject matter of this report.

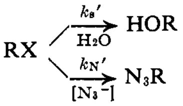
The earlier suggestion[2] was predicated upon the following observations: (1) reaction of optically active 2-octyl brosylate in 75 vol. % aqueous dioxane (25% water) containing sodium azide gave rise to inverted 2-octyl azide[3] at a rate dependent on the concentration of azide ion. Clearly the reaction exhibits the defining characteristics of an SN2 reaction, bimolecular kinetics and inversion of configuration. (2) On the other hand when optically active 2-octyl mesylate was solvolyzed in the more aqueous system, 25 vol. % aqueous dioxane (75% water), in the presence of sodium azide, 2-octyl azide was again obtained[3] at a rate *nearly independent* of the concentration of sodium azide. Significantly, the 2-octyl azide formed in this system proved to be highly inverted. Clearly, in this more aqueous system, an intermediate must be formed in the rate-determining step whose transition state does not include azide ion (kinetic fact) but which must be asymmetric since subsequent attack by azide ion gives rise to optically inverted 2-octyl azide. It was suggested[2] that this intermediate is an ion pair.

The above evidence seemed consistent with, if not conclusive for, a common mechanism for the reactions of 2-octyl sulfonates in the two solvent systems, a mechanism which includes in both an ion-pair intermediate whose formation is rate determining in the more aqueous solvent $((k_s + k_N[N_3^-]) > k_{-1})$ and whose destruction (by water and azide ion) is rate determining in the poorer ionizing solvent $(k_{-1} > (k_s + k_N[N_3^-]))$.



$$RX \underset{k_{-1}}{\overset{k_1}{\rightleftarrows}} R^+X^- \begin{cases} \xrightarrow[H_2O]{k_s} HOR \\ \xrightarrow[[N_3^-]]{k_N} N_3R \end{cases} \qquad (1)$$

If this were the case it seemed to us that there should exist some solvent composition intermediate between the above extremes, in which the rate of formation of ion pair was comparable in magnitude with its rate of destruction. In such a solvent system a clean experimental distinction can be made between the suggested ion-pair scheme (1) and a true SN2 mechanism (2) in which attack by nucleophiles takes place directly on covalent starting material. In essence this distinction arises since in a true SN2 process rates and products



$$RX \begin{cases} \xrightarrow[H_2O]{k_s'} HOR \\ \xrightarrow[[N_3^-]]{k_N'} N_3R \end{cases} \qquad (2)$$

are determined in the same steps of reaction, whereas in the ion-pair mechanism products are determined in the steps labeled k_s and k_N while the rate is a composite function of all four rate constants. The following equations provide a quantitative basis for this distinction.

A steady-state treatment of the ion-pair mechanism (1) establishes the following relationship[4]

$$k_{\text{exptl}}/k_{\text{NA}} = (x + 1)(1 + k_N[N_3^-]/k_s)/(x + 1 + k_N[N_3^-]/k_s) \qquad (3)$$

where k_{exptl} is the experimental rate constant, k_{NA} the rate constant in the absence of azide ion, x is defined as k_{-1}/k_s, and the ratio k_N/k_s is given experimentally as the slope of a plot of $[RN_3]/[ROH]$ *vs.* $[N_3^-]$. Simple algebra establishes the following relationship (4) for a true SN2 reaction (2) where k_N'/k_s' is given experimentally as the slope of a plot of $[RN_3]/[ROH]$ *vs.* $[N_3^-]$.

$$k_{\text{exptl}}/k_{\text{NA}} = 1 + k_N'[N_3^-]/k_s' \qquad (4)$$

Kinetic data for solvolyses of 2-octyl mesylate in both 25 and 30 vol. % aqueous dioxane were obtained titrimetrically. Since alkyl azide formation is not accompanied by the liberation of acid, the difference between the experimental and theoretical infinity titers was used to determine the relative amounts of 2-octanol and of 2-octyl azide. Since rate constants (treated as pseudo first order) were calculated using the experimental infinity titers they are measures of the sum of the rate constants for all processes which result in the destruction of starting material. Corrections (relatively small) for the normal salt effects produced on rates by sodium azide were made by assuming them to be equal in magnitude to those produced by lithium perchlorate[5] and by assuming them to be linear in $[N_3^-]$. The data are summarized in Tables I and II and the data of Table II are represented graphically in Figure 1. Scrutiny will make it immediately apparent that the

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(1) Supported in part by the National Science Foundation.

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

(3) Accompanied by inverted 2-octanol.

(4) Note that, in the limit, as x becomes very large, eq 3 reduces to eq 4. As x becomes very small eq 3 reduces to $k_{\text{exptl}}/k_{\text{NA}} = 1$; *i.e.*, to SN1 behavior.

(5) In separate control experiments it has been established that sodium nitrate, lithium bromide, sodium acetate, and lithium perchlorate all have nearly identical salt effects in these solvent systems.

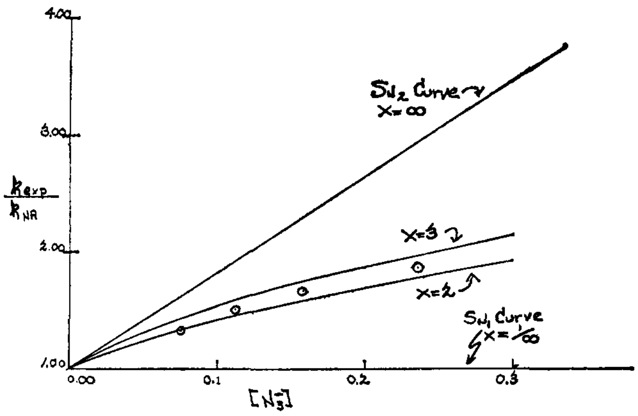

Figure 1. Plot of $k_{\text{exptl}}/k_{\text{NA}}$ *vs.* $[N_3^-]$ for the reaction of 2-octyl mesylate with sodium azide and water in 25 vol. % aqueous dioxane. The solid lines are theoretical plots from eq 3 with $k_N/k_S = 8.22$ and varying values of $x = k_{-1}/k_s$. The experimental points are encircled.

experimental data (k_{exptl}) are well correlated by the ion-pair mechanism (k_{ip}) but deviate considerably, especially at higher salt concentrations, from the rate constants calculated for a true S$_N$2 process (k_{S_N2}).

Table I. Kinetics of Solvolyses of 2-Octyl Mesylate in 30 Vol. % Aqueous Dioxane at 36.2°

$[NaN_3]$	% RN_3, exptl	% RN_3,[a] calcd	k_{exptl}, sec^{-1} × 10^4	k_{S_N2},[b] sec^{-1} × 10^4, calcd	k_{ip},[c] sec^{-1} × 10^4, calcd
...	...	...	1.74 ± 0.04	...	...
0.0543	38.4	32.3	2.43 ± 0.08	2.74	2.41
0.0571	39.3	34.1	2.26 ± 0.11	2.80	2.43
0.0979	52.5	47.0	2.67 ± 0.14	3.61	2.90
0.152	54.5	57.8	3.65 ± 0.14	4.84	3.50
0.199	64.0	64.3	3.78 ± 0.12	5.88	3.92
0.258	69.3	70.0	4.71 ± 0.08	7.36	4.47
0.311	74.6	73.8	4.91 ± 0.15	8.77	4.92

[a] Calculated from the equation $[RN_3]/[ROH] = 9.04[N_3^-]$. [b] Rate constant calculated from eq 4 assuming an S$_N$2 mechanism with $k_N'/k_s' = 9.04$ and $k_{NA} = 1.74 \times 10^{-4}(1 + 1.04[N_3^-])$. [c] Rate constant calculated from eq 3 assuming an ion-pair mechanism with $k_N/k_s = 9.04$, $x = k_{-1}/k_s = 2.59$, and $k_{NA} = 1.74 \times 10^{-4}(1 + 1.04[N_3^-])$.

Table II. Kinetics of Solvolyses of 2-Octyl Mesylate in 25 Vol. % Aqueous Dioxane at 36.2°

$[NaN_3]$	% RN_3, exptl	% RN_3,[a] calcd	k_{exptl}, sec^{-1} × 10^4	k_{S_N2},[b] sec^{-1} × 10^4, calcd	k_{ip},[c] sec^{-1} × 10^4, calcd
...	...	...	2.21 ± 0.08	...	...
0.0758	36.6	38.3	3.18 ± 0.12	3.98	3.28
0.113	44.0	48.1	3.76 ± 0.07	4.80	3.74
0.156	52.2	57.7	4.34 ± 0.17	5.90	4.23
0.237	67.1	66.1	5.18 ± 0.22	8.21	5.17

[a] Calculated from the equation $[RN_3]/[ROH] = 8.22[N_3^-]$. [b] Rate constant calculated from eq 4 assuming an S$_N$2 mechanism with $k_N'/k_s' = 8.22$ and $k_{NA} = 2.21 \times 10^{-4}(1 + 1.08[N_3^-])$. [c] Rate constant calculated from eq 3 assuming an ion-pair mechanism with $k_N/k_s = 8.22$, $x = k_{-1}/k_s = 2.33$, and $k_{NA} = 2.21 \times 10^{-4}(1 + 1.08[N_3^-])$.

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(6) National Institutes of Health Predoctoral Fellow, 1965–1966.

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Received February 7, 1966

A New Linear Free Energy Relationship and Its Use as a Diagnostic for Ion-Pair Intermediates[1]

Sir:

That a qualitative relationship exists between the stability of a carbonium ion and its selectivity, as measured by the relative rates of its attack by anions and by solvent, has long been appreciated.[2] That this relationship can be expressed quantitatively is herein reported. More significantly, deviations from this correlation are shown to serve as useful diagnostics for the intermediacy of ion pairs.

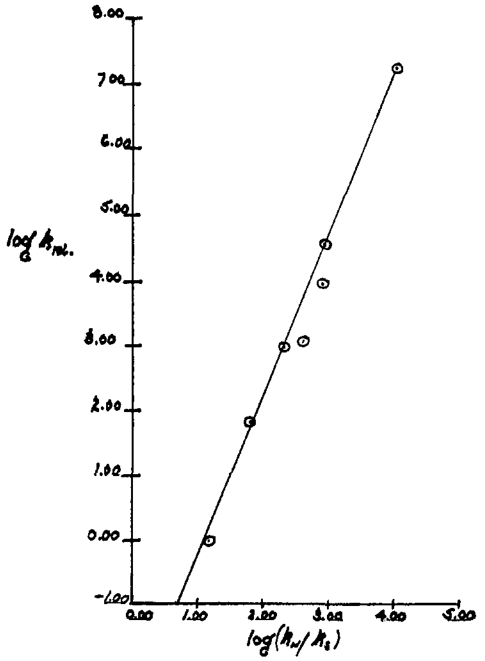
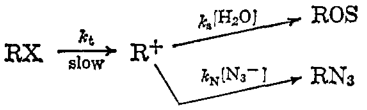


Figure 1. Plot of the logarithm of the relative rates of solvolysis of a series of alkyl chlorides in 80% aqueous acetone at 0° (log k_t) *vs.* the logarithm of the ratio of rates of attack on the corresponding carbonium ions by azide ion and water (log k_N/k_S).

In Table I are assembled rate and selectivity data for a number of alkyl halides and esters known to react *via* carbonium ion intermediates. The nucleophile in all cases is azide ion. The solvolysis rate constant (k_t) and the selectivity ratio (k_N/k_s)[3] are those defined by the scheme



The data have been collected from a number of sources[4]

(1) Supported in part by the National Science Foundation.

(2) C. G. Swain, C. B. Scott, and K. H. Lohmann, *J. Am. Chem. Soc.*, **75**, 136 (1953).

(3) This ratio is defined so as to exclude solvent concentration; *i.e.*, $d[ROS]/dt = k_s[H_2O][R^+]$.

(4) An equation originally derived by Swain[2] for the determination of the ratio k_N/k_s is incorrect in that it neglects the consumption of azide ion by liberated strong acid.[5]

$$N_3^- + HX \longrightarrow HN_3 + X^-$$

When this is taken into account the following equation results, which, although it cannot be solved in closed terms, can be solved by successive approximations.

$$\frac{k_N}{k_s} = \frac{[H_2O]}{[ROH]_\infty} \ln \frac{[H_2O] + k_N[N_3^-]_0/k_s}{[H_2O] + k_N\{[N_3^-]_0 - [RX]_0\}/k_s}$$