

carbon.<sup>14</sup> Experiments and standardization on the compounds<sup>15</sup> in Figure 1 displayed the following results: A + Cl<sup>-</sup> resulted in a percentage production of C (the "inverted" product) from A of 91 ± 14 (eight experimental runs); B + Cl<sup>-</sup> resulted in a percentage production of D (the "inverted" product from B) of 86 ± 19 (seven experimental runs).<sup>16</sup> Therefore neutral detection of the distinguishable isomeric products indicates a nucleophilic displacement mechanism proceeding with predominant inversion of stereochemistry. Such a reaction mechanism corresponds to Walden inversion and backside attack<sup>17</sup> for the particular ion-molecule reactions depicted in Figure 1.

Neutral detection has allowed us to identify the products arising from ion-molecule reactions and has demonstrated the stereochemical pathway for a negative ion displacement reaction. With the increasing complexity of ion-molecule systems related to solution processes, mere identification of ionic species will often be inadequate to describe the total chemical reaction, thus the importance of neutral detection techniques. We suspect that icr detection will be but one of many methods utilized in the determination of mechanistic information retained in the neutral products of ion-molecule reactions.

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(14) The chloride-containing neutral product gives rise to a ratio of (parent - H<sub>2</sub>O)<sup>+</sup>/(parent)<sup>+</sup> positive mass peaks characteristic of *cis* or *trans* 1,4-stereochemistry.

(15) D. S. Noyce, B. N. Bastian, and R. S. Monson, *Tetrahedron Lett.*, 863 (1962); D. S. Noyce, B. N. Bastian, P. T. S. Lau, R. S. Monson, and B. Weinstein, *J. Org. Chem.* 34, 1247 (1969).

(16) The predominant *cis* 1,4-elimination produces differences in the mass spectrum of the *cis*- and *trans*-4-chlorocyclohexanols which allows identification of the ion-molecule neutral product by monitoring the ratio of the (parent) ion peak/(parent - H<sub>2</sub>O) ion peak, characteristic for *cis* Cl (C) and *trans* Cl (D) in Figure 1.

(17) J. Hine, "Physical Organic Chemistry," 2nd ed, McGraw-Hill, New York, N. Y., 1962, Chapter 6.

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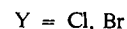
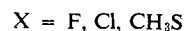
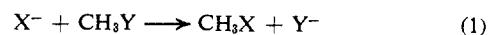
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## Gas-Phase Nucleophilic Displacement Reactions

Sir:

Nucleophilic displacement is among the most widely studied of all chemical reactions. Structural changes<sup>1</sup> in nucleophile, leaving group, and substrate, as well as solvent effects<sup>2</sup> have been investigated extensively. Recent evidence, however, suggests that the medium can play a determining role in some ionic reactions<sup>3</sup> and thus leaves the analysis of other solution reactions in question. We report here the rates of some nucleophilic displacement reactions in the gas phase, eq 1.<sup>4</sup>



The results show that nucleophilicity and leaving group ability cannot be treated as intrinsic properties. Indeed, nucleophilicity appears to depend on the specific substrate and leaving group ability to depend on the nucleophile.

Our experiments were conducted with the trapped ion, pulsed icr technique,<sup>5</sup> which permits observation of both reactant and product ions as a function of time.<sup>6</sup> Exclusive detection of a particular reaction channel was facilitated by initially ejecting undesired ions with one or two irradiating frequencies.<sup>7</sup> The anions utilized in this study were F<sup>-</sup> from NF<sub>3</sub>, Cl<sup>-</sup> from CHCl<sub>3</sub>, and CH<sub>3</sub>S<sup>-</sup> from CH<sub>3</sub>SSCH<sub>3</sub>. (CH<sub>2</sub>S<sup>-</sup> was eliminated by ion ejection.)

For each reaction, both reactant loss and product appearance were followed as a function of time. In all cases the total collision rate constant was also measured by the phase coherence method.<sup>8a</sup>

We believe that the reactions studied, eq 1, are nucleophilic displacement reactions for the following reasons. (a) They are clearly first order each in nucleophile and substrate. (b) In almost all cases, eq 1 is the only reasonable exothermic channel.<sup>9</sup> (c) When 1-chloro- and 1-bromoadamantane were used as substrates, they did not react. (d) Neutral detection in all cases examined showed only the expected product.<sup>10</sup> (e) In the 4-bromocyclohexanol system, neutral detection showed products with inversion of configuration.<sup>10</sup> Consequently, we believe that this gas-phase reaction corresponds closely to the analogous SN<sub>2</sub> reaction in solution.

The results are shown in Table I. The rate differences are substantially larger than any differences in total collision rate constant ( $k_{coll}$  (exptl)) as measured independently by phase coherence decay studies.<sup>8a</sup> Also included in Table I are the rate constants calculated from the Gioumousis-Stevenson theory<sup>8b</sup> and from the modified ion-dipole theory of Su and Bowers.<sup>8c</sup> The rate constants observed do not appear to be well correlated with any simple property, including the exothermicity. Thus, when F<sup>-</sup> reacts with a 1:1 mixture of methyl chloride and methyl bromide, Cl<sup>-</sup> is produced

(4) Previous reports of similar reactions have appeared: (a) L. B. Young, E. Lee-Ruff, and D. K. Bohme, *J. Chem. Soc., Chem. Commun.* 35 (1973); (b) D. K. Bohme and L. B. Young, *J. Amer. Chem. Soc.*, 92, 7354 (1970).

(5) R. T. McIver, Jr., and R. C. Dunbar, *Int. J. Mass Spectrom. Ion Phys.*, 7, 471 (1971).

(6) Pressures were measured with an MKS Baratron, and rate constants were calculated for the involved processes.

(7) For a similar experimental approach see J. I. Brauman, C. A. Lieder, and M. J. White, *J. Amer. Chem. Soc.*, 95, 927 (1973).

(8) (a) C. A. Lieder, R. W. Wien, and R. T. McIver, Jr., *J. Chem. Phys.*, 56, 5184 (1972); (b) G. Gioumousis and D. P. Stevenson, *J. Chem. Phys.*, 29, 294 (1958); (c) T. Su and M. T. Bowers, *J. Chem. Phys.*, 58, 3027 (1973); *Int. J. Mass Spectrom. Ion Phys.*, 12, 347 (1973).

(9) Thermochemical data were obtained from D. R. Stull, E. F. Westrum, Jr., and G. C. Sinke, "The Chemical Thermodynamics of Organic Compounds," Wiley, New York, N. Y., 1969; S. W. Benson, "Thermochemical Kinetics," Wiley, New York, N. Y., 1968; J. L. Franklin, *et al.*, "Ionization Potentials, Appearance Potentials, and Heats of Formation of Positive Ions," NSRDS-NBS 26 U. S. Government Printing Office, Washington D. C., 1969.

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(1) A. Streitwieser, Jr., "Solvolytic Displacement Reactions," McGraw-Hill, New York, N. Y., 1962.

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Table I.<sup>a,b</sup> Rate Constants for the Reaction  $X^- + CH_3Y \rightarrow CH_3X + Y^-$ 

X	Y	Rel rate	$k_{rxn}$ (exptl)	$k_{sol}$ (exptl)	$k_{gs}$ (calcd) <sup>c</sup>	$k_d$ (calcd) <sup>d</sup>	$\Delta H_{rxn}$
F	Cl	10	$8.0 \pm 0.9 \times 10^{-10}$	$19 \pm 3 \times 10^{-10}$	$14.8 \times 10^{-10}$	$23.6 \times 10^{-10}$	-28.8
F	Br	8	$6.0 \pm 0.6$	$19 \pm 3$	14.8	22.5	-37.0
Cl	Cl	~0.1	$\sim 0.06 \pm 0.02$	$18 \pm 3$	12.1	19.3	0
Cl	Br	1	$0.80 \pm 0.10$	$18 \pm 3$	11.6	17.7	-8.2
CH <sub>3</sub> S	Cl	1	$0.78 \pm 0.12$	$17 \pm 3$	11.1	17.8	-32.7
CH <sub>3</sub> S	Br	2	$1.4 \pm 0.2$	$18 \pm 3$	10.5	16.0	-40.9

<sup>a</sup> Absolute rate constants expressed in  $\text{cm}^3 \text{molecule}^{-1} \text{sec}^{-1}$ . <sup>b</sup> Heats of formation of ions from ref 9 and K. J. Reed, Stanford University (personal communication). <sup>c</sup> Reference 8b. <sup>d</sup> Reference 8c.

rapidly; the  $\text{Cl}^-$  then reacts somewhat more slowly to produce  $\text{Br}^-$ . Although the nucleophilic order,  $\text{F}^- > \text{CH}_3\text{S}^- > \text{Cl}^-$ , is maintained for both methyl chloride and methyl bromide, the relative nucleophilicity  $\text{F}^- : \text{CH}_3\text{S}^- : \text{Cl}^-$  changes from 10:1:0.1 toward methyl chloride, to 8:2:1 toward methyl bromide. Even more striking is the reversal in leaving group ability (LGA) dependence on the nucleophile. Thus the relative LGA of  $\text{Cl}^- : \text{Br}^-$  is 10:8 when  $\text{F}^-$  is the nucleophile, 1:2 when  $\text{CH}_3\text{S}^-$  is the nucleophile, and 1:10 when  $\text{Cl}^-$  is the nucleophile. Such reversals are not unique to the gas phase but have been observed in solution both for nucleophilicity<sup>11</sup> and LGA.<sup>12</sup> Steric effects in ion-molecule nucleophilic displacements have been previously suggested for both nucleophile<sup>4b</sup> and neutral reactant.<sup>13</sup> The variation of nucleophile size may be involved in the difference in absolute rate between  $\text{F}^-$  and  $\text{CH}_3\text{S}^-$ , but similar arguments seem unprofitable for comparison of  $\text{Cl}^-$  and  $\text{CH}_3\text{S}^-$ . In summary, it is impossible to establish any general scale or order of either nucleophilicity or leaving group ability without direct reference to the specific reaction.<sup>14</sup>

The data appear to be best correlated with a model in which the rate is relatively fast when the nucleophile and leaving group have similar properties. The phenomenon which we observe here is strongly reminiscent of that observed in solution and discussed by Bunnett.<sup>15</sup> Such synergistic or "symbiotic" behavior in which polarizable nucleophiles are relatively more effective in displacing polarizable leaving groups has also been discussed extensively by Pearson and Songstad.<sup>16</sup> The zeroth order explanation of the effect, in which resonance contributions to the transition state of the form  $\text{X}-\text{R} \text{Y}^- \leftrightarrow \text{X}^- \text{R}-\text{Y}$  are maximized when X and Y are similar, breaks down for the identity reaction  $\text{Cl}^- + \text{CH}_3\text{Cl} \rightarrow \text{ClCH}_3 + \text{Cl}^-$ , which is quite slow. Thus, as suggested previously,<sup>15</sup> other effects such as exothermicity must be considered. The fact that this reaction is the slowest of those studied also suggests that energy barriers rather than orientations or steric effects are the key factors which affect the reaction rates. It is unreasonable to expect either of the latter effects to slow this reaction selectively. However, its lack of

exothermicity would be expected to raise the activation energy relative to the exothermic reactions. Most other ion-molecule reactions have no apparent activation barriers.<sup>17</sup> Our experimental findings of a barrier are in agreement with theoretical calculations of  $\text{SN}_2$  reactions.<sup>18</sup>

The changes observed here are modest, but they are quite significant in terms of ion-molecule reaction rates which usually tend to be relatively insensitive to structural change.<sup>19</sup> Consequently, we feel that, because of the absence of solvent, these experiments provide strong evidence for the existence of interactive effects in nucleophilic displacement reactions.

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(17) For an example of another reaction which may have an activation barrier see ref 7.

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(20) National Science Foundation Predoctoral Fellow.

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## Stereoselective Epoxidation of Octadiene Catalyzed by an Enzyme System of *Pseudomonas oleovorans*

Sir:

Recent work from this laboratory has established that the " $\omega$ -hydroxylation" system of *Pseudomonas oleovorans* catalyzes the epoxidation of olefins<sup>1-5</sup> in addition to the previously known methyl group hydroxylation of alkanes and fatty acids.<sup>6-12</sup> Accordingly, the substrate 1,7-octadiene, which does not con-

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(15) J. F. Bunnett, *J. Amer. Chem. Soc.*, **79**, 5969 (1957); J. F. Bunnett and J. D. Reinheimer, *ibid.*, **84**, 3284 (1962).

(16) R. G. Pearson and J. Songstad, *J. Org. Chem.*, **32**, 2899 (1967); *J. Amer. Chem. Soc.*, **89**, 1827 (1967).