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Medium effects in nucleophilic substitution reactions

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MEDIUM EFFECTS IN NUCLEOPHILIC SUBSTITUTION REACTIONS

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INTRODUCTION

One of the most important and least understood ways to influence a chemical reaction is by solvent variation. In the past thirty years there has been enormous progress toward the empirical correlation of substituent effects on rates and equilibria through linear free energy relationships (1,2,3). Yet during this same period it has become increasingly clear that the interaction of solvents with molecules, ions, and radicals often cannot be accounted for satisfactorily by continuum properties of the solvent, such as dielectric constant, but that quite specific interactions between substrate and solvent molecules are also important (4,5,6).

Within recent years numerous solvent parameters have been introduced with the intent of providing an empirical measure of the effect on an organic reaction by changing the solvent (3,7). Probably the most ambitious attempt to correlate reaction rates with solvent composition is that of Winstein and his students (8 and previous papers in the series). Winstein's Y values measure the ionizing power of the solvent while his m values measure the sensitivity of the solvolysis rate for a particular substrate. However, the m value is not strictly independent of the solvent so that a better correlation of reaction rates with solvent composition is that formulated by Swain (9). Swain's treatment includes a nucleophilicity parameter, n, which is "constant" for each particular

nucleophile. Kosower has found that the positions of the charge transfer absorption band of pyridinium iodide complexes reflect the ionizing power of the solvent (10). The transition energies (which correspond to the tabulated Z values) for 1-ethyl-4-carbomethoxypyridinium iodide in various solvents are linearly related to Winstein's Y values. Reichardt's E_t values (11) which also measure the ionizing power of the solvent spectroscopically have, however, a wider range of application than do the Z values. The dielectric constant is generally a poor measure of solvating power and gives only a fair correlation with other parameters when the systems being compared are limited to a single chemical type, for instance, alcohols (3,7). Other parameters, such as Berson's Ω polarity scale (12), Hildebrand's cohesive energy density (13,14), δ, and numerous others (3,7), have also been introduced.

All of the above mentioned parameters with the exception of Swain's equation (15,16,17), Equation 1,

$$\log (k/k^0) = c_1 d_1 + c_2 d_2 \qquad 1$$

measure "solvent polarity" exclusively. Swain's equation when applied to the reaction of nucleophiles with neutral substrates contains nucleophilic and electrophilic terms and the notation given by Equation 2 is used (9). However, when applied to

$$\log (k/k^0) = sn + s'e \qquad 2$$

solvolysis reactions, Swain points out that these terms may not measure nucleophilic and electrophilic reactivity of the solvent and in order to avoid the implication that it does, he changes the notation to that of Equation 1.

Nucleophilicity is concerned with the rate that a given substrate undergoes a certain nucleophilic reaction (Hine 16, p. 77). Thus if substance A is more nucleophilic than substance B, A will undergo a nucleophilic reaction faster than B will undergo this reaction.

The term "solvent nucleophilicity" is a rather vague term and its meaning is complicated by the fact that a change of solvent changes the medium. It is therefore impossible to talk about "solvent nucleophilicity" in a given medium as one can do with "anion nucleophilicity." Nevertheless, the term "solvent nucleophilicity" should have some meaning since many of the characteristics of anions, such as basicity and solvation, which affect "anion nucleophilicity" are also present in solvents.

In order to discuss "solvent nucleophilicity" we propose the following definition: "solvent nucleophilicity" is a measure of the tendency of a solvent to attack as a nucleophile some electron-deficient center relative to the tendency of a standard nucleophile to undergo a standard nucleophilic reaction in that solvent. Since one might expect a different order of solvent nucleophilicities with each different class of

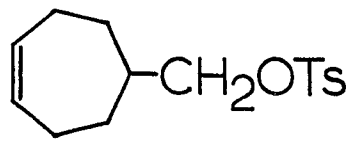
reactions (Hine 16, pp. 160-162), one must restrict each set of nucleophilicities to a certain type of reaction. In order for "solvent nucleophilicity" to be a useful general term and measurable, it should be independent of the substrate at least for a certain type of reaction. In other words, if solvent A is more nucleophilic than solvent B, solvent A should attack any substrate in a nucleophilic fashion faster than solvent B. In order for this situation to exist, both ground state and transition state changes must be relatively independent of the substrate.

In recent years there has been considerable interest in the intramolecular participation by olefins in solvolytic reactions. A double bond placed in the 2,3-, 3,4-, or 5,6-position of an ionizable substrate has been shown under solvolytic conditions to stabilize the transition state; in most cases this stabilization of the activated complex can be interpreted as formation of an intermediate which contains a three-center, two-electron bond, i.e., a "nonclassical" ion. The enhanced reactivity of ionizable allyl (2-alkenyl) derivatives is reasonably explained by the ability of a positive charge, as developed during solvolysis of a 2-alkenyl halide, to be delocalized over three carbon atoms (Streitwieser 17, pp. 79-81). This explanation is reinforced by the observation of rearranged products (Streitwieser 17, pp. 58, 79-81).

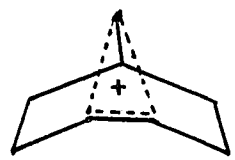
Organic halides and sulfonate esters containing a double

bond in the 3,4-position generally have increased solvolytic reactivity relative to their saturated analogs and lead to rearranged products (Streitwieser 17, pp. 153-157, 182-183). The unsymmetrical homoallylic systems have been extensively explored, the observations strongly indicating charge delocalization over three carbon atoms (Streitwieser 17, pp. 153-157, 182-183). Rogan (18) has found that acetolysis of 4-methyl-3-pentenyl tosylate gives a rate enhancement of greater than 10^3 compared to ethyl tosylate and leads to 13% of 2-cyclopropylpropene. Similarly, Roberts (19) has observed rate acceleration and rearranged products in the formolysis of substituted 3-butenyl tosylates. Other examples of this homoallylic participation include the solvolytic rearrangement of 2-(1-cyclopentenyl)ethyl p-bromobenzenesulfonate (20, 21) and 2-naphthalenesulfonate (22), and the deamination of 2-cyclopentenylmethyl (23), 2-(1-cyclohexenyl)ethyl (22), and 2-(1-cyclopentenyl)ethyl (22) amines.

Among ionizable compounds that lead to cyclic materials some of the best evidence for olefin participation during solvolysis is found in compounds having a double bond in the 5,6-position relative to the departing group and symmetrically placed, so that its two carbon atoms are equidistant from C-1 or nearly so. In 1960 Le Ny (24) found that 4-cycloheptenylmethyl p-toluenesulfonate (I) underwent acetolysis at least



I

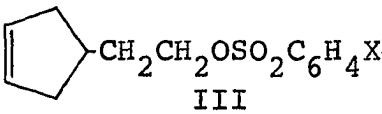
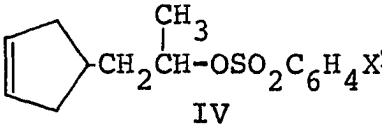
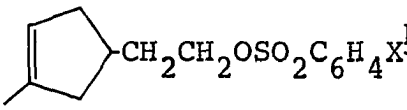
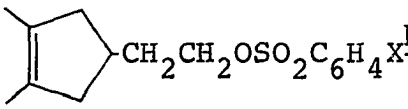
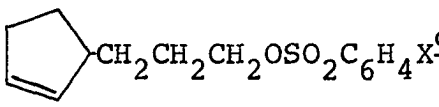
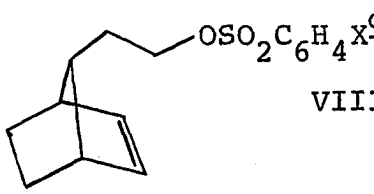


II

30-times faster than the corresponding saturated analog and yielded a single cyclic acetate whose configuration was uniquely consistent with the intervention of the symmetrical bridged ion II. Likewise, Cope (25) and Le Ny (26) have found evidence for double bond participation in the acetolysis of 4-cyclooctenylmethyl p-bromobenzenesulfonate. In 1961 Lawton (27) showed that 2-(3-cyclopentenyl)ethyl p-nitrobenzenesulfonate, III, is solvolyzed in glacial acetic acid at a rate 95 times faster than the saturated compound, producing exo-norbornyl acetate as the sole product. In an independent study Bartlett and Bank (28) solvolyzed the corresponding p-toluenesulfonate in three solvolyzing media and found similar results.

Bartlett and Sargent (29) have shown that the solvolysis of 2-(3-cyclopentenyl)ethyl derivatives involves anchimeric assistance by the double bond such as to place nearly equal amounts of positive charge simultaneously on the two originally double bonded carbon atoms. A comparison of the ratios for

Table 1. Solvolysis of compounds which show anchimeric assistance by the 5,6-double bond

Compound	-X	Solvent	Temp. °C	k_a/k_u	Ref.
 III	CH_3	50% EtOH-H_2O	70	5.7	30
	CH_3	HOAc	100	74	30
	NO_2	HCOOH	25	640	30
	NO_2	HOAc	54	87	30
	NO_2	HOAc	60	95	27
 IV	NO_2	HOAc	54	2.2	30
 V	NO_2	HOAc	60	605	29
 VI	NO_2	HOAc	60	3315	29
 VII	Br	EtOH	80	1.0	31
	Br	HOAc	80	3.8	31
	Br	97% HCOOH	70	19	31
 VIII	Br	HOAc	25	140,000	32

[a]Reference compound was the saturated analog.

[b]Reference compound was 2-(3,4-dimethylcyclopentyl)ethyl p-nitrobenzenesulfonate.

[c]Reference compound was 2-cyclopentylethyl p-bromobenzenesulfonate.

[d]Reference compound was the anti-isomer.

assisted vs. unassisted solvolysis, k_a/k_u, in Table 1 for compounds III, V, and VI shows that the rate acceleration from the addition of one methyl group is nearly the same as the increase found by the addition of a second methyl substituent; that is, there is a cumulative acceleration by methyl substituents. On the other hand, substitution of a methyl group on C-1, compound IV, has an expected decelerating effect on the rate of acetolysis. This work strongly suggests that the ring closure is a true intramolecular process by the double bond and is not a two step process initiated by unassisted ionization. A comparison of the effects of methyl groups placed on the double bond and at position 1 of the sulfonate led to the conclusion (29) that the transition state bears more positive charge at the carbon atoms of the original double bond than at the carbon atom from which the anion departed. These results, as well as the results of labeling experiments by Lee and Lam (33), are all consistent with the view that the initial product of ionization is a bridged or "nonclassical" ion.

The importance of symmetry can also be seen from the data in Table 1. Clearly rate enhancement in the formolysis of 2-(3-cyclopentenyl)ethyl p-nitrobenzenesulfonate, III, where the double bond is symmetrically located, is greater than that of 3-(2-cyclopentenyl)propyl p-bromobenzenesulfonate, VII, where the double bond is unsymmetrically placed. The requisite of C-5 and C-6 equidistant from C-1 is distinctly noticeable

in the solvolysis of 3-vinylcyclopentyl bromide (34) which gives only unrearranged product and no rate acceleration. When C-1 is forced near the olefinic bond, as in VIII, assisted solvolysis proceeds at an extremely rapid rate relative to the unassisted solvolysis. Other data have supported these observations (35, 36, 37).

Acetolysis of 5-hexenyl p-nitrobenzenesulfonate has been found to be 1.7 times faster than that of its saturated analog and gives cyclic products (38-42), 1-methylcyclopentene, cyclohexene, and cyclohexyl acetate, both observations supporting anchimeric assistance by the olefin. In addition, it is known (38,41) that acetolysis of cyclohexyl p-nitrobenzenesulfonate does not give ring contracted products (1-methylcyclopentene, methylenecyclopentane, 1-methylcyclopentyl acetate, or cyclopentylmethyl acetate) or ring opened products (acyclic hexadienes or 5-hexenyl acetate). That cyclohexyl p-nitrobenzenesulfonate does not yield the same products on acetolysis as does 5-hexenyl p-nitrobenzenesulfonate strongly indicates that the transition states for formation of cyclic and open products are different. The mechanism of the acetolysis of 5-hexenyl p-nitrobenzenesulfonate in the presence of urea may be written as shown in Chart 1 (41,42). Urea must be used as the base to neutralize the arenesulfonic acid instead of the usual alkali metal acetate since added acetate ion enters into an Sn2 reaction with the primary p-nitro-

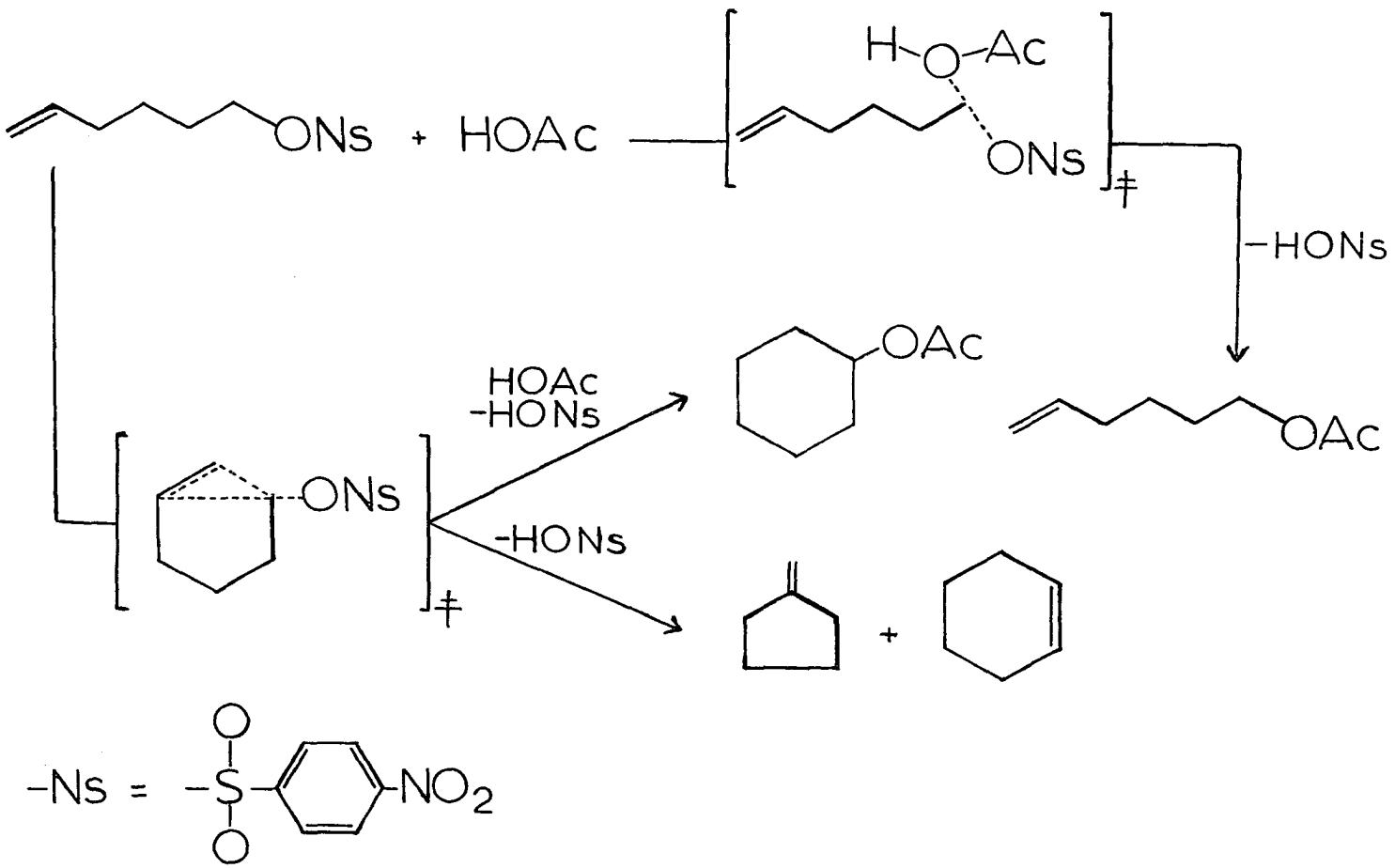


Chart 1. Mechanistic scheme for the acetolysis of 5-hexenyl p-nitrobenzenesulfonate in the presence of urea

benzenesulfonate (41). Solvolysis of 5-hexenyl p-nitrobenzenesulfonate may be viewed as two competitive nucleophilic reactions: (a) external nucleophilic attack by the hydroxylic solvent, acetic acid (43), which leads to acyclic material, and (b) internal nucleophilic attack by the olefin which leads to cyclic materials.

A measure of the ratio of open to cyclic products from the solvolysis of 5-hexenyl p-nitrobenzenesulfonate offers the possibility of being a sensitive measure of the relative solvent nucleophilicity of a solvent mixture towards attack on alkyl arenesulfonates or halides. The internal olefin should be an excellent standard nucleophile since it is nonpolar and should thus not be highly solvated. Because the olefin is nonpolar its nature should not change much from solvent to solvent. Moreover, the low solvation of the olefin suggests that the energy needed to bring about the conformational changes in going from the open chain ground state to the cyclic transition state should be independent of solvent changes. Thus the cyclization reaction should be a good standard nucleophilic reaction. Since the substrate is in both ground states, any change in the ground state free energies must reflect a change in the solvent nucleophilicity. However, the ratio of open to cyclic products will measure solvent nucleophilicity only if the transition states of both reactions are affected in a similar manner by solvent changes.

If this condition exists, solvolysis of 5-hexenyl p-nitrobenzenesulfonate in a solvent mixture that is more nucleophilic than acetic acid should lead to less cyclic materials and vice versa.

In this study we have measured the yields of the products from the solvolysis of 5-hexenyl p-nitrobenzenesulfonate and other 5-hexenyl derivatives in binary solvent mixtures. The changes in the yields of these products are analyzed and discussed with respect to solvent nucleophilicity. Factors determining nucleophilic reactivity, the effect of variation of the leaving group on the transition states leading to cyclic and open product, and the mechanism for formation of cyclohexene from 5-hexenyl derivatives are dealt with. Results from the solvolysis of 6-heptenyl p-nitrobenzenesulfonate in several solvents of low nucleophilicity are also presented.

RESULTS AND DISCUSSION

Solvolysis of 5-Hexenyl p-Nitrobenzenesulfonate in 20% Acetic Acid - 80% Nonhydroxylic Solvent Mixtures

In Table 2 are presented the data from the solvolysis of 5-hexenyl p-nitrobenzenesulfonate in media composed of 20% acetic acid and 80% nonhydroxylic solvent. In no case were we able to recover greater than 90% of the theoretical yield of products. One possible product, 1,5-hexadiene, was not formed while three unidentified products were observed by gas liquid partition chromatography (g.l.p.c.) in less than 2% total yield. Addition by acetic acid into the double bond of the 5-hexenyl moiety is unlikely since there was little difference in the total recovery when 5-hexenyl p-nitrobenzenesulfonate was solvolyzed in acetic acid for 12 hours (Table 4) and for 50 hours (Table 2). In a control experiment in which the three major products, cyclohexene, cyclohexyl acetate, and 5-hexenyl acetate were added to acetic acid, sulfolane, or nitrobenzene and then extracted in the same manner as that used in the preparation of the solvolysis runs for g.l.p.c. analysis, the percent recovery after workup was quantitative. However, solvolysis of 5-hexenyl p-nitrobenzenesulfonate in 97% formic acid for three hours at 90^0 (Table 13) led to 95% total recovery of products. Thus, the longer reaction time in acetic acid must lead to side reactions of the reactants. The most likely explanation may be an intermolecular reaction between an olefin

and 5-hexenyl sulfonate ester since nearly quantitative recovery of hexyl acetate was obtained after acetolysis of hexyl p-nitrobenzenesulfonate (Table 3).

1-Methylcyclopentene was formed when 5-hexenyl p-nitrobenzenesulfonate was solvolyzed in acetic acid (41). No methylenecyclopentane was found. The absence of this product was, therefore, assumed for all binary solvent mixtures unless otherwise noted. It is also known (41,42) that detectable amounts of 1-methylcyclopentyl and cyclopentylmethyl acetates are not produced in the acetolysis reaction. For acetolyses in mixed solvents 1-methylcyclopentyl acetate was not found, and it was assumed that cyclopentylmethyl acetate was not formed. An olefin whose identity remains unknown was produced in the acetolysis reactions. The yield of this olefin was approximately equal to that of 1-methylcyclopentene and was assumed to be a hexadiene.

In order to determine an approximate half-life for the acetolysis of 5-hexenyl p-nitrobenzenesulfonate in the binary solvent mixtures, we solvolyzed hexyl p-nitrobenzenesulfonate in several of these solvents for a period of usually less than one half-life. Using the known reaction rate for the acetolysis of the saturated ester at 80^0 (37) to obtain the rate constant in acetic acid at 100^0 we were able to calculate an approximate half-life for solvolysis in acetic acid. With the data from incomplete solvolyses we were able to determine an

approximate half-life and solvolysis rate in the binary solvents. The rate of reaction in the binary solvents relative to acetic acid was also calculated. This data is given in Table 3.

In an identical manner approximate rate constants were calculated for the solvolysis of 5-hexenyl p-nitrobenzenesulfonate in several binary solvent mixtures, the results being presented in Table 4. From the approximate rates for acetolysis of hexyl and 5-hexenyl p-nitrobenzenesulfonates, a ratio of assisted to unassisted solvolysis was calculated. Comparison of the cyclohexene to cyclohexyl acetate ratios at 12 hours and 50 hours shows that no noticeable interconversion of these products takes place over a 50 hour period. Comparison of the ratio of percent open product to percent cyclic products shows consistently greater relative amounts of cyclic products being produced in the 12 hour solvolyses (Table 4). It is unlikely that this observation of initial preference for formation of cyclic prdoucts could be explained merely by fortuitous experimental error. As the solvolysis reaction proceeds the amount of ureaonium p-nitrobenzenesulfonate increases. It is reasonable, therefore, to expect some type of salt effect on the reaction; and in view of the fact that 0.3M lithium perchorate increases the amount of cyclic products twofold (38), the much smaller increases in cyclic products which we observe are compatable with a salt effect.

Table 2. Solvolysis of 5-hexenyl p-nitrobenzenesulfonate at 100° in 20% acetic acid - 80% solvent mixtures[a]

Solvent No.	Solvent[c] (No. of runs)	Reaction time, hrs.	Mole ratio (Solvent/HOAc)	% Recovery[d]
1)	Acetic Acid (4)	50	-	90
Esters				
2)	Triacetin (2)	50	1.22	78
3)	γ-Butyrolactone (2)	50	3.00	47
4)	Methyl Benzoate (2)	50	1.83	83
5)	Ethyl Stearate (2)[e]	40	0.63	78
Ethers				
6)	Ethyl Ether (2)	48	2.21	77
7)	Benzyl Ether (2)	50	1.20	74
8)	p-Methyl Anisole (2)[f]	50	1.83	78
9)	Phenyl Ether (2)	50	1.47	81
10)	Phenyl Sulfide (2)	50	1.38	68
11)	Tetrahydrofuran (2)	50	-	34
Halides				
12)	Carbon Tetrachloride (3)	50	2.38	89
13)	Chloroform (2)	50	2.87	74
14)	1,1,2,2-Tetrachloroethane (2)	50	2.20	83
15)	o-Dichlorobenzene (2)	50	2.04	89
16)	Trichloroethylene (2)	50	2.55	60

[a] [RONs] = 0.1 M, [urea] = 0.2 M.

[b] Relative yield of products. The accuracy of analysis is subject to the analytical method used and is estimated to be within 3% of the reported value of each product. From duplicate runs the precision of analysis was calculated to be well within the accuracy limits.

[c] Acetone, 2,4-pentanedione, methyl methanesulfonate, and tetramethyl orthosilicate were also used, but because of interferring side reactions total analysis was not possible.

[d] Percent recovery was based on g.l.p.c. analysis of the expected solvolysis products.

[e] An approximately 0.002 M solution of ethyl acetate was produced.

[f] Due to the difficulty of separation of solvent from the acetate products, anisole itself could not be used. In anisole the absolute yield of cyclohexene averaged from two runs was 12.8% and that of 1-methylcyclopentene was 0.2%. Assuming a recovery of 78% the relative yields of these two products are 16.4% and 0.3% respectively, which compares very favorably with the reported values of p-methyl anisole.

Solvent No.	Analysis[b] 1-Methylcyclopentene	A, Cyclohexene	B, Cyclohexyl Acetate	5-Hexenyl Acetate	% Open / % Cyclic Products	A/B
1)	0.9	13.2	31.1	54.8	1.21	0.42
2)	0.9	14.0	19.1	66.0	1.94	0.73
3)	0.6	15.0	18.6	65.6	1.91	0.81
4)	0.8	18.6	9.4	71.2	2.47	1.98
5)	0.4	8.0	8.8	82.8	4.81	0.91
6)	0.1	8.4	0.9	90.6	9.64	9.3
7)	0.4	16.2	8.6	74.8	2.97	1.88
8)	0.6	16.0	5.6	77.8	3.50	2.86
9)	1.0	16.5	14.2	68.3	2.15	1.16
10)	0.9	19.8	12.3	67.0	2.03	1.61
11)	1.2	7.5	4.4	86.9	6.63	1.70
12)	0.4	7.4	7.8	84.4	5.41	0.95
13)	0.6	24.8	13.0	61.6	1.61	1.90
14)	1.1	38.8	12.4	47.7	0.91	3.13
15)	0.9	17.0	13.4	68.7	2.20	1.27
16)	0.5	9.6	9.8	80.1	4.03	0.98

Table 2 (Continued)

Solvent No.	Solvent[c] (No. of runs)	Reaction time, hrs.	Mole Ratio (Solvent/HOAc)	% Recovery[d]
Ketones				
17)	Acetophenone (2)	50	1.96	71
18)	Benzil (2)[g]	50	1.09	30
Nitriles				
19)	Acetonitrile (2)	50	4.32	42
20)	Benzonitrile (2)	50	2.24	56
Nitro Compounds				
21)	Nitromethane (2)	50	4.25	59
22)	Nitrobenzene (2)	50	2.23	86
Phosphorus Compounds				
23)	Triphenyl Phosphite (4)	50	-	41
24)	Hexamethylphosphoramide (2)	53	-	69
25)	Trimethyl Phosphate (2)[h]	50	2.00	27
26)	Triphenyl Phosphate (2)	50	-	68
27)	Tris-(Tetrahydrofurfuryl) Phosphate (1)	50	-	57
Sulfur Compounds				
28)	Sulfolane (2)	40	2.40	66
29)	Butyl Sulfone (2)[i,j]	53	1.28	81
30)	Methyl Phenyl Sulfone (2)[i]	50	1.46	74
31)	Vinyl Sulfone (2)	53	-	80

[g]A 72.5% solution of benzil.

[h]An approximately 0.06 M solution of methyl acetate was formed. N.m.r. spectrum of the solvolysis products after extraction shows no proton resonance attributable to cyclohexene.

[i]Density of the solvent assumed to be 1.00.

[j]An approximately 0.001 M solution of butyl acetate was produced.

Solvent No.	Analysis[b] 1-Methylcyclopentene	A, Cyclohexene	B, Cyclohexyl Acetate	5-Hexenyl Acetate	% Open % Cyclic Products	A/B
17)	0.9	11.9	11.0	76.2	3.20	1.08
18)	0.6	13.8	72.3	13.3	0.15	0.19
19)	1.0	31.7	13.3	54.0	1.17	2.38
20)	2.0	25.5	15.0	57.5	1.35	1.70
21)	0.7	59.7	19.7	19.7	0.25	3.03
22)	2.2	39.6	18.7	39.5	0.65	2.12
23)	4.2	74.4	5.9	15.5	0.18	12.6
24)	0	0	36.4	63.6	1.75	0
25)	0	0	11	89	8.1	0
26)	0.8	19.2	13.5	66.5	1.98	1.42
27)	0.1	9.9	6.3	83.7	5.14	1.57
28)	1.6	48.8	12.6	37.0	0.59	3.87
29)	0.6	20.9	11.8	66.7	2.00	1.77
30)	2.4	38.6	18.8	40.2	0.67	2.05
31)	1.2	44.2	16.4	38.2	0.62	2.70

Table 2 (Continued)

Solvent No.	Solvent[c] (No. of runs)	Reaction time, hrs.	Mole Ratio (Solvent/HOAc)	% Recovery[d]
Sulfur Compounds (Continued)				
32)	1,4-Butanesultone (3)	50	-	60
33)	Dimethyl Sulfoxide (2)[k]	50	-	45
Miscellaneous Solvents				
34)	Benzene (4)	50	2.58	84
35)	Furan (2)	50	3.18	77
36)	N,N-Dimethylformamide (2)[l]	50	2.98	51
37)	Tripentyl Borate (2)	50	-	45
38)	Pyridine-N-Oxide (1)	12	-	39

[k]5-Hexenal was formed in approximately 15% yield. 5-Hexen-1-ol was found in about 10% yield and approximately 20% of a product believed to be 5-hexenyl methyl sulfide was found. Dimethyl sulfide and methyl acetate were also produced.

[l]Less than a 0.002 M solution of pentyl acetate was formed.

[m]Not analyzed.

Solvent No.	Analysis[b] 1-Methylcyclopentene	A, Cyclohexene	B, Cyclohexyl Acetate	5-Hexenyl Acetate	% Open / % Cyclic Products	A/B
32)	1.5	39.9	38.5	20.1	0.25	1.04
33)	0	0	0	100	-	-
34)	0.2	15.4	8.9	75.5	3.08	1.73
35)	0.5	11.6	11.8	76.1	3.18	0.98
36)	0	0	25.1	74.9	2.98	0
37)	0.4	10.8	10.8	78.0	3.54	1.00
38)	m	7.3	0	92.7	12.7	-

Table 3. Solvolysis of hexyl p-nitrobenzenesulfonate at 100° in 20% acetic acid - 80% solvent mixtures[a]

Solvent No.	Solvent (No. of runs)	Reaction Time, hrs.	% Hexyl Acetate[b]	$t_{\frac{1}{2}}$, hrs.[c]	$10^5 k_1$, sec.[-1][d]	$k_{rel.}$
1)	Acetic Acid (2)	24	99.8	2.2[e]	8.6[e]	100
2)	Triacetin (1)	8	27.6	16	1.0	12
3)	γ-Butyrolactone (1)	8	26.4	18	0.7	8
4)	Methyl Benzoate (1)	8	27.0	17	0.9	10
5)	Ethyl Stearate (1)	8	40.0	10	1.9	22
9)	Phenyl Ether (1)	8	34.0	13	1.4	16
12)	Carbon Tetrachloride (1)	8	38.4	12	1.5	17
20)	Benzonitrile (1)	8	25.9	18	0.7	8
22)	Nitrobenzene (1)	8	25.8			
	(2)	24	72.3			
	(1)	48	84.8	15	1.2	14
	(1)	72	96.3			
23)	Triphenyl Phosphite (1)	8	10.2	40	0.5	6
24)	Hexamethylphosphoramide (1)	8	41.5	10	1.9	22
27)	Tris-(Tetrahydrofurfuryl) Phosphate (1)	8	30.7	14	1.3	15
28)	Sulfolane (1)	8	37.6			
	(2)	24	67.0			
	(1)	48	69.6	9	2.1	24
	(1)	72	79.4			
30)	Methyl Phenyl Sulfone[f] (1)	8	45.5	10	1.9	22
32)	1,4-Butane Sultone (1)	8	32.3	15	1.2	14
34)	Benzene (1)	8	29.5	15	1.2	14

[a] See footnote a, Table 2.

[b] See footnote d, Table 2. Accuracy of the analysis estimated to be within 4% of the reported value of % hexyl acetate.

[c] Approximate half-life. Estimated from a plot of -log (relative yield) verses time. Relative yield was calculated assuming 100% hexyl acetate was attainable for solvents other than nitrobenzene and sulfolane. For those solvents relative yield was calculated on the basis that the 72 hour runs gave the maximum yield of hexyl acetate.

[d] Calculated from the half-life of the reaction.

[e] Calculated using the known reaction rate at 80° (38) together with the appropriate activation parameters (37).

[f] See footnote i, Table 2.

Table 4. Solvolysis of 5-hexenyl p-nitrobenzenesulfonate at 100° for 12 hours in 20% acetic acid - 80% solvent mixtures[a]

Solvent No.	Solvent (No. of runs)	% Recovery[c]	$t_{1/2}$, hrs.[d]	$10^5 k_e$, sec.$^{-1}$	k_{rel}	$\frac{k\ 5\text{-hexenyl}}{k_{hexyl}}$
1)	Acetic Acid (3)	82	1.3[g]	15[g]	100	1.7
3)	γ-Butyrolactone (3)	32	16	1.2	8	1.7
5)	Ethyl Stearate (3)	56	7	2.8	19	1.5
9)	Phenyl Ether (3)	50	9	2.2	15	1.6
20)	Benzonitrile (2)	38	14	1.4	9	2.0
22)	Nitrobenzene	57	7	2.8	19	2.3
28)	Sulfolane (3)	65	5	3.9	26	1.9

[a]See footnote a, Table 2.

[b]Precision of the analysis is within 5% of the reported value of each product.

[c]See footnote d, Table 2.

[d]Approximate half-life. Estimated from a plot of -log (relative yield) versus time. Relative yield was calculated assuming 82% yield of products was attainable for solvents.

[e]See footnote d, Table 3.

[f]Since the ratios are calculated from the relative yields in an incomplete reaction, any inherent errors in the yields are compounded in these values.

[g]See footnote e, Table 3.

Solvent No.	Analysis[b] 1-Methylcyclopentene	A, Cyclohexene	B, Cyclohexyl Acetate	5-Hexenyl Acetate	% Open / % Cyclic Products[f]	$\frac{A}{B}$[f]
1)	1.1	13.8	30.8	54.3	1.19	0.45
3)	1.0	16.6	23.6	58.8	1.43	0.70
5)	0.6	9.1	13.8	76.5	3.27	0.66
9)	1.4	21.0	19.1	58.5	1.41	1.10
20)	1.8	26.6	19.3	52.3	1.09	1.38
22)	2.4	44.8	19.3	33.5	0.50	2.32
28)	2.8	52.0	14.4	30.8	0.44	3.61

Table 5. Solvolysis of 5-hexenyl p-nitrobenzenesulfonate at 100° in 20% acetic acid - 80% substituted nitrobenzene mixtures[a]

Solvent No.	Solvent[c] (No. of runs)	Reaction Time, hrs.	Mole Ratio (Solvent/HOAc)	% Recovery[d]
22)	Nitrobenzene (2)	50	2.23	86
39)	o-Nitrotoluene (2)	50	1.95	83
40)	2-Nitro-m-Xylene (2)	40	1.69	87
41)	p-Nitrotoluene (3)	50	1.90	87
42)	2,4-Dinitrotoluene (2)	50	1.66	78
43)	2,6-Dinitrotoluene (2)	50	1.61	80
44)	m-Dinitrobenzene (5)	50	2.14	63
45)	1-Chloro-2-nitrobenzene (4)	50	1.99	84
46)	1-Chloro-4-nitrobenzene (4)	50	2.21	80
47)	o-Nitroanisole (2)[e]	50	1.87	77
48)	m-Nitroanisole (3)[f]	50	2.05	82
49)	p-Nitroanisole (3)[g]	50	1.84	78
50)	2,4-Dinitroanisole (2)[h]	70	1.55	80

[a] See footnote a, Table 2.

[b] Relative yield of products. Precision of analysis was generally ± 5% of the reported value for solvents which were solids. For liquid solvents see footnote b, Table 2.

[c] Except for nitrobenzene, o-nitroanisole, o-nitrotoluene, and 2-nitro-m-xylene, all the solvents listed in this table were solids at room temperature.

[d] See footnote d, Table 2.

[e] No methyl acetate was detected.

[f] An approximately 0.05 M solution of methyl acetate was produced.

[g] Both a 0.02 M and a 0.06 M solution of methyl acetate were formed in two separate runs.

[h] An approximately 0.02 M solution of methyl acetate was produced.

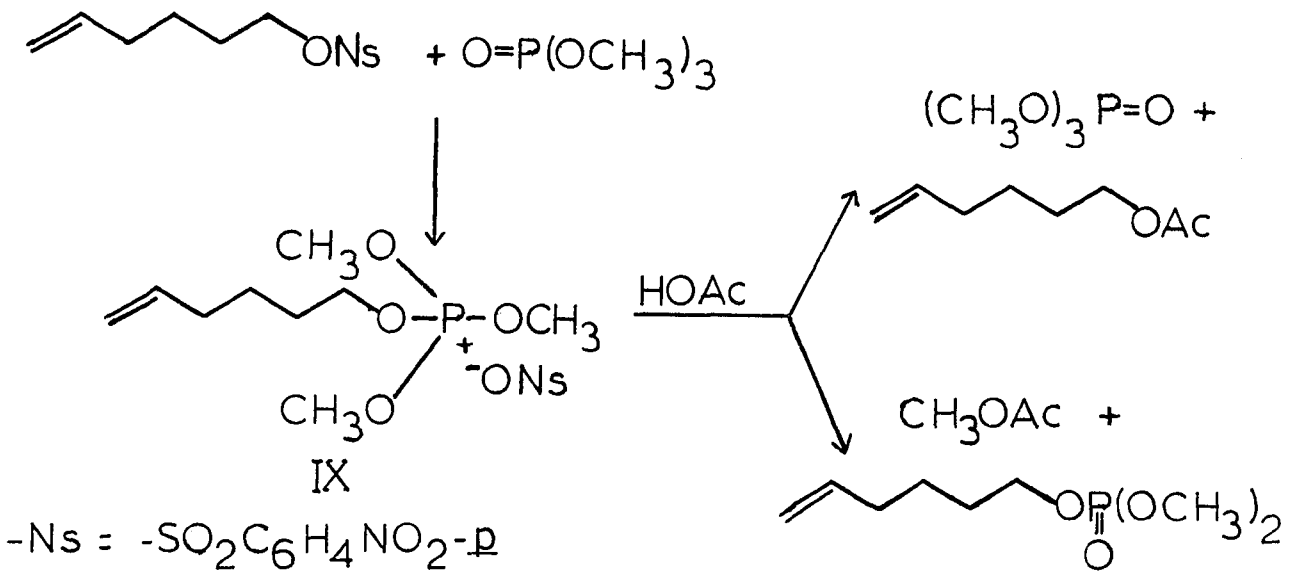
Solvent No.	Analysis[b] 1-Methylcyclopentene	A, Cyclohexene	B, Cyclohexyl Acetate	5-Hexenyl Acetate	% Open / % Cyclic Products	A/B
22)	2.2	39.6	18.7	39.5	0.65	2.12
39)	1.5	34.0	15.4	49.1	0.96	2.20
40)	1.3	30.0	20.4	48.3	0.93	1.47
41)	1.6	38.7	14.1	45.6	0.84	2.74
42)	1.8	34.5	20.5	43.2	0.76	1.68
43)	1.8	29.8	19.7	48.7	0.95	1.51
44)	2.1	50.1	21.7	26.1	0.35	2.30
45)	1.5	34.4	19.2	44.9	0.81	1.79
46)	1.7	30.6	16.9	50.8	1.03	1.81
47)	1.8	44.2	18.0	36.0	0.56	2.46
48)	1.1	35.7	14.3	48.9	0.96	2.50
49)	1.6	34.3	16.5	47.6	0.91	2.08
50)	2.0	38.6	24.8	34.6	0.53	1.56

In Table 5 are presented the results of solvolysis of 5-hexenyl p-nitrobenzenesulfonate in solvent mixtures composed of 20% acetic acid - 80% substituted nitrobenzene.

Because of the low total yields of the four main products (see Table 2) and the detection of other products in several cases, we must conclude that the solvents γ-butyrolactone, tetrahydrofuran, trichloroethylene, benzil, acetonitrile, benzonitrile, all phosphorus compounds, sulfolane, 1,4-butanesultone, dimethyl sulfoxide, dimethyl formamide, tripentyl borate, and pyridine-N-oxide are not inert. These solvents interfere with the solvolysis reaction either by competing with acetic acid as a nucleophile, forming derivative products, or by destruction of the products formed.

The observation of methyl acetate and the low percent recovery of expected solvolysis products found when trimethyl phosphate was used as the nonhydroxylic solvent points toward displacement of the p-nitrobenzenesulfonate group by this solvent as shown in Chart 2. Laughlin (44) has found that phosphate esters react with alkyl halides at high temperatures to produce substituted phosphates, and that this reaction involves nucleophilic displacement by phosphoryl oxygen on the alkyl halide. That acetolysis of trimethyl phosphate did not first occur to produce dimethyl hydrogenphosphate which then attacked 5-hexenyl p-nitrobenzenesulfonate is indicated by the data in Table 6. If this were the case the yield of

Chart 2. Solvolysis of 5-hexenyl p-nitrobenzenesulfonate in 20% acetic acid - 80% trimethyl phosphate



methyl acetate from these solvolyses should not only be greater, a one to one correspondence between dimethyl hydrogen phosphate produced and displacement on the 5-hexenyl sulfonate ester seems unlikely; but, also, the trend of increasing methyl acetate with time suggests that methyl acetate is produced at some time after the displacement of the sulfonate ester. Further confirmation that nucleophilic displacement by trimethyl phosphate actually occurs comes from identification of a product from the solvolysis which appears to be 5-hexenyl dimethyl phosphate. This compound most reasonably corresponds to the amount of the 5-hexenyl moiety found missing in Table 6. The intermediacy of the tetraalkoxyphosphorus cation, IX, in

Table 6. Solvolysis of 5-hexenyl p-nitrobenzenesulfonate at 100° in 20% acetic acid - 80% trimethyl phosphate[a]

No. of runs	Reaction Time, hrs.	Analysis[b] Methyl Acetate[c]	Y, 5-Hexenyl Acetate	Z, Cyclohexyl Acetate	X, % Completed Reaction[d]	X-(Y+Z), %[e]
2	12	12	17.0	0.5	68	50
2	24	22	20.2	1.4	81	60
1	48	43	24.4	0.8	98	73
2	50	49	24.8	2.0	100	75
2	72	67	25.6	1.1	100	75

[a]See footnote a, Table 2.

[b]Actual yield of products based on g.l.p.c. analysis.

[c]Relative thermal conductivity assumed to be 1.00. It is unlikely that significant amounts of methyl acetate were lost during the workup because of the consistent results observed.

[d]Computed by assuming 25% of 5-hexenyl acetate to be the maximum amount produced.

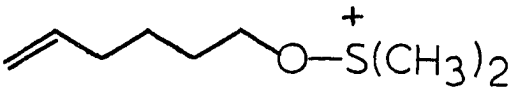
[e]Percent of the 5-hexenyl group unaccounted for.

the above reaction scheme is not unreasonable in view of our data, and similar structures have been written (45,46) for other reactions with phosphorus compounds.

There appears to be no direct displacement on 5-hexenyl p-nitrobenzenesulfonate by acetic acid. Since only about 25% 5-hexenyl and cyclohexyl acetates are produced and the amount of methyl acetate approaches 75% it is reasonable to conclude that acetic acid displacement is not directly involved and

that the acetates produced result from a statistical attack by acetic acid on the tetraalkoxyphosphorus cation, IX. This requires that trimethyl phosphate be significantly more nucleophilic than acetic acid.

In dimethyl sulfoxide - acetic acid mixtures the solvolysis reaction becomes complicated by the imposition of an oxidative reaction. It is well known that primary alkyl sulfonate esters are oxidized by dimethyl sulfoxide under fairly mild conditions to aldehydes (47,48). Since oxidation by dimethyl sulfoxide of 5-hexenyl p-nitrobenzenesulfonate to 5-hexenal also produces dimethyl sulfide, there is a competition between acetic acid, dimethyl sulfoxide, and dimethyl sulfide for available 5-hexenyl ester. Reaction of the p-nitrobenzenesulfonate ester in 80% dimethyl sulfoxide - 20% acetic acid for 24, 50, and 100 hours showed a definite increase in the amount of 5-hexenyl methyl sulfide formed with time as well as a decrease in the amount of 5-hexen-1-ol produced. At 24 hours 5-hexenyl acetate was the major product. After 100 hours 5-hexenyl methyl sulfide predominated. Since water was excluded from these reactions one cannot write a reasonable mechanism that accounts for the direct production of 5-hexen-1-ol. More likely alcohol is produced during the product workup by the fast hydrolysis of the intermediate formed in the solvolytic oxidation, the 5-hexenyl dimethylsulfoxonium cation, X, which should be moderately stable in



X

a dimethyl sulfoxide - acetic acid mixture.

No definite evidence has yet been obtained concerning alternate modes of reaction that occur when γ-butyrolactone, tetrahydrofuran, trichloroethylene, benzil, acetonitrile, all phosphorus compounds except trimethyl phosphate, sulfolane, 1,4-butanesultone, dimethylformamide, tripentyl borate and pyridine-N-oxide are used as nonhydroxylic solvents. However, in several cases unidentified products were detected in significant yields, and for many of the solvents which did not give high yields of expected solvolysis products reasonable schemes could be written either for nucleophilic displacement or product destruction by these solvents. It is interesting that of the dipolar aprotic solvents used only nitrobenzene, vinyl sulfone, and methyl phenyl sulfone were inert in the solvolysis reaction toward side reactions.

In Table 7 the yields of cyclic products in solvent mixtures that gave high total recovery of products (>70%) are given. Since (% open product/% cyclic products) is a measure of (k unassisted/k assisted) (38,40) it is seen that the rate ratio varies from 9.64 in ethyl ether to 0.62 for vinyl sulfone. Although a factor of 16 is not a large number, it is

significant in that it is responsible for changing a reaction from one that leads to largely acyclic materials to one that yields mainly cyclic materials. Of the solvents listed in Table 7, 1,1,2,2-tetrachloroethane, nitrobenzene, methyl phenyl sulfone, and vinyl sulfone lead to the most cyclization.

Table 7. Yield[a] of cyclic products from the solvolysis of 5-hexenyl p-nitrobenzenesulfonate at 100° in binary solvent mixtures composed of 20% acetic acid and 80% nonhydroxylic solvent[b]

Nonhydroxylic Solvent	% Cyclic Products	Nonhydroxylic Solvent	% Cyclic Products
Ethyl Ether	9.4	Phenyl Ether	31.7
Carbon Tetrachloride	15.6	Phenyl Sulfide	33.0
Ethyl Stearate	17.2	Butyl Sulfone	33.3
p-Methyl Anisole	22.2	Triacetin	34.0
Acetophenone	23.8	Chloroform	38.4
Furan	23.9	Acetic Acid[c]	45.2
Benzene	24.5	1,1,2,2-Tetrachloroethane	52.3
Benzyl Ether	25.2	Methyl Phenyl Sulfone	59.8
Methyl Benzoate	28.8	Nitrobenzene	60.5
o-Dichlorobenzene	31.3	Vinyl Sulfone	61.8

[a]Yields are relative with total recovery being greater than 70%.

[b]Reaction time was usually 50 hours.

[c]Pure acetic acid.

Compared to acetic acid, nonpolar solvents such as ethyl ether, carbon tetrachloride, ethyl stearate, acetophenone, and benzene substantially increase the amount of 5-hexenyl acetate. A priori one might have expected that decreasing the concentration of acetic acid by the addition of a nonpolar diluent

should have decreased the amount of direct displacement instead of increasing it.[1]

The solvents listed in Table 7 may be qualitatively separated into four classes. Binary solvent systems containing a polar solvent as the nonhydroxylic component, generally solvents which have a high dielectric constant, lead to the most cyclization. Included in this class are nitrobenzene, vinyl and methyl phenyl sulfones. Solvents such as chloroform and 1,2,2,2-tetrachloroethane which may donate a hydrogen for hydrogen bonding (49,50) also give a significant amount of cyclic products. This is to be contrasted with solvents such as ethyl ether which may form a hydrogen bond to acetic acid (Pimentel 50, pp. 196-199), but without contributing a hydrogen to the hydrogen-bonding scheme. The fourth class of binary solvents include relatively nonpolar solvents such as carbon tetrachloride and ethyl stearate whose major effect may be merely a dilution of the acetic acid.

An attractive explanation for the fact that polar solvents or solvents that possess hydrogens that can hydrogen bond lead to the most cyclization is that these solvents can solvate acetic acid. Solvation of the acetic acid should increase the stability of the ground state that leads to direct

[1]More appropriate diluents, such as the hydrocarbons heptane and cyclohexane, were only slightly miscible with acetic acid and for this reason could not be used.

displacement (open product). Indeed, Arnett has shown that the rate of solvolysis of t-butyl chloride in aquous alcohol mixtures is determined by changes in the stability of the ground state and not of the transition state (51-54). It would appear then that the decrease in the nucleophilicity of acetic acid with increasing polarity of the added nonhydroxylic solvent is primarily a ground state change.

Kosower's Z-values (10) were measured by Richard Ehlers in this laboratory for several of the solvent mixtures in order to determine the effect of "solvent polarity" on the amount of cyclization. These values are given in Table 8 for 20% acetic acid - 80% nonhydroxylic solvent mixtures. The Z-values for all of the mixtures are the same within experimental error. We, therefore, concluded that either "solvent polarity" is of no importance when considering these binary solvents or the indicator used in the measurement of these Z-values is specifically solvated by the more polar component of our solvent mixtures.

Inspection of the ratio of assisted to unassisted solvolysis ($k_{5\text{-hexenyl}}/k_{\text{hexyl}}$) in Table 4 shows a remarkable correlation between this value and the ratio of percent cyclic to percent open product. For those solvents which do not interfere with the solvolysis reaction this data, although crude, constitutes a further proof that the scheme written for the solvolysis reaction in Chart 1 is adequate, and that alter-

Table 8. Z values for 20% acetic acid - 80% nonhydroxylic solvent mixtures[a]

Solvent	λmax[b] (mμ)	Z[c]
Acetic Acid[d]	366.5	77.9
Ethyl Ether	369.7	77.4
Carbon Tetrachloride	371.1	77.0
1,1,2,2-Tetrachloroethane	370.0	77.2
Benzene	369.2	77.4

[a]Data obtained by Richard Ehlers.

[b]Average of at least three determinations. Mean deviation is $\pm$ 0.5 mμ.

[c]$Z = 2.859 \times 10^{-3}(1/\lambda)$ where λ is in $cm.^{-1}$

[d]Pure acetic acid.

nate modes of reaction, such as that suggested by Streitwieser (43) and discussed in a later section (p. 90 to p. 91 in this copy), do not occur to a significant extent.

In Table 5 are presented the data for solvent mixtures composed of 20% acetic acid - 80% substituted nitrobenzenes. It is seen that the relative yields of cyclic products only vary from 50% to 74%, and most of the mixtures result in about 55% cyclization. Thus the addition of one nitro group to benzene seems to have a large effect, but additional substituents have only a small effect. There appears to be no correlation between the electronic effect of the added substituent and the amount of cyclization since, for example, in

1-chloro-4-nitrobenzene - acetic acid less cyclic products are formed than in the corresponding solution containing p-nitroanisole, and less cyclic products are formed in p-nitroanisole - acetic acid than in p-nitrotoluene - acetic acid solution. One might argue that placing a methyl substituent ortho to the nitro group noticeably retards association of this molecule with acetic acid because of steric repulsion. This, however, is not satisfactorily shown by the data in Table 5 since o-nitrotoluene and 2-nitro-m-xylene produce essentially the same amount of cyclic products. In this series bulk solvation properties may be important. Addition of another substituent to the nitrobenzene molecule may well disrupt the close-packing arrangement which the nitrobenzene-acetic acid mixture was able to enjoy, thus decreasing the stability of the substituted nitrobenzene - acetic acid association relative to that of nitrobenzene - acetic acid.

We concluded from this study that nitrobenzene itself is the optimum solvent to use for solvent mixtures of low nucleophilicity. The dinitrobenzene-solvent mixtures that lead to more cyclization are difficult to work with because the dinitrobenzenes are solids at room temperature. Although the o-nitroanisole mixture is slightly superior to the nitrobenzene mixture, use of the nitrobenzene mixture is advocated since the increase in cyclization in the o-nitroanisole mixture is not that great, nitrobenzene is a more common

material that has been used extensively as a solvent, and the methoxy group of the anisole could act as a nucleophile in certain cases.

Variation of Percent Composition of Acetic Acid-Nonhydroxylic Solvent Mixtures

In Table 9 are presented the data from the solvolysis of 5-hexenyl p-nitrobenzenesulfonate in acetic acid-nitrobenzene in which the percent composition of the components of the binary solvents are varied. Similar data are presented in Tables 10 and 11 for acetic acid - ethyl ether and acetic acid - carbon tetrachloride solutions, respectively. The main features of these data are shown diagramatically in Figures 1, 2, and 3.

The most striking feature of these data is the observed increase in the amount of cyclic products with an increase of percent nitrobenzene in the binary solvent mixture. From Figure 1 one can clearly see a maximum for percent cyclic products between 60% and 80% nitrobenzene, the amount of cyclic products dropping off sharply after 80% nitrobenzene - 20% acetic acid is reached. The observed maximum occurs between mole ratio of nitrobenzene to acetic acid of 0.84 and 2.23. Because of the inherent error of the product detection method used and the flatness of the top of the curve the exact location of this maximum cannot be pinpointed; however, it would be reasonable to expect the maximum to occur at mole ratio

Table 9. Solvolysis of 5-hexenyl p-nitrobenzenesulfonate at 100° in acetic acid - nitrobenzene mixtures[a]

% Nitrobenzene (No. of runs)	Reaction Time, hrs.	Mole Ratio ($C_6H_5NO_2$/HOAc)	% Recovery[c]	% Open / % Cyclic Products	A/B
0 (4)	50	0.00	90	1.21	0.42
10 (2)	50	0.06	88	1.04	0.54
20 (2)	50	0.14	92	0.94	0.66
30 (2)	50	0.24	90	0.85	0.78
40 (2)	50	0.37	88	0.81	0.95
50 (2)	50	0.56	91	0.75	1.11
60 (3)	50	0.84	86	0.67	1.34
70 (2)	50	1.30	87	0.64	1.58
80 (2)	50	2.23	86	0.65	2.12
90 (2)	50	5.02	88	0.99	3.27
99[d] (3)	72	27.2	47	0.53	5.24

[a]See footnote a, Table 2.

[b]See footnote b, Table 2.

[c]See footnote d, Table 2.

[d]Because % recovery was low in this case the values obtained may have no meaning.

% Nitrobenzene	Analysis[b]				
	1-Methylcyclopentene	A, Cyclohexene	B, Cyclohexyl Acetate	5-Hexenyl Acetate	% Cyclic Products
0	0.9	13.2	31.1	54.8	45.2
10	1.3	16.7	30.9	51.1	48.9
20	1.3	20.0	30.1	48.6	51.4
30	1.4	23.0	29.6	46.0	54.0
40	1.4	26.2	27.6	44.8	55.2
50	1.6	29.2	26.2	43.0	57.0
60	1.7	33.4	25.0	39.9	60.1
70	2.0	36.0	22.8	39.2	60.8
80	2.2	39.6	18.7	39.5	60.5
90	1.6	37.3	11.4	49.7	50.3
99[d]	1.4	53.5	10.2	34.9	65.1

Table 10. Solvolysis of 5-hexenyl p-nitrobenzenesulfonate at 100° in acetic acid - ethyl ether mixtures[a]

% Ethyl Ether (No. of runs)	Reaction Time, hrs.	Mole Ratio (Et_2O/HOAc)	% Recovery[c]	% Open / % Cyclic Products	A/B
0 (4)	50	0.00	90	1.21	0.42
10 (2)	50	0.06	86	1.32	0.47
20 (2)	50	0.14	87	1.43	0.57
30 (2)	50	0.24	86	1.67	0.70
40 (2)	50	0.37	83	1.96	0.78
50 (2)	50	0.55	86	2.28	1.03
60 (1)	50	0.82	85	3.23	1.18
70 (2)	50	1.28	85	4.76	1.39
80 (2)	50	2.21	85	7.7	2.59
90 (3)	76	4.96	79	18	7.83

[a]See footnote a, Table 2.

[b]See footnote b, Table 2.

[c]See footnote d, Table 2.

% Ethyl Ether	Analysis[b] 1-Methyl-cyclo-pentene	A, Cyclo-hexene	B, Cyclo-hexyl Acetate	5-Hexenyl Acetate	% Cyclic Products
0	0.9	13.2	31.1	54.8	45.2
10	0.6	13.6	29.0	56.8	43.2
20	0.5	14.8	26.0	58.7	41.3
30	0.6	15.2	21.8	62.4	37.6
40	0.6	14.6	18.6	66.2	33.8
50	0.5	15.2	14.8	69.5	30.5
60	0.4	12.5	10.6	76.5	23.5
70	0.2	10.0	7.2	82.6	17.4
80	0.1	8.3	3.2	88.4	11.6
90	trace	4.7	0.6	94.7	5.3

Table 11. Solvolysis of 5-hexenyl p-nitrobenzenesulfonate at 100° in acetic acid - carbon tetrachloride mixtures[a]

% Carbon Tetrachloride (No. of runs)	Reaction Time, hrs.	Mole Ratio (CCl_4/HOAc)	% Recovery[c]	% Open / % Cyclic Products	A/B
0 (4)	50	0.00	90	1.21	0.42
10 (2)	50	0.07	90	1.23	0.49
20 (2)	50	0.15	89	1.30	0.52
30 (2)	50	0.26	88	1.33	0.57
40 (2)	50	0.40	90	1.47	0.60
50 (2)	50	0.60	86	1.88	0.68
60 (3)	50	0.89	86	2.32	0.73
70 (2)	50	1.39	84	3.33	0.91
80 (2)	50	2.38	81	5.36	1.13
90 (3)	76	5.34	80	11.1	2.07

[a]See footnote a, Table 2.

[b]See footnote b, Table 2.

[c]See footnote d, Table 2.

% Carbon Tetrachloride	Analysis[b] 1-Methylcyclopentene	A, Cyclohexene	B, Cyclohexyl Acetate	5-Hexenyl Acetate	% Cyclic Products
0	0.9	13.2	31.1	54.8	45.2
10	1.1	14.4	29.6	54.9	45.1
20	1.1	14.5	28.0	56.4	43.6
30	1.0	15.1	26.6	57.3	42.7
40	1.0	14.8	24.6	59.6	40.4
50	0.9	13.6	20.1	65.4	34.6
60	0.9	12.3	16.8	70.0	30.0
70	1.0	10.6	11.7	76.7	23.3
80	0.7	8.0	7.1	84.2	15.8
90	trace	5.6	2.7	91.7	8.3

Figure 1. Product yield vs. solvent composition for nitrobenzene - acetic acid mixtures

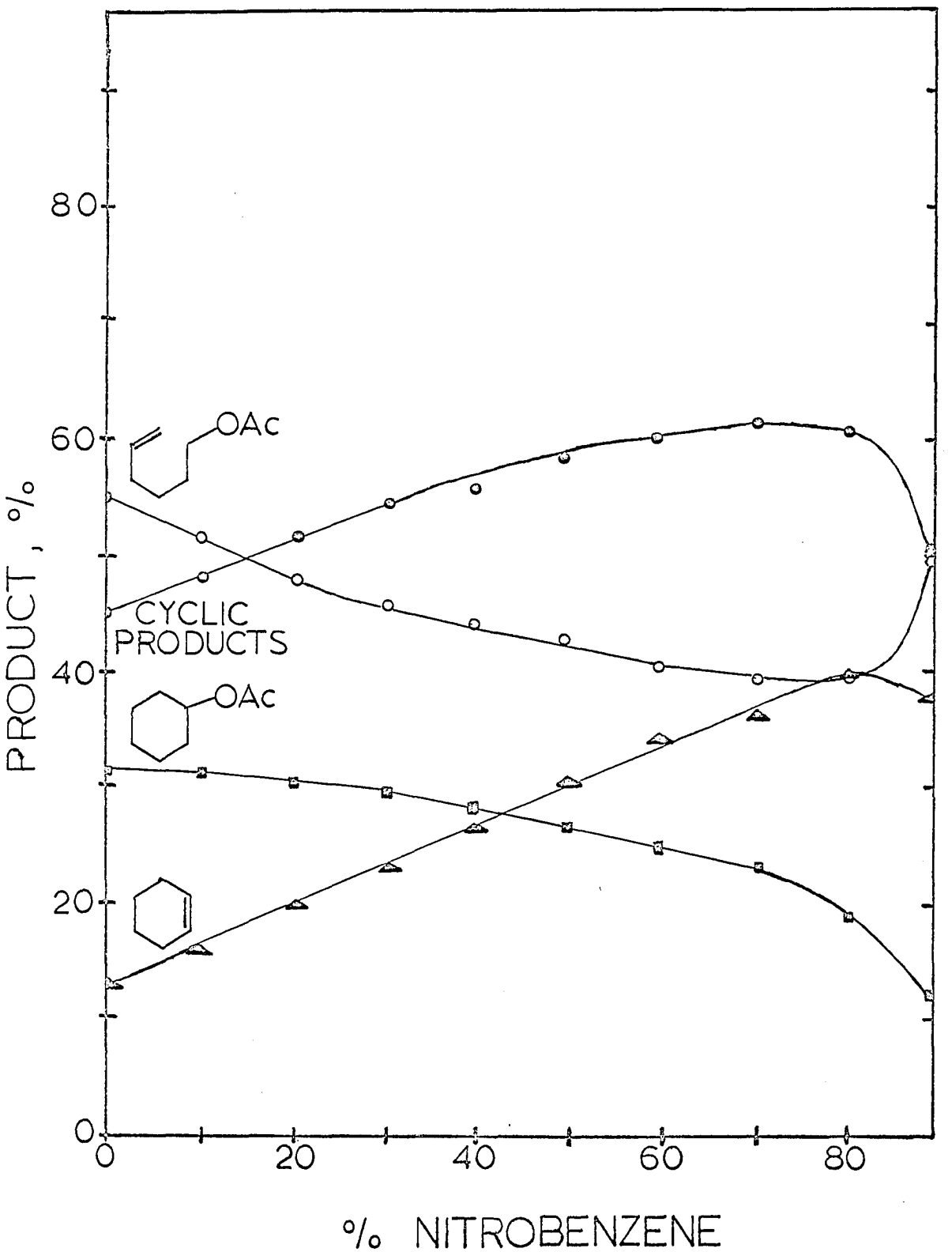

80
60
40
20
0
PRODUCT, %
OAc
CYCLIC
PRODUCTS
OAc
0
20
40
60
80
% NITROBENZENE

Figure 2. Product yield vs. solvent composition for ethyl ether - acetic acid mixtures

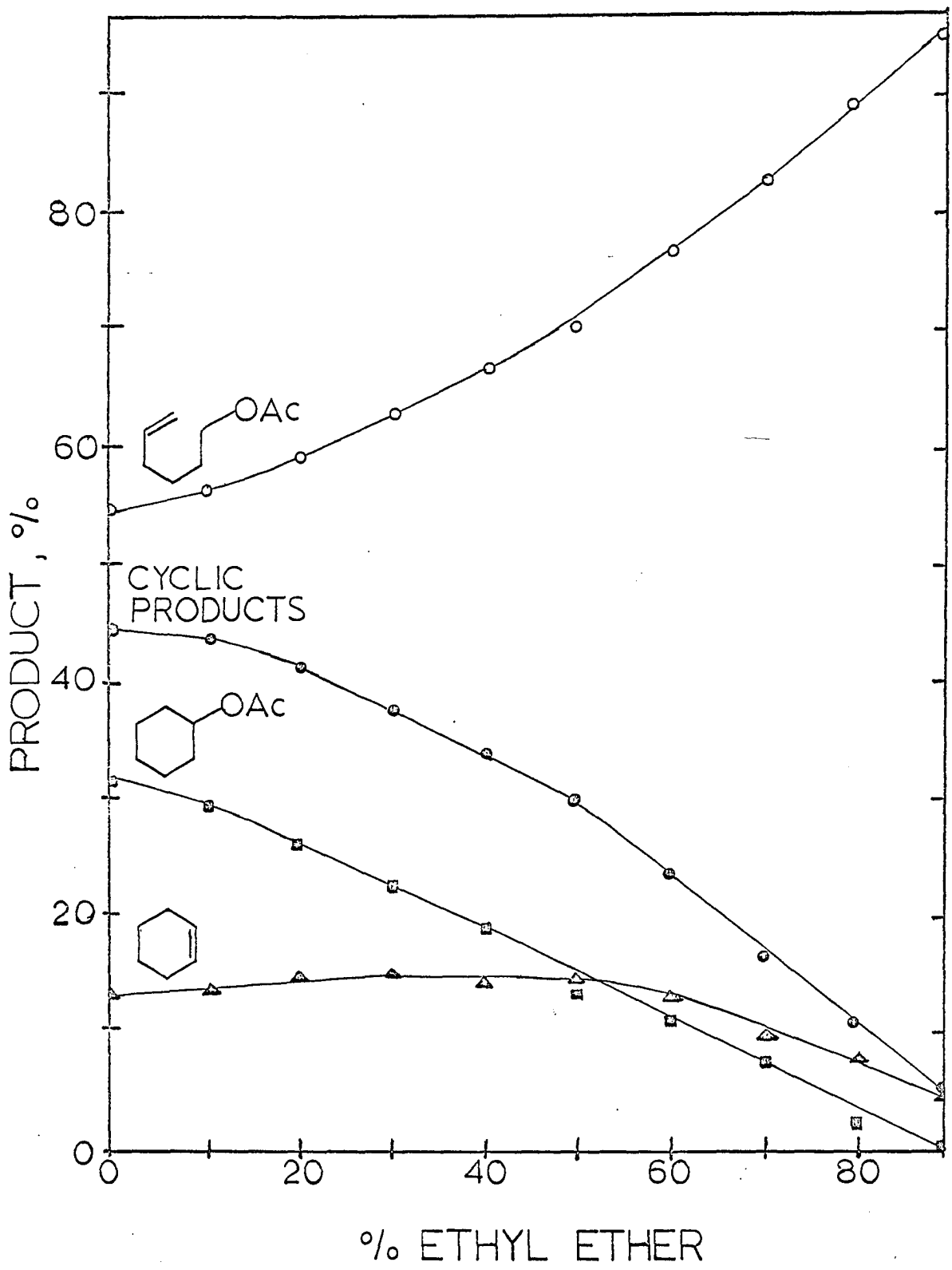
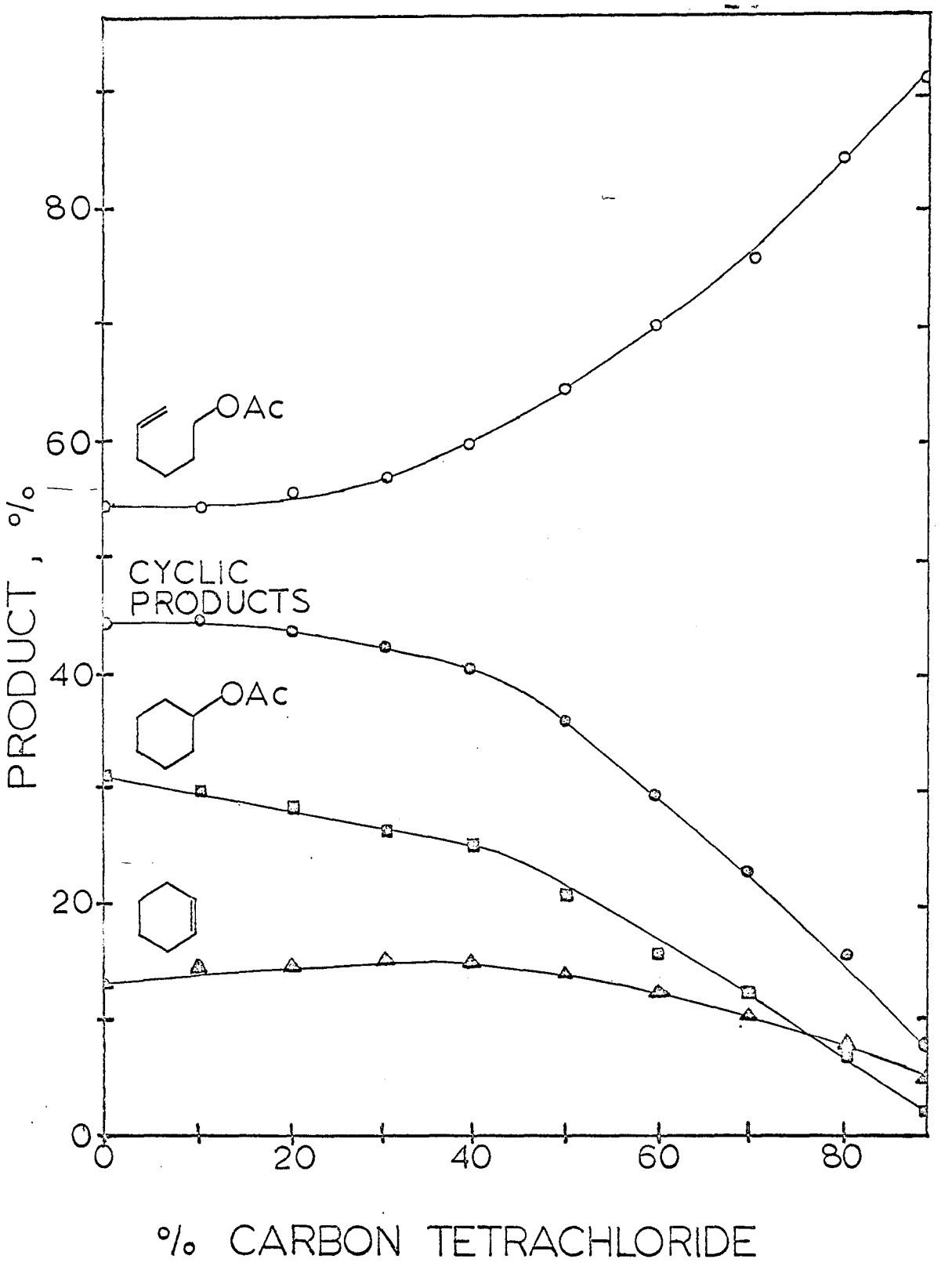

80
60
40
20
0
PRODUCT, %
OAc
CYCLIC
PRODUCTS
OAc
0
20
40
60
80
% ETHYL ETHER

Figure 3. Product yield vs. solvent composition for carbon tetrachloride - acetic acid mixtures


PRODUCT, %
0
20
40
60
80
OAc
CYCLIC
PRODUCTS
OAc
0
20
40
60
80
% CARBON TETRACHLORIDE

1.00. That is, the maximum increase in percent cyclic products occurs when the solution contains exactly one molecule of acetic acid to one molecule of nitrobenzene. It is known that aliphatic acids form dimers with closed rings (Hildebrand and Scott, 55, p. 172) and Taft has shown (56) that dimerization of nitrobenzene in solution involves localized polar groups. Apparently then, acetic acid and nitrobenzene form a complex which is more stable than either the nitrobenzene-nitrobenzene or the acetic acid-acetic acid dimers. A similar observation has been made by Delpuech (57) for water - formic acid mixtures in which he finds that the entropy of activation for the solvolysis of butyl bromide reaches a minimum at a point corresponding to a 1:1 complex between water and formic acid.

A peculiar feature of Figure 1 is the apparent linear increase of cyclohexene with increasing nitrobenzene composition. The amount of cyclohexyl acetate steadily decreases, especially after reaching 70% nitrobenzene composition. These observations are apparently related to the association of nitrobenzene with acetic acid; the particular mechanism whereby these transformations occur, however, cannot be elucidated with only this one example.

From Figures 2 and 3 it is evident that no stable complex exists between acetic acid and ethyl ether or carbon tetrachloride. The steady decrease in percent cyclic products with

increasing amounts of nonhydroxylic solvent argues that association of these solvents with acetic acid is either negligible or that the association gives rise to a more nucleophilic mixture. There is little difference between Figures 2 and 3. Both show the percent cyclohexene going through a slight maximum at about 40% to 50% nonhydroxylic solvent. In fact the yields of cyclohexene in these two solvent mixtures is exactly the same within experimental error. The amount of 5-hexenyl and cyclohexyl acetates formed in acetic-acid ethyl ether mixtures sharply rise and fall, respectively, almost immediately upon addition of the nonhydroxylic solvent. In carbon tetrachloride - acetic acid mixtures, however, the corresponding rise and fall do not become important until after 30 or 40% carbon tetrachloride is added, and then the changes are as great as those shown in Figure 2. The changes in the acetate products that occur in carbon tetrachloride - acetic acid mixtures, then, are nearly the same as those that occur in the ethyl ether mixtures except that they occur later, only after a certain amount of carbon tetrachloride is already present in the solution.

These data for polar (nitrobenzene) and nonpolar (carbon tetrachloride and ethyl ether) nonhydroxylic solvents give further credence to the argument that solvation of the acetic acid increases the stability of the ground state that leads

to direct displacement. Observation of a maximum for the amount of cyclic products formed in nitrobenzene-acetic acid mixtures can certainly be reasonably interpreted as a specific solvation of acetic acid. The results from the solvolysis of 5-hexenyl p-nitrobenzenesulfonate in ethyl ether and carbon tetrachloride mixtures indicate either solvation of acetic acid gives a more nucleophilic mixture or that these solvents simply dilute the acetic acid.

Solvolysis of 5-Hexenyl p-Nitrobenzenesulfonate in Various Hydroxylic Solvents and Hydroxylic Solvent Mixtures

Table 12 presents data for the solvolysis of 5-hexenyl p-nitrobenzenesulfonate in solvent mixtures in which the hydroxylic component is varied. The product analyses were carried out on the initially formed esters except when o-nitrobenzoic acid was used. The o-nitrobenzoate esters were converted to the corresponding acetates.

In Table 13 results are presented for the solvolysis of 5-hexenyl p-nitrobenzenesulfonate in formic acid and formic acid - nitrobenzene mixtures using both sodium formate and urea to neutralize the arenesulfonic acid produced. The percent recovery of expected solvolysis products is lower by as much as 15% when urea is used than when sodium formate is used. In addition, when the 5-hexenyl sulfonate was solvolyzed in 80% formic acid - 20% acetic acid with added urea as

Table 12. Solvolysis of 5-hexenyl p-nitrobenzenesulfonate at 100° in various solvent mixtures in which the hydroxylic solvent is varied[a]

Solvent No.	Solvent[c] (No. of runs)	Reaction Time, hrs.	Mole Ratio ($C_6H_5NO_2$/Acid)	% Recovery[d]
1)	Acetic Acid (4)	50	-	90
22)	20% Acetic Acid - 80% Nitrobenzene (2)	50	2.23	86
51)	Deuterioacetic Acid (3)	24	-	81
52)	Pivalic Acid (2)[e]	24	-	75
53)	20% Pivalic Acid - 80% Nitrobenzene (2)[e]	50	4.28	67
54)	20% o-Nitrobenzoic acid - 80% Nitrobenzene[f]	64	4.13	89

[a]See footnote a, Table 2.

[b]See footnote b, Table 2.

[c]For solvolyses of 5-hexenyl p-nitrobenzenesulfonate in 20% hydroxylic solvent - 80% nitrobenzene for 64 hours the yields of 1-methylcyclopentene and cyclohexene were respectively: benzoic acid, 1.4%, 43.8%; p-nitrobenzoic acid, 1.2%, 30.4%; o-methoxybenzoic acid, 0.7%, 18.7%; chloroacetic acid, 3.1%, 50.3%; maleic acid, 1.7%, 28.5%; and phenol, 1.6%, 36.4%.

[d]See footnote d, Table 2.

[e]The low % recovery was probably due to incomplete reaction.

[f]Yield of products was based on g.l.p.c. analysis for 1-methylcyclopentene and cyclohexene from three runs, on analysis for cyclohexyl and 5-hexenyl acetates, formed from the corresponding o-nitrobenzoate esters by basic hydrolysis followed by conversion of the alcohols to acetates using acetyl chloride, from one run.

Solvent No.	Analysis[b] 1-Methylcyclopentene	A, Cyclohexene	B, Cyclohexyl Carboxylate	5-Hexenyl Carboxylate	% Open / % Cyclic Products	A/B
1)	0.9	13.2	31.1	54.8	1.21	0.42
22)	2.2	39.6	18.7	39.5	0.65	2.12
51)	0.2	6.6	22.2	71.0	2.44	0.30
52)	0.6	11.1	12.6	75.7	3.12	0.88
53)	1.2	42.5	7.5	48.8	0.95	5.67
54)	3.2	62.3	20.3	14.2	0.17	3.07

Table 13. Solvolysis of 5-hexenyl p-nitrobenzenesulfonate at 90° in formic acid and 20% formic acid - 80% nitrobenzene with urea or sodium formate as the base[a]

Solvent No.	Solvent	Base	Reaction Time, hrs.	% Recovery[c]
55)	Formic Acid	urea[f]	3	82.0
			3	81.4
		sodium formate[g]	3	94.0
			3	98.3
56)	20% Formic Acid-80% Nitrobenzene[h]	urea[i]	24	88.6
			24	87.6
		sodium formate[i]	24	93.6
			24	95.3

[a] [RONs] = 0.1M, [Base] = 0.2 M. The formic acid used contained less than 3% water.

[b] Actual yield of products. Neither 1-methylcyclopentyl nor cyclopentylmethyl formate were found to be present.

[c] See footnote d, Table 2.

[d] Precise identity of olefin is unknown. Product is not 1,5-hexadiene or 1-methylcyclopentene, neither of which are present except possibly in trace amounts. Assumed thermal conductivity of the olefin to be the same as that of cyclohexene.

[e] For runs when urea was used as the base assumed a percent recovery of 95% to include 1,5-hexyl diformate in this calculation. Also, this calculation assumes that the olefin produced is a hexadiene.

[f] A product was observed by g.l.p.c. analysis which corresponds to 1,5-hexyl diformate.

[g] Only a trace amount of 1,5-hexyl diformate was observed.

[h] Mole ratio of nitrobenzene to formic acid is 1.46.

[i] The g.l.p.c. peak assigned to 1,5-hexyl diformate could not be separated from the nitrobenzene solvent peak. This product is most certainly present when urea is used.

Solvent No.	Analysis[b] Olefin[d]	A, Cyclohexene	B, Cyclohexyl Formate	5-Hexenyl Formate	% Open / % Cyclic Products[e]	A/B
55)	11.8	4.1	62.0	4.1	0.44	0.066
	13.3	4.2	59.7	4.2	0.49	0.070
	13.7	6.8	49.8	23.7	0.66	0.14
	12.9	7.2	53.0	25.2	0.63	0.14
56)	7.1	14.9	53.8	12.8	0.38	0.28
	7.4	17.1	50.1	13.0	0.41	0.34
	5.7	27.4	22.1	38.4	0.89	1.24
	5.0	28.6	23.3	38.4	0.83	1.23

the base (Table 15) no 5-hexenyl esters were found. From these data it is evident that urea is ineffective in preventing addition by formic acid into the double bond of the 5-hexenyl moiety. Analysis of the products from these formolysis reactions showed a compound which corresponds to 1,5-hexyl diformate.

If it can be determined that olefinic products and not reactant 5-hexenyl sulfonate ester are destroyed by addition of formic acid into the olefin then we can calculate a ratio of percent open to percent cyclic products with reasonable accuracy. To do this we must first calculate an approximate rate for the addition reaction and then compare this rate to the rate of formolysis. To obtain a rate for the addition reaction we will make use of the conversion of cyclohexene to cyclohexyl formate which, as expected, does occur during the formolysis reaction when urea is used as the base.

It is known (41) that the added base in an acetolysis reaction has no effect on the ratio of percent cyclohexene to percent cyclohexyl acetate whether these products are formed from cyclohexyl or 5-hexenyl p-nitrobenzenesulfonate (also see Table 25). The only condition stipulated is that the base is sufficiently strong to neutralize the sulfonic acid produced. One should expect then that, like the similar acetolysis reaction, identical ratios of percent cyclohexene to cyclohexyl formate should be found in the formolysis reac-

tion regardless of the base, providing, of course, that the added base can effectively neutralize the sulfonic acid produced. Yet, as can be seen from Table 13, in formic acid this ratio is a factor of two larger when sodium formate was the base than when urea was used. Since sodium formate effectively neutralizes the sulfonic acid produced, as is seen from the high percent recovery in Table 13 when this base was used, the implication is that urea is an ineffective base and, because of this, cyclohexene is converted to cyclohexyl formate. This conversion occurs, however, at a relatively slow rate compared to the actual solvolysis reaction. One can approximately estimate that if the actual ratio of cyclohexene to cyclohexyl formate is 0.14, then the half-life for conversion of cyclohexene to cyclohexyl formate is approximately three hours at 90^0. This value should be compared to an estimated half-life of less than one hour at 75^0 for the formolysis of 5-hexenyl p-nitrobenzenesulfonate (39).

Because of the estimated slow conversion of cyclohexene to cyclohexyl formate compared to the solvolysis reaction it was assumed that formic acid added into the double bond of the olefinic products from the formolysis reaction and not into the double bond of 5-hexenyl p-nitrobenzenesulfonate. In this way the calculation of percent open to percent cyclic products includes an estimated amount of 1,5-diformatohexane, calculated as the difference between the percent recovery for products

from formolysis with sodium formate and urea as the base, as open product. It was also assumed for this calculation that the olefin formed in these solvolyses was an acyclic hexadiene.

Although sodium formate is effective in neutralizing the sulfonic acid produced during formolysis reactions, a considerable amount of direct displacement by formate ion occurs. Comparing the data within Table 13 for solvolysis in formic acid shows that approximately 7% more cyclic products are produced when urea was used as the base than when sodium formate was used. The corresponding data in 20% formic acid - 80% nitrobenzene are even more pronounced, showing that as much as 20% more cyclic products are produced with urea as the base. Our data compare favorably with that of W. S. Johnson and coworkers (39) for formolysis of 5-hexenyl p-nitrobenzenesulfonate using sodium formate as the base even though the concentration of reactants used by Johnson were five times less than those which we used. We do suspect, however, his report that 73% cyclic products were formed during formolysis (39) is rather high.

From Tables 12 and 13 it can be seen that, except for deuterioacetic acid, the more acidic solvents lead to the greatest amount of cyclic products. This is qualitatively shown in Table 14 where the ratio of percent open to percent cyclic products is compared to the pKa of the various acids in water. Indeed, when the solvolysis of 5-hexenyl p-nitrobenzene-

Table 14. Comparison of the ratio of % open to % cyclic products from the solvolysis of 5-hexenyl p-nitrobenzenesulfonate with the acid dissociation constant and monomer - dimer equilibrium constant for several carboxylic acids

Solvent	% Open/% Cyclic Products 100% Solvent	20% Solvent-80% $C_6H_5NO_2$	pKa	$K_{eq.}$ [a]
Pivalic Acid	3.12	0.95	5.05[b]	690
Deuteroacetic Acid	2.44	-	5.26[c]	296
Acetic Acid	1.21	0.65	4.76[b]	131
Formic Acid	0.46	0.40	3.77[b]	126
o-Nitrobenzoic Acid	-	0.17	2.18[b]	-

[a]Data taken from Pimentel and McClellan (50, pp. 365-386).

[b]Data taken from Dippy (58). Dissociation constants were measured in water.

[c]Data taken from Brescia et al. (59).

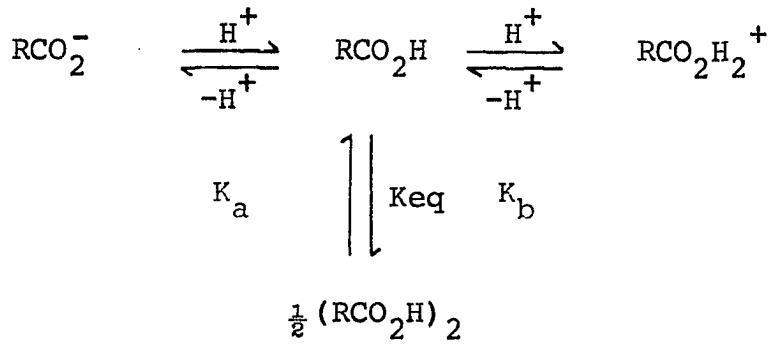
sulfonate was carried out in trifluoroacetic acid (discussed later in this section), the percent recovery of cyclohexyl trifluoroacetate, the only identified cyclic product, was approximately 80%. This qualitative correlation with acidity of these acids is reasonable since among monocarboxylic acids the most acidic solvents are usually also the least basic. The fact that the more acidic solvents in a series of monocarboxylic acids lead to a greater amount of cyclic products may also be explained by the ground state solvation of these acids. With few exceptions the greater the acidity of these acids the weaker is the hydrogen bonding capability (Pimentel and McClellan 50, pp. 24, 47, 365-386). The types of hydrogen

bonding to a carboxylic acid may be classed into three types according to the system of Pimentel and McClellan (50): bonding from an acid, from a base, and from an acid-base.

Bonding from an acid type to a carboxylic acid is the case in which a hydrogen bond is donated to the carboxylic acid. This is of a type mentioned before for possible bonding between chloroform or 1,1,2,2-tetrachloroethane and acetic acid. The chloroform cannot accept a hydrogen in a hydrogen bonding scheme and is thus differentiated from the base type of hydrogen bonding which was mentioned earlier for ethyl ether-acetic acid complexation. A combination of the acid and base types occurs when carboxylic acid dimers are considered. A carboxylic acid has the ability to donate and accept hydrogen bonds from another carboxylic acid and is, therefore, classed as an acid-base type. Of the three types of hydrogen bonding the base type should obviously give the most nucleophilic mixture since the carboxylic acid is given more anion character. Bonding of the acid type should lead to the least nucleophilic mixture since electron density is withdrawn from the carbonyl oxygen. Between these two classes in solvent nucleophilicity is the type of bonding found in carboxylic acid dimers.

Deno (60) has found that the base strength of a carboxylic acid, as measured by the equilibrium between carboxylic acid and protonated carboxylic acid (K_b), decreases as the acidity,

measured by the ionization constant of the carboxylic acid (K_a), increases. We have seen that as the acidity increases

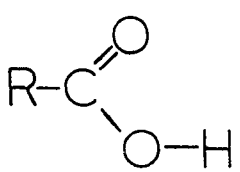


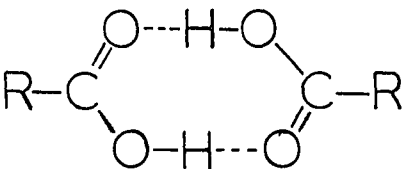
the percent of carboxylic acid dimer decreases (see Table 14). Now, putting these all together, as the acidity increases the amount of carboxylic acid dimer and the basicity decreases; as the acidity decreases the reverse is true for the amount of carboxylic acid dimer and the basicity. Thus there is a correlation between acidity, basicity, and monomer - dimer equilibrium for carboxylic acids which suggests that the nucleophilicity of the carboxylic acid should increase as the amount of acid dimer increases. This is what is found. The value of the equilibrium constant between monomer and dimer is usually larger when the dissociation constant of the carboxylic acid is smaller (50). Representative values for the monomer-dimer equilibrium constant are given in Table 14.

The fact that deuterioacetic acid, a weaker acid than pivalic acid, gives a lower ratio of percent open to percent cyclic products than does pivalic acid can also be explained by ground state solvation of the nucleophile. As shown in

Table 14 for deuterioacetic acid the equilibrium constant for monomer-dimer exchange (Pimentel and McClellan 50, pp. 24, 47, 365-386) is greater than that of acetic acid, yet less than the corresponding value for pivalic acid. The percent of carboxylic acid dimer, therefore, does appear to influence the nucleophilicity of the solvent, and indicates that the ratio of percent open to percent cyclic products from the solvolysis of 5-hexenyl p-nitrobenzenesulfonate is a measure of solvent nucleophilicity.

The question arises as to which carboxylic acid species is the more nucleophilic, the monomer or the dimer. At first glance the monomer would appear to be the more nucleophilic since in the dimer electron density is pulled away from the carbonyl oxygen. However, at the same time more electron

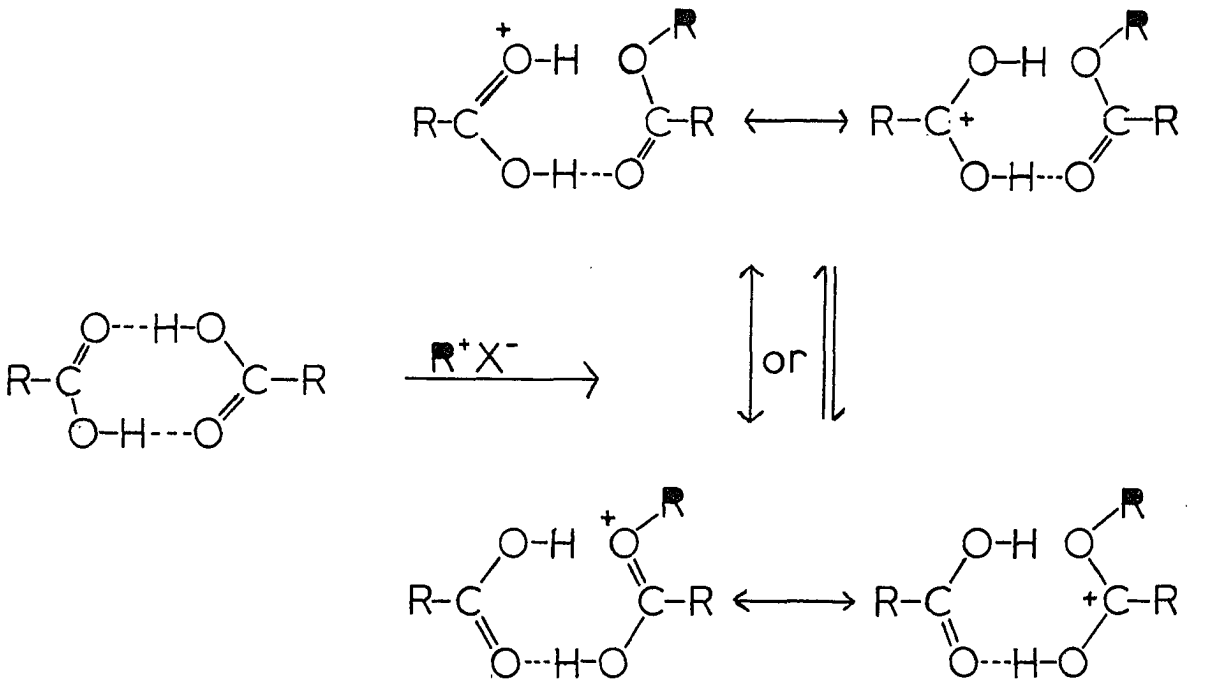




density is placed on the hydroxy oxygen which makes the choice between monomer and dimer a toss-up. Apparently this problem cannot be answered independently of our own work and points out difficulty of asking such questions of the medium. From our data it is evident that as the percent of carboxylic acid dimer increases so does the nucleophilicity. The greater the concentration of monomer, then, the less is the tendency of

the nucleophile to attack an ionizable substrate. The dimer, therefore, appears to be the more nucleophilic species and, very likely, also more basic.

That the carboxylic acid dimer is more basic than the monomer in solution can be reasoned in the following way. Attack by this dimer on some ionizeable substrate, R^+X^-, where R^+ may be a proton or an alkyl cation, leads to a species, shown below, which is able to stabilize the positive charge throughout the dimer. The same degree of stabilization is not possible for the species resulting from monomer attack on R^+X^-.



From Tables 12 and 13 it is also evident that as the basicity of the carboxylic acid decreases so does the influence of nitrobenzene in increasing the amount of cyclic products.

For pivalic acid the difference in the amount of cyclic products produced in the pure solvent and in 20% pivalic acid - 80% nitrobenzene is 26%. The corresponding values for acetic acid and formic acid are 15% and 3%, respectively. These results are reasonable in light of our earlier explanations concerning ground state stabilization of the carboxylic acid nucleophile. We have already seen that for nitrobenzene - acetic acid mixtures there possibly exists a one to one complex and that this complex is more stable than either acetic acid or nitrobenzene dimers. From these data it is reasonable to expect a nitrobenzene carboxylic acid complex for both pivalic and formic acids. We have also observed that there is qualitative agreement between the percent of carboxylic acid dimer and the amount of direct displacement on 5-hexenyl p-nitrobenzenesulfonate. These processes may be represented as in Chart 3.

Chart 3. Complexation in binary solvent mixtures composed of hydroxylic solvent and nitrobenzene

$$\begin{array}{ccccc} HA & + & C_6H_5NO_2 & \rightleftharpoons & C_6H_5NO_2 \cdot HA \\ \downarrow\uparrow & & \downarrow\uparrow & & \\ \tfrac{1}{2}(HA)_2 & & \tfrac{1}{2}(C_6H_5NO_2)_2 & & \end{array}$$

The most basic species in this scheme is probably the carboxylic acid dimer, $(HA)_2$. Now, although this remains speculative, if the complexing ability of nitrobenzene and carboxylic acid follows the same trend as does dimer formation for carboxylic

acids, then as the acid becomes less basic and the monomer-dimer equilibrium constant becomes smaller so also will the equilibrium constant for the nitrobenzene - acid complex be less. It would then be expected that the stabilizing effect of nitrobenzene on the carboxylic acid would be less as the basicity of the acid decreases, and that the influence of nitrobenzene in increasing the amount of cyclic products should correspondingly decrease. This is what in fact is found.

In Tables 15, 16, and 17 data are presented for the solvolysis of 5-hexenyl p-nitrobenzenesulfonate in several acid mixtures. Solvolyses of this type permit comparison of the reactivities of several nucleophiles under identical substrate ionizing conditions. The "ionizing power" of the individual solutions is constant which means that any change in the product ratio of cyclohexyl or 5-hexenyl derivatives from the mole ratio of the nucleophiles present must be due to factors other than "solvent polarity." Although the "ionizing power" of the individual solutions is constant it is not true that the "ionizing power" of one binary mixture is the same as that of a different binary mixture (8).

The ratios of cyclohexyl products and of 5-hexenyl products as compared to the mole ratio of the carboxylic acids (product ratio/mole ratio) are shown in Table 18. In no case was the product ratio equal to the mole ratio. In formic acid - acetic

Table 15. Solvolysis of 5-hexenyl p-nitrobenzenesulfonate at 90° in several formic acid - acetic acid mixtures[a]

Solvent No.	Solvent	Reaction Time, hrs.	Mole Ratio (HCO_2H/HOAc)	% Recovery[c]	% Open / % Cyclic Products[d]
57)	20% Formic Acid-	19	0.38	82.7	1.16
	80% Acetic Acid	19	0.38	87.1	1.02
58)	80% Formic Acid-	19	6.10	67.8	0.53
	20% Acetic Acid	19	6.10	81.3	0.41

[a]See footnote a, Table 13. Urea was used as the base.

[b]Actual yield of products.

[c]See footnote d, Table 2.

[d]See footnote e, Table 13.

[e]See footnote d, Table 13.

Table 16. Solvolysis of 5-hexenyl p-nitrobenzenesulfonate at 100° in several acetic acid - pivalic acid mixtures[a]

Solvent No.	Solvent	Reaction Time, hrs.	Mole Ratio (HCO_2H/HOAc)	% Recovery[c]	% Open / % Cyclic Products
59)	17% Acetic Acid-	24	0.39	73	2.37
	83% Pivalic Acid				
60)	20% Acetic Acid-	24	0.48	75	2.60
	80% Pivalic Acid	24	0.48	74	2.24
61)	80% Acetic Acid-	24	7.86	108	1.30
	20% Pivalic Acid	24	7.86	83	1.37

[a]See footnote a, Table 2.

[b]See footnote b, Table 2.

[c]See footnote d, Table 2.

Solvent No.	Analysis[b] Olefin[e]	Cyclohexene	C, Cyclohexyl Acetate	D, Cyclohexyl Acetate	E, 5,Hexenyl Formate	F, 5-Hexenyl Acetate
57)	1.4	9.2	9.7	24.9	11.7	25.8
	1.6	9.7	11.4	25.9	12.0	26.5
58)	5.6	3.0	51.4	7.8	0	0
	14.1	6.8	53.5	6.9	0	0

Solvent No.	Analysis[b] 1-Methylcyclopentene	Cyclohexene	C, Cyclohexyl Acetate	D, Cyclohexyl Pivalate	E, 5-Hexenyl Acetate	F, 5-Hexenyl Pivalate
59)	1.0	13.3	6.5	8.9	38.5	31.8
60)	0.9	11.8	7.5	7.6	43.1	29.1
	1.1	14.3	7.1	8.4	40.7	28.4
61)	1.4	15.4	25.7	1.0	53.8	2.7
	1.2	14.9	24.7	1.3	55.3	2.6

Table 17. Solvolysis of 5-hexenyl p-nitrobenzenesulfonate at 90° in several formic acid - pivalic acid mixtures[a]

Solvent No.	Solvent	Reaction Time, hrs.	Mole Ratio (HCO_2H/Me_3CCO_2H)	% Recovery[c]	% Open % Cyclic Products
62)	20% Formic Acid-	20	0.73	72.2	1.37
	80% Pivalic Acid	20	0.73	75.0	1.30
63)	80% Formic Acid-	20	12.0	45.2	-
	20% Pivalic Acid	20	12.0	44.5	-

[a]See footnote a, Table 13. Urea was used as the base.

[b]Actual yield of products.

[c]See footnote d, Table 2.

Solvent No.	Analysis[b]					
	1-Methylcyclopentene	Cyclohexene	C, Cyclohexyl Formate	D, Cyclohexyl Pivalate	E, 5-Hexenyl Formate	F, 5-Hexenyl Pivalate
62)	1.2	16.0	17.8	6.8	21.5	8.9
	1.2	16.4	17.3	7.5	22.3	10.3
63)	trace	trace	43.6	1.6	0	0
	trace	trace	43.0	1.5	0	0

acid mixtures only slightly more formate ester is produced, while in both acetic acid - pivalic acid and formic acid - pivalic acid mixtures pivalate products are produced in substantially smaller amounts. One must conclude from these data that the nucleophilic reactivity of formic acid is approximately the same as acetic acid and the reactivity of both of these acids is greater than pivalic acid. Comparison of the ratios of cyclohexyl products ($\frac{C}{D}$/mole ratio) with those of 5-hexenyl products ($\frac{E}{F}$/mole ratio) shows slight differences which may certainly be attributable to the differences in the transition states for formation of cyclohexyl ester and 5-hexenyl ester.

As was mentioned earlier Swain has used a four-parameter equation (15) which includes a nucleophilic term and an electrophilic (ionizing power) term in an attempt to measure nucleophilicity. When applied to solvolysis reactions, however, he points out that this equation may not be measuring nucleophilic and electrophilic reactivity of the solvent. Measurement by this solvent parameter shows that the nucleophilic character (not the nucleophilicity) of acetic acid is about the same as formic acid but that the nucleophilicity of acetic acid is much greater than that of formic acid. Assuming equal nucleophilic reactivity for formic and acetic acids Winstein (8 and previous papers in the series) has found that the "ionizing power" of formic acid is significantly greater than

Table 18. Comparison of product ratios with mole ratios in the solvolysis of 5-hexenyl p-nitrobenzenesulfonate in mixed carboxylic acid solutions[a]

Solvent Mixture (20:80)	Derivative[b] C,E	Derivative[b] D,F	C/D Mole Ratio	E/F Mole Ratio
HCOOH - HOAc	$-O_2CH$	-OAc	1.1	1.2
HOAc - HCOOH	$-O_2CH$	-OAc	1.2	-
HOAc - Me_3CCO_2H	-OAc	$-O_2CCMe_3$	1.9	3.0
Me_3CCO_2H - HOAc	-OAc	$-O_2CCMe_3$	2.9	2.6
HCOOH - Me_3CCO_2H	$-O_2CH$	$-O_2CCMe_3$	3.4	3.1
Me_3CCO_2H - HCOOH	$-O_2CH$	$-O_2CCMe_3$	2.3	-

[a]Data calculated from the results in Tables 15, 16, and 17. Ratios were averaged from two runs.

[b]C,D,E, and F are defined in Tables 15, 16, and 17.

that of acetic acid. The "ionizing power" of pivalic acid is almost certainly much less than acetic acid, although this has not been determined. Both Swain's and Winstein's solvent parameters overlap somewhat so that measurement of only nucleophilic reactivity or only "solvent polarity" is almost impossible and an independent determination would be desirable.

In our measurements the "ionizing power" of the individual solution is the same for each carboxylic acid nucleophile. Because of this we believe that we can measure only nucleophilic reactivity provided factors other than "solvent polarity" are not important. We have seen from the data of Tables 15-17 that formic and acetic acids have nearly identical nucleophilic

reactivity and that pivalic acid is the least reactive nucleophile. The fact that pivalic acid is less reactive than either formic or acetic acids is reasonable if one considers the bulk of the nucleophiles. Pivalic acid may be sterically hindered in its attack on a substrate.

Although pivalic acid is less reactive than either formic or acetic acids, solvolysis of 5-hexenyl p-nitrobenzenesulfonate in this acid leads to less cyclic products than the corresponding acetolysis or formolysis reaction (Tables 12 and 13). This must be due to differences in the "ionizing power" of the solution. An increase in "solvent polarity" must dictate a greater amount of cyclic products. In Figures 4 and 5 percent cyclic products is plotted against percent of the better ionizing carboxylic acid for formic acid - acetic acid and acetic acid - pivalic acid mixtures. Because of the assumption made that 95% recovery was obtainable and that the difference between this value and the percent recovery in Table 15 was due to formation of 1,5-diformatohexane, there is some excess scattering of points in Figure 4. For formic acid - pivalic acid mixtures the relative yield of cyclic products is too uncertain even to attempt a guess and so this data is not plotted. There appears, however, to be a distinct linear relationship between percent cyclic products and percent of the better ionizing nucleophile. Thus, if "solvent polarity" is a ground state phenomenon such that transition state changes are rela-

Figure 4. Relationship between % cyclic products and % formic acid from the solvolysis of 5-hexenyl p-nitrobenzenesulfonate in formic acid - acetic acid mixtures

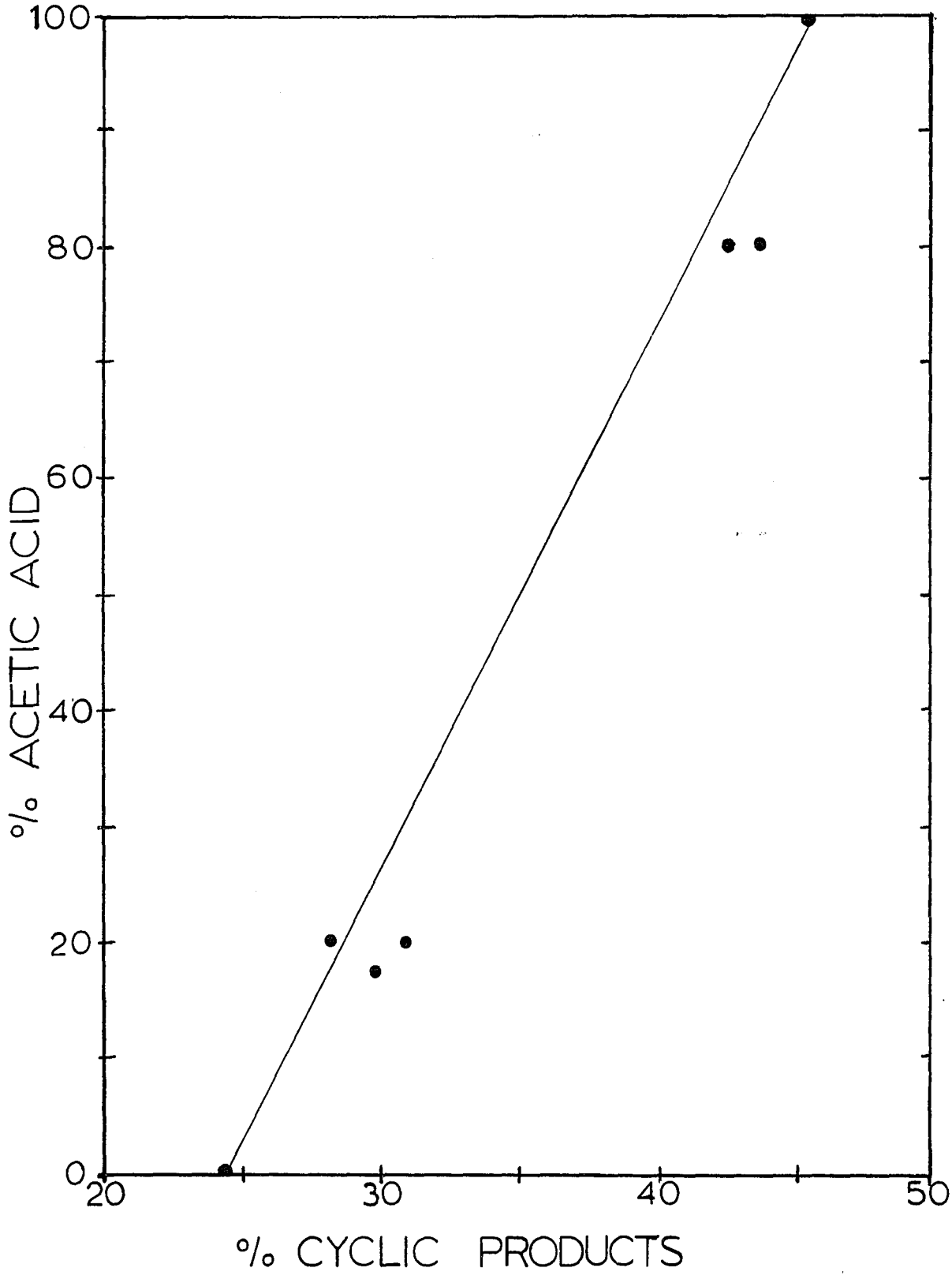
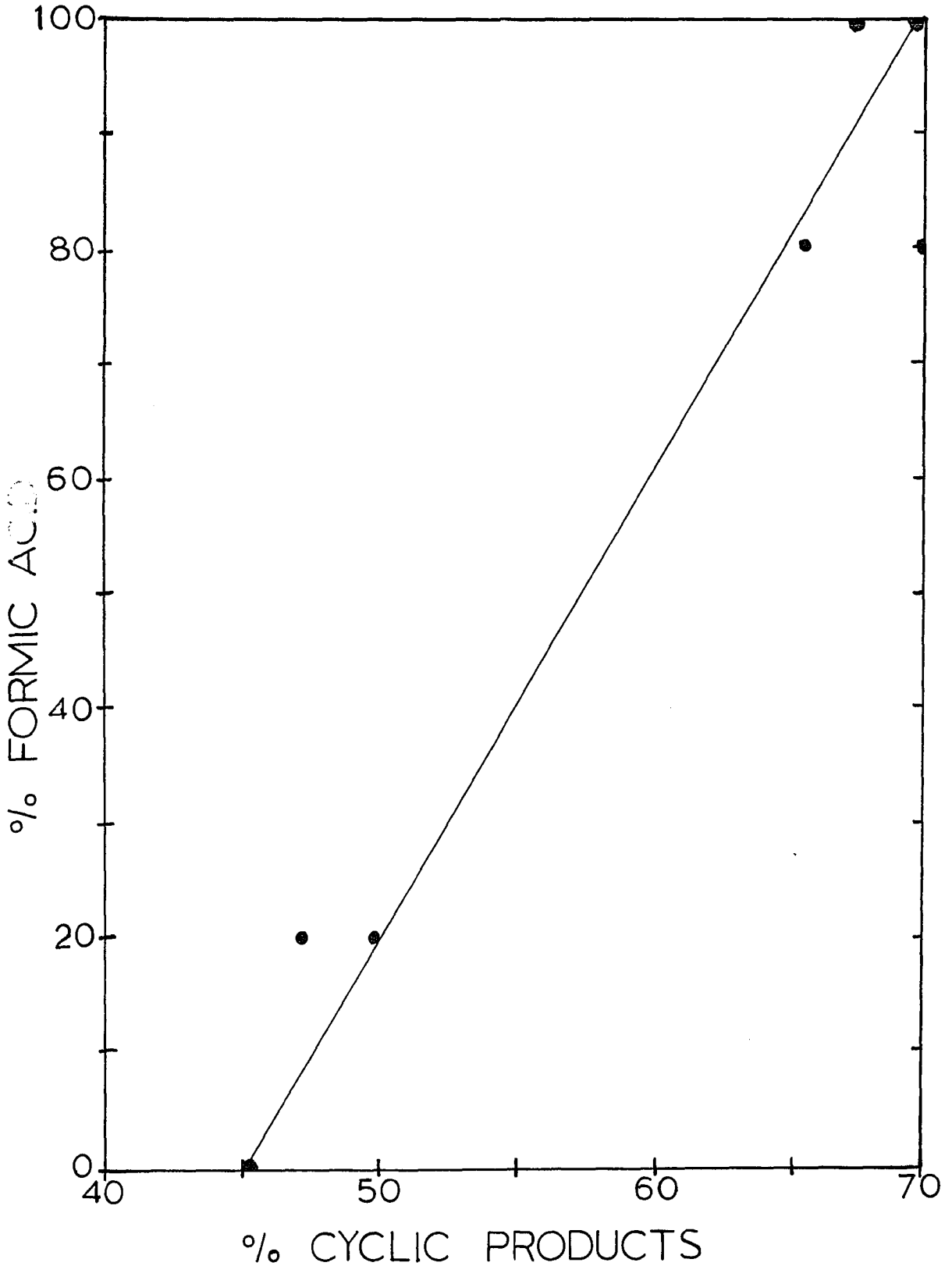

100
80
60
40
20
0
% ACETIC ACID
20
30
40
50
% CYCLIC PRODUCTS

Figure 5. Relationship between % cyclic products and % acetic acid from the solvolysis of 5-hexenyl p-nitrobenzenesulfonate in acetic acid - pivalic acid mixtures

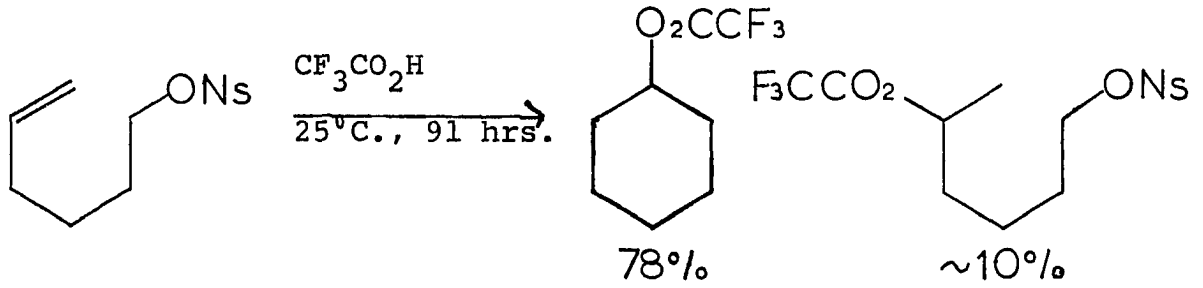

100
80
60
40
20
0
% FORMIC ACID
40
50
60
70
% CYCLIC PRODUCTS

tively unimportant then it is associated with total nucleophilic reactivity (nucleophilicity).

We have spoken previously of "ionizing power" and nucleophilic reactivity in S_N2 reactions as separate entities. These two factors both contribute to solvent nucleophilicity. Swain's solvent parameter (9,15), mentioned before, attempts to measure nucleophilic and electrophilic (ionizing power) character. Nucleophilicity is measured by the difference between the nucleophilic and electrophilic terms. We also find that nucleophilic reactivity and "ionizing power" contribute to solvent nucleophilicity. By comparing the ratios of cyclic to open products for individual nucleophiles we may be measuring relative solvent nucleophilicity. By a measure of the ratio of derivative products from the solvolysis of an ionizable substrate in mixtures of several nucleophiles we can estimate the relative nucleophilic reactivity of the individual nucleophiles. The difference in these values gives an indication of the "solvent polarity". Thus, although pivalic acid has the least nucleophilic character of the three acids studied, it is the most nucleophilic. Acetic acid and formic acid have approximately the same nucleophilic character, yet the nucleophilicity of acetic acid is greater than that of formic acid. Thus, the "ionizing power" (electrophilic character) of the solvent appears to be very important in determining solvent nucleophilicity.

Our results are in qualitative agreement with Swain's data (15). Considering the vastly different approach which we have used we think that this agreement substantiates our claim to measure solvent nucleophilicity even if only semiquantitatively. However, we have only looked at a few nucleophiles so that further data is required before we can make an exact claim of another measure of solvent nucleophilicity.

Peterson has shown that trifluoroacetic acid is a solvent of extremely low nucleophilicity in solvolysis reactions (61). This solvent has been used for the solvolysis of 5-cycloocten-1-yl p-bromobenzenesulfonate (62) in which case the products obtained were almost entirely bicyclic. The similarity of this solvolysis with that of 5-hexenyl p-nitrobenzenesulfonate led us to solvolyze this latter compound under similar conditions. Solvolysis of the 5-hexenyl sulfonate at 25^0 in trifluoroacetic acid led to cyclohexyl trifluoroacetate in 78% actual yield (averaged from two runs), confirmed by spectra, g.l.p.c. analysis, and conversion to cyclohexanol. The only other identified product is 5-trifluoroacetohexyl-1-p-nitrobenzenesulfonate. This latter product was identified by an n.m.r. spectrum of the solvolysis mixture. The reasonableness of this product as opposed to the expected formation of 1,5-ditrifluoroacetoxyhexane is seen from solvolysis of 5-hexenyl p-nitrobenzenesulfonate in 80% formic acid - 20% perchloric acid. Only one product was observed after 97 hours and that



[RONs] = 0.1 M (92% recovery of products) + Unknown No. 1, Unknown No. 2 } 3.4%
[urea] = 0.2 M

was 5-formatohexyl-1-p-nitrobenzenesulfonate.

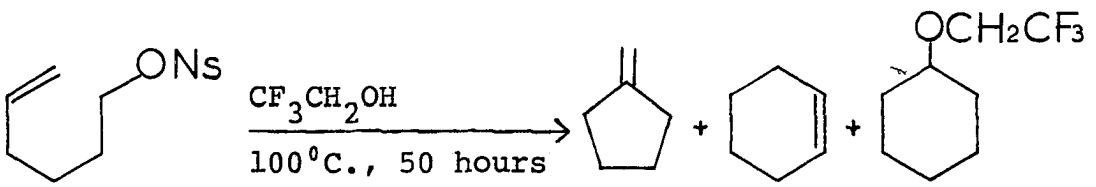
It is known that when a remote electron withdrawing substituent is substituted on an alkene, the rate of addition of trifluoroacetic acid to the olefin is substantially decreased (63). This explains why it is possible to obtain cyclic product when 5-hexenyl sulfonates are solvolyzed in trifluoroacetic acid; the sulfonate group retards addition into the double bond. In addition, a polar substituent in a remote position may decrease the rate of solvolysis of alkyl sulfonates which may explain why the solvolysis of 5-trifluoroacetohexyl-1-p-nitrobenzenesulfonate does not occur at 25°.

Peterson has suggested that the rapid rates for solvolysis in trifluoroacetic acid may be due to acid catalysis (61). As mentioned previously when 5-hexenyl p-nitrobenzenesulfonate was solvolyzed in 20% perchloric acid - 80% formic acid no cyclic products were formed. Although perchloric acid is a stronger acid than trifluoroacetic acid the fact that no cyclic products are formed in the 20% perchloric acid solution does

argue against acid catalysis of the cyclization reaction.

Another solvent that has been considered because of its low nucleophilicity is 2,2,2-trifluoroethanol. Although comparitively little is known about the properties of this fluorinated alcohol its effectiveness as a good ionizing solvent, being 900 times more effective than ethanol, has been noted (64). In addition, the acidity of this alcohol is comparable to that of phenol (65). These two criteria, being a better ionizing solvent and also a weaker base than ethanol, distinctly indicate that 2,2,2-trifluoroethanol is a solvent of low nucleophilicity.

Solvolysis of 5-hexenyl p-nitrobenzenesulfonate in 2,2,2-trifluoroethanol containing urea for 50 hours at 100° led to a 78% yield of cyclic products as indicated. The yields reported are recovered yields and are averaged from



[RONs] = 0.1 M
[urea] = 0.2 M

(Total recovery = 84%)

Unknown No. 1 - 1.7%
Unknown No. 2 - 1.2%
Unknown No. 3 - 1.7%
Unknown No. 4 - 1.5%

three separate runs. Four unknown products were formed in 6% yield and may, in fact, all be cyclic products. Unknown no. 4, however, is suspected to be 5-hexenyl 2,2,2-trifluoroethyl

ether, although confirmation has not been obtained. The relative yield of known cyclic products is 93% and may prove to be as high as 98 or 100%, making this solvent the best we have used so far to effect cyclization of 5-hexenyl p-nitrobenzenesulfonate.

Because trifluoroacetic acid adds into olefins it is inferior to 2,2,2-trifluoroethanol. However, since we did not observe the formation of any 1,5-ditrifluoroacetoxyhexane when 5-hexenyl p-nitrobenzenesulfonate was solvolyzed in trifluoroacetic acid, a product which would have indicated displacement by the acid, comparison between trifluoroethanol and trifluoroacetic acid with regard to solvent nucleophilicity is not possible in the 5-hexenyl system. Solvolysis of 6-heptenyl p-nitrobenzenesulfonate in these solvents, which will be discussed later, can be used to compare their relative nucleophilicity.

It is noteworthy that use of trifluoroacetic acid and 2,2,2-trifluoroethanol, both of which are known independently to be solvents of low nucleophilicity (61,64) leads to high amounts of cyclic products during the solvolysis of 5-hexenyl p-nitrobenzenesulfonate. These results support our contention that the ratio of open to cyclic products from the solvolysis of this sulfonate ester measures solvent nucleophilicity.

Leaving Group Effect on the Solvolysis of 5-Hexenyl Derivatives in Acetic Acid and Acetic Acid - Nonhydroxylic Solvent Mixtures

Earlier we mentioned that in the solvolysis of 5-hexenyl p-nitrobenzenesulfonate the external nucleophilic attack requires a molecule of acetic acid while internal attack does not require an added nucleophile. This simple scheme led us to study the effect of solvent variation on the relative rates of external verses internal substitution with the intention of elucidating a method for measuring solvent nucleophilicity. We stated that for solvent nucleophilicity to be a useful term and measureable it should be independent of the substrate. In our system the substrate is in both ground states so that any change in the ground state free energies must reflect a change in the solvent nucleophilicity. Indeed, the changes we observe are consistent with ground state stabilization of the external nucleophile and would appear to afford a sensitive measure of solvent nucleophilicity. However, solvent changes in our system may also alter the relative rates of the two competing reactions by affecting the transition state stabilities. If the relative rates of external verses internal nucleophilic attack are determined merely by ground state solvation we should expect no change in the relative yield of cyclic and open products when the leaving group is varied. Any differences observed with a change in the leaving group must be a result of the effect of the leaving group on the relative

stabilities of the transition state that leads to open product and the transition state that leads to closed product, since the effect of the leaving group on both ground states must be the same.

In Table 19 are presented the data from the solvolysis of various 5-hexenyl sulfonates in several solvent mixtures. The relative yield of cyclic products from the solvolysis of these 5-hexenyl derivatives is shown more clearly in Table 20. From these results it is evident that the leaving group does affect the relative amount of cyclization. One gets slightly different amounts of cyclic products with different leaving groups. In addition, there is a different ordering of solvents as the leaving group is changed. For 5-hexenyl p-nitrobenzenesulfonate, solvolysis in 80% nitrobenzene - 20% acetic acid produces 15% more cyclic products than solvolysis in glacial acetic acid. On the other hand, solvolysis in 80% nitrobenzene - 20% acetic acid for the p-methoxybenzenesulfonate produces 4% less cyclic products than the corresponding solvolysis in acetic acid. If only ground state solvation were important solvolysis in the nitrobenzene - acetic acid mixture should always lead to more cyclic products than solvolysis in acetic acid.

Varying the leaving group not only reverses the relative ordering of solvents but also changes the degree of difference in percent cyclic products formed in two different binary

Table 19. Solvolysis of 5-hexenyl sulfonates at 100° in acetic acid and 20% acetic acid - 80% solvent mixtures[a]

Solvent (No. of runs)	Reaction Time, hrs.	% Recovery[c]
5-Hexenyl 2,4-Dinitrobenzenesulfonate		
Acetic Acid (3)	24	81
20% Acetic Acid - 80% Nitrobenzene (3)	50	83
5-Hexenyl o-Nitrobenzenesulfonate		
Acetic Acid (3)	25	88
20% Acetic Acid - 80% Nitrobenzene (1)	48	72
20% Acetic Acid - 80% Nitrobenzene (2)	75	74
5-Hexenyl p-Nitrobenzenesulfonate		
Acetic Acid (3)	12	82
Acetic Acid (4)	50	90
20% Acetic Acid - 80% Nitrobenzene (3)	12	57
20% Acetic Acid - 80% Nitrobenzene (2)	50	86
20% Acetic Acid - 80% Benzene (4)	50	84
5-Hexenyl m-Nitrobenzenesulfonate		
Acetic Acid (3)	24	91
20% Acetic Acid - 80% Nitrobenzene (3)	50	84
5-Hexenyl p-Bromobenzenesulfonate		
Acetic Acid (2)	36	87
20% Acetic Acid - 80% Nitrobenzene (2)	36	61
20% Acetic Acid - 80% Nitrobenzene (3)	72	82
5-Hexenyl Benzenesulfonate		
Acetic Acid (3)	72	85
20% Acetic Acid - 80% Nitrobenzene (3)	150	79

[a] [ROX] = 0.1 M, [urea] = 0.2 M.

[b] See footnote b, Table 2.

[c] See footnote d, Table 2.

Analysis[b]					
1-Methyl-cyclo-pentene	A, Cyclo-hexene	B, Cyclo-hexyl Acetate	5-Hexenyl Acetate	% Open / % Cyclic Products	A/B
1.1	13.6	31.9	53.4	1.15	0.43
2.5	45.7	18.2	33.6	0.50	2.51
1.3	15.7	32.4	50.6	1.02	0.48
2.4	46.5	18.4	32.7	0.49	2.52
2.2	46.4	18.4	33.0	0.49	2.52
1.1	13.8	30.8	54.3	1.19	0.45
0.9	13.2	31.1	54.8	1.21	0.42
2.4	44.8	19.3	33.5	0.50	2.32
2.2	39.6	18.7	39.5	0.65	2.12
0.2	15.4	8.9	75.5	3.08	1.73
0.9	12.4	29.8	56.9	1.32	0.42
1.7	40.1	19.0	39.2	0.64	2.11
1.0	13.3	28.0	57.7	1.37	0.47
2.0	38.1	18.0	41.9	0.72	2.12
1.4	34.6	16.3	47.8	0.92	2.12
0.8	11.6	26.5	61.1	1.56	0.44
0.9	25.8	12.7	60.6	1.54	2.03

Table 19 (Continued)

Solvent (No. of runs)	Reaction Time, hrs.	% Recovery[c]
5-Hexenyl p-Toluenesulfonate		
Acetic Acid (3)	72	87
20% Acetic Acid - 80% Nitrobenzene (3)	200	84
5-Hexenyl p-Methoxybenzenesulfonate		
Acetic Acid (3)	72	90
20% Acetic Acid - 80% Nitrobenzene (2)	100	73
20% Acetic Acid - 80% Nitrobenzene (2)	200	86
5-Hexenyl 2,4,6-Trimethylbenzenesulfonate		
Acetic Acid (4)	72	88
20% Acetic Acid - 80% Nitrobenzene (1)	96	58
20% Acetic Acid - 80% Nitrobenzene (2)	206	88
5-Hexenyl Methanesulfonate		
Acetic Acid (3)	24	71
Acetic Acid (2)	48	86
20% Acetic Acid - 80% Nitrobenzene (1)	72	64
20% Acetic Acid - 80% Nitrobenzene (2)	120	82
20% Acetic Acid - 80% Benzene (3)	120	84

Analysis[b]					
1-Methyl-cyclo-pentene	A, Cyclo-hexene	B, Cyclo-hexyl Acetate	5-Hexenyl Acetate	% Open / % Cyclic Products	A/B
0.6	10.2	23.0	66.2	1.96	0.44
0.7	20.6	10.8	67.9	2.13	1.90
0.7	10.1	21.9	67.3	2.04	0.46
0.6	18.4	11.0	70.0	2.33	1.67
0.7	18.7	9.1	71.5	2.50	2.06
0.7	8.1	15.2	76.0	3.13	0.53
0.5	14.2	5.7	79.6	3.85	2.49
0.5	12.4	6.0	81.1	4.35	2.07
1.1	12.0	22.9	64.0	1.78	0.52
0.8	10.1	19.5	69.6	2.27	0.52
1.1	22.4	12.1	64.4	1.82	1.85
1.0	20.5	11.5	67.0	2.04	1.78
0.2	6.4	6.7	86.7	6.52	0.96

Table 20. Yield of cyclic products from the solvolysis of various 5-hexenyl sulfonates at 100° in acetic acid and 20% acetic acid - 80% solvent mixtures[a]

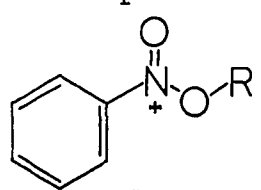
Leaving Group	% Cyclic Products[b]		
	HOAc	20% HOAc-80% $C_6H_5NO_2$	20% HOAc-80% C_6H_6
2,4-Dinitrobenzenesulfonate	46.6	66.4	-
o-Nitrobenzenesulfonate	49.4	67.0	-
p-Nitrobenzenesulfonate	45.2	60.5	24.5
m-Nitrobenzenesulfonate	43.1	60.8	-
p-Bromobenzenesulfonate	43.3	52.2	-
Benzenesulfonate	38.9	39.4	-
p-Toluenesulfonate	33.8	32.1	-
p-Methoxybenzenesulfonate	32.7	28.5	-
2,4,6-Trimethylbenzenesulfonate	24.0	18.9	-
Methanesulfonate	30.4	33.0	13.3

[a]Data taken from Table 19 for the completed reaction.

[b]Relative yield.

solvents. Comparing the p-nitrobenzenesulfonate with the methanesulfonate leaving group shows that the difference in percent cyclic products produced by changing the binary solvent from nitrobenzene-acetic acid to benzene-acetic acid is reduced from approximately 35% to 20%, respectively. Therefore, because these changes do occur we cannot state that solvation of the acetic acid alone determines the relative amounts of cyclic and open product. The nature of the leaving group is also important.

Streitwieser and Schaeffer (43) have found that the amount of racemization during the acetolysis of optically active 1-butyl-1-d p-nitrobenzenesulfonate increases in going from pure acetic acid to 10% acetic acid - 90% nitrobenzene. They suggest that a possible explanation for this result is that a considerable amount of acetate with retained configuration is produced by the intermediate formation of a nitrobenzene derivative, XI. If formation of XI takes place with



XI

inversion of configuration, acetolysis of XI should lead to overall retention. If another nitrobenzene molecule attacks XI, racemization should result. Our results indicate that an intermediate such as XI cannot be the exclusive precursor of the products in 20% acetic acid - 80% nitrobenzene mixtures

since the amount of cyclization that occurs depends on the leaving group that is present in the starting material. However, it is possible that an ion pair composed of an intermediate such as XI and the leaving group is formed and that the different anions change the amount of cyclization.

The data for acetolysis of 5-hexenyl bromide and iodide are presented in Table 21. These results have been used (66) to show the failure of the principle of hard and soft acids and bases (67) to explain the amount of cyclization from various 5-hexenyl derivatives. As shown in Figure 6, a plot of log [RX] verses time, where RX is 5-hexenyl iodide or bromide, shows considerable curvature. This rate retardation with increasing amounts of ureaonium iodide could either be due to a salt effect or conversion of 5-hexenyl acetate to 5-hexenyl halide. In a control experiment in which equivalent amounts of sodium iodide and 5-hexenyl acetate were heated together in acetic acid at 100^0 for 350 hours no detectable amount of 5-hexenyl iodide or cyclohexyl acetate was produced, a fact which indicates that 5-hexenyl acetate is stable under the reaction conditions towards displacement by iodide. A salt effect, therefore, seems the more likely explanation. We may note that the same factor responsible for rate retardation, namely the salt effect, may also be responsible for the increase in the relative amount of cyclic products with time as is clearly shown in Table 21. It is interesting that more

Table 21. Acetolysis of 5-hexenyl halides at 100°[a]

5-Hexenyl Halide	Reaction Time, hrs.	% Recovery[c]	% Open / % Cyclic Product	A/B
Bromide	96	82	5.3	0.72
	262	83	4.4	0.68
	396	83	4.1	0.76
	396	85	3.7	0.77
Iodide	48	87	4.9	0.62
	168	89	4.4	0.64
	432	83	2.8	1.01
	432	85	3.0	1.01
	672	85	2.5	0.82

[a] [RX] = 0.1 M, [urea] = 0.2 M.

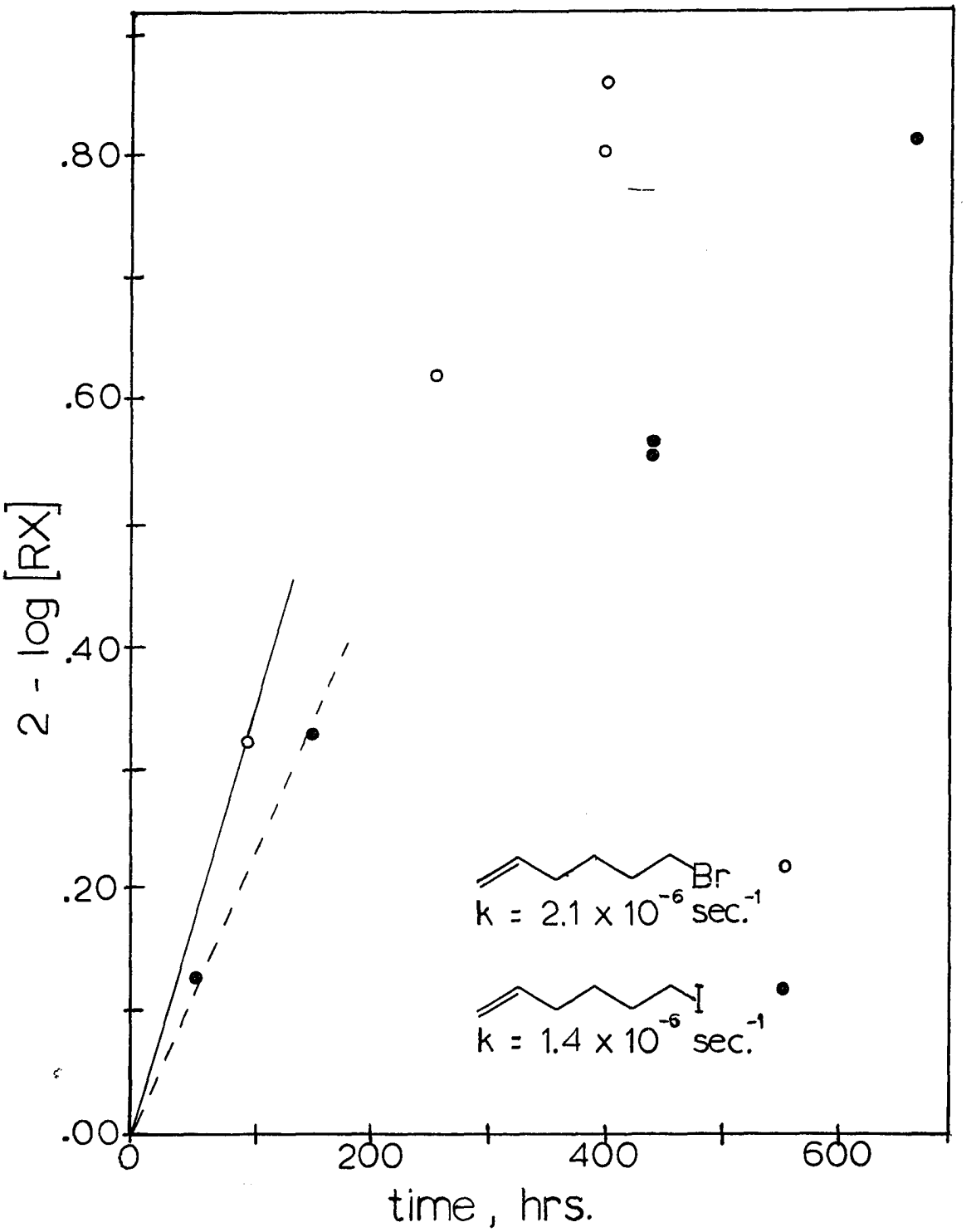
[b] Relative yields except for 5-hexenyl halide. The yield of 5-hexenyl halide was quantitatively determined by g.l.p.c. The relative yield of acetolysis products was determined by assuming a total yield of 100 - % 5-hexenyl halide. Also see footnote b, Table 2.

[c] See footnote d, Table 2.

[d] The measured thermal conductivity (relative) of 5-hexenyl iodide was 1.00. The thermal conductivity of 5-hexenyl bromide was assumed to have the same value.

Analysis[b]					
1-Methyl-cyclo-pentene	A, Cyclo-hexene	B, Cyclo-hexyl Acetate	5-Hexenyl Acetate	Unreacted Starting Material[d]	Cyclic Products
0.2	3.4	4.7	43.8	47.9	8.3
0.4	5.4	7.9	60.5	24.8	13.7
0.6	7.0	9.2	69.2	14.0	16.8
0.6	7.5	9.7	66.0	16.2	17.8
0	1.6	2.6	20.6	75.3	4.2
0.1	3.8	5.9	43.1	47.1	9.8
0.3	9.6	9.5	53.4	27.2	19.4
0.3	8.9	8.8	54.4	27.6	18.0
0.4	10.8	13.1	60.1	15.6	24.3

Figure 6. Kinetic plot for the acetolysis of 5-hexenyl halides


.80
.60
.40
.20
.00
2 - log [RX]
0
200
400
600
time , hrs.
Br
k = 2.1 x 10^-6 sec.^-1
I
k = 1.4 x 10^-6 sec.^-1

cyclic products are produced when the amount of ureaonium halide increases; when 5-hexenyl p-nitrobenzenesulfonate is solvolyzed in binary solvent mixtures we observed less relative amount of cyclic products at the longer reaction times (compare Tables 2 and 4).

The data from the acetolysis of 5-hexenyl halides when compared with the corresponding data for acetolysis of 5-hexenyl sulfonate esters (Table 19) show that less cyclic products are formed when either 5-hexenyl bromide or iodide is used. This experimental observation is easily rationalized by the proposal suggested by DePuy and Bishop (68) and confirmed experimentally by Hoffmann (69). Hoffmann found that the ratio of rate constants for substitution reactions of p-toluenesulfonates and bromides can vary from 0.36 to 5000 depending on the particular reaction. If the nucleophile is powerful and the substrate does not tend to ionize, then k_{OTs}/k_{Br} is small. Hoffmann (69) concluded that k_{OTs}/k_{Br} increases as the degree of charge separation from the central carbon to the leaving group increases. Thus, less cyclization with 5-hexenyl iodide and bromide indicates that acetic acid is a stronger nucleophile than the olefin and, therefore, the transition state leading to direct displacement has less carbon - leaving group bond breaking than the transition state for cyclization. Moreover, the overall solvolysis rate of 5-hexenyl p-toluenesulfonate is only about five times faster

than that of 5-hexenyl bromide which indicates that little carbon-leaving group bond breaking has occurred in either the transition state that leads to cyclization or the one that leads to direct displacement.

The effect of solvent on the ground and transition states in solvolysis reactions has been extensively studied in aqueous alcohols. Through use of thermodynamic and extra-thermodynamic properties of the medium the conclusion drawn is that the specific effect of solvation is adequately explained by ground state changes (51-54, 70-71). However, this conclusion has been recently challenged by Hudson (72-75) who believes that changes in the transition state dictate the specific effect of solvation, and that the relationship of ground state changes to solvation effects is probably true only for highly aqueous solutions (72).

For solvolyses of 5-hexenyl derivatives the leaving groups which are better able to support a negative charge, the better ionizing groups, lead to greater amounts of cyclic products. This must reflect a difference in the relative stabilities of the transition state leading to open product and the transition state leading to cyclic products, the transition state leading to cyclic products demanding a greater amount of charge separation, since, as mentioned earlier, the leaving group is in both ground states. The fact that 5-hexenyl p-toluenesulfonate solvolyzes only about five times

faster than 5-hexenyl bromide indicates, however, that neither the transition state leading to acyclic product nor the transition state leading to cyclic products is far along the reaction coordinate. Thus, although charge separation is not appreciable in the transition state for either reaction there is a small difference in the polarity of the two transition states which might be a factor responsible for the change in the amount of cyclic products when the leaving group is changed.

When the solvent is changed the stabilities of the two transition states may be affected differently in two ways. The variation of solvent may alter the stability of these transition states by direct solvation. Thus, although change to a more "polar" solvent will increase the stability of both transition states (Ingold 76, pp. 345-355), the effect of solvation as observed in the products will differ as the requirement for solvation of the activated complexes differ. Alternation of the solvent may also change the nature of the leaving group which in turn may change the energies of the transition states. If the leaving group is able to form an appreciably strong leaving group - solvent complex, the ionizing ability of the leaving group may change. In support of this mechanism for solvent effect on the transition state several chemists (6, 77-83) have observed highly specific solute - solvent interactions between polar solvents and aromatic compounds.

We must conclude from these data that the open to cyclic product ratio seems to depend on two factors: a) ground state changes and b) transition state changes. The ground state changes must be independent of the reaction since both ground states contain the substrate. The correlation of percent cyclic products with the ability of the added solvent to solvate acetic acid as well as the trends observed when the nuclophile is varied implies that solvation of the nucleophile is the prime ground state change and ground state changes are more important than transition state changes. However, the effect of changing the leaving group shows that transition state changes may be as large as ground state changes. Since the transition state changes are so important, the yield of open to cyclic products from the solvolysis of 5-hexenyl p-nitrobenzenesulfonate may or may not measure solvent nucleophilicity. It is not possible with the data at hand to tell how important the transition state changes brought about by changing the solvent are.

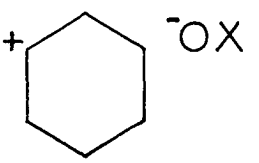
An argument can be made for the ratio of percent open to percent cyclic products from the solvolysis of 5-hexenyl p-nitrobenzenesulfonate as being a measure of solvent nucleophilicity. As was mentioned several times previously, in order for this ratio to be a good measure of solvent nucleophilicity transition state changes must be unimportant relative to ground state changes. We have noted that in changing the leaving

group we obtain slightly different amounts of cyclic products as well as a different ordering of solvents. However, we have also found that the p-nitrobenzenesulfonate leaving group lends itself to the study of solvent nucleophilicity. The products from the solvolysis of 5-hexenyl p-nitrobenzenesulfonate in mixtures of 20% acetic acid - 80% nonhydroxylic solvents, in mixtures in which the percent composition of nonhydroxylic solvent is varied, and in mixtures in which the hydroxylic solvent is changed seems to reflect, at least qualitatively, solvent nucleophilicity. Thus we must ask if the transition state changes are relatively significant when the p-nitrobenzenesulfonate leaving group is used. That a different ordering of solvents occurs when the leaving group is changed from p-nitro- to p-methoxybenzenesulfonate (see Table 20) can be most easily explained by alteration of the leaving group through formation of a specific leaving group - solvent complex by those leaving groups which show the nitrobenzene mixtures to be more nucleophilic than acetic acid, namely the p-methoxy-, p-methyl-, and the 2,4,6-trimethylbenzenesulfonates. These leaving groups might have been expected to interact with nitrobenzene through some sort of Π-complex (6, 84) since similar interactions have been noted (6, 77-83); and, also, in going from p-nitro- to p-methoxybenzenesulfonate as the leaving group, the effect of added nitrobenzene in increasing the amount of cyclic products rela-

tive to acetic acid becomes less (Table 20) indicating that the nitrobenzene solvent somehow affects the leaving group. The nitrobenzenesulfonate leaving group should not interact with nitrobenzene in the same manner as would the p-methoxybenzenesulfonate because of the similarity of the electronic structures. However, this does not rule out a specific localized complex of the nitro groups similar to that observed by Taft (56). If the change in solvent ordering which occurs by changing the leaving group can thus be explained by a specific leaving group - solvent interaction which does not occur when like molecules are used, as with the p-nitrobenzenesulfonate and nitrobenzene, then we are left to consider only direct solvation in the transition states for production of open and cyclic products. In Table 20 one observes that the change in percent cyclic products from the acetolysis of 5-hexenyl sulfonates is approximately 20%. This difference is smaller than the changes we have observed for solvolyses in 20% acetic acid - 80% nonhydroxylic solvents. Also, in changing the leaving group the degree of direct solvation in the transition state also changes, but it does not follow that changes in the solvent affect the transition states in the same way. Variation of the leaving group may change the direct solvation in the transition state whereas varying the solvent does not alter the relative transition state stabilities. Thus if solvent complexes with the leaving group only when the two

species are electronically unlike and if direct solvation is constant for a particular leaving group as the solvent is changed, then the ratio of percent open to percent cyclic products from the solvolysis of 5-hexenyl p-nitrobenzenesulfonate is a measure of solvent nucleophilicity.

The ratio of cyclohexene to cyclohexyl acetate from the solvolysis of 5-hexenyl sulfonate esters (Table 19) is summarized in Table 22. The data presented in this table show definite independence of the leaving group and a marked dependence on the solvent system. The data presented in Tables 2,5,9,10, and 11 among others also show definite changes in the ratio of cyclohexene to cyclohexyl acetate when the solvent is varied, even to the extent that solvent variation from acetic acid to 90% acetic acid - 10% nonhydroxylic solvent changes the ratio appreciably (Tables 9,10, and 11). Since the cyclization reaction places the leaving group on the opposite side of the cation, it is reasonable that the solvent



XII

and not the leaving group would remove the proton to form cyclohexene. It must be true that the intermediate cation - leaving group ion pair, XII, does not undergo exclusive internal return to produce the cyclohexyl sulfonate ester which

Table 22. The ratio of cyclohexene to cyclohexyl acetate from the solvolysis of 5-hexenyl sulfonates[a]

Leaving Group	% Cyclohexene/ % Cyclohexyl Acetate	
	HOAc	20% HOAc-80% $C_6H_5NO_2$
2,4-Dinitrobenzenesulfonate	0.43	2.51
o-Nitrobenzenesulfonate	0.48	2.52
p-Nitrobenzenesulfonate	0.42	2.12
m-Nitrobenzenesulfonate	0.42	2.11
p-Bromobenzenesulfonate	0.47	2.12
Benzenesulfonate	0.44	2.03
p-Toluenesulfonate	0.44	1.90
p-Methoxybenzenesulfonate	0.46	2.06
2,4,6-Trimethylbenzenesulfonate	0.53	2.07
Methanesulfonate	0.52	1.78
Average	0.46 ± 0.04	2.12 ± 0.14

[a]Data taken from Table 19.

then undergoes solvolysis since the ratio of cyclohexene to cyclohexyl acetate is much greater when cyclohexyl sulfonates are solvolyzed (Table 23). Indeed, it has been estimated (38) that the maximum amount of internal return that can occur is 33%. Although all of the leaving groups are sulfonates, the changes of the leaving groups should be large enough to effect some change in the cyclohexene to cyclohexyl acetate ratio if

the leaving group removed the proton from the intermediate cation to form cyclohexene. The rates of acetolysis of methyl derivatives of these leaving groups differ by at least a factor of 25 (Streitwieser 17, p. 82). This difference means that the basicity of these sulfonates should differ by at least a factor of 25 and consequently they should extract protons from cations at different rates (Hine 16, pp. 114-119).

In order to determine if we could observe a change in the cyclohexene to cyclohexyl acetate ratio with only sulfonate leaving groups we solvolyzed cyclohexyl p-nitrobenzenesulfonate and p-toluenesulfonate in acetic acid and 20% acetic acid - 80% nitrobenzene. These data are shown in Table 23. Within experimental error the ratios of cyclohexene to cyclohexyl acetate are identical. This result might have been expected if formation of cyclohexene occurs by a diaxial mode of elimination, in which case the leaving group departs away from the β-hydrogens. This is the mechanism suggested by Winstein's data from the solvolysis of cis- and trans-4-t-butylcyclohexyl p-toluenesulfonate (85,86). However, Hirschmann and Ramseyer (87) have recently found evidence for appreciable amounts of cis-elimination, and through the use of deuterium labeling experiments several chemists (88,89) have argued that the transition state in the solvolysis of cyclohexyl derivatives has a non-chair (twist-boat) conformation. This latter evidence suggests that it may be possible that the

Table 23. Solvolysis of cyclohexyl sulfonates at 100° in acetic acid and 20% acetic acid - 80% nitrobenzene[a]

Solvent (No. of runs)	Reaction Time, hrs.	% Recovery[c]	Analysis[b] A, Cyclohexene	Analysis[b] B, Cyclohexyl Acetate	A/B
Cyclohexyl p-Nitrobenzenesulfonate					
Acetic Acid (2)	2	88	78.3	21.7	3.60
20% Acetic Acid - 80% Nitrobenzene (3)	13	94	90.4	9.6	9.42
Cyclohexyl p-Toluenesulfonate					
Acetic Acid (3)	13	93	78.5	21.5	3.65
20% Acetic Acid - 80% Nitrobenzene (3)	37	93	90.9	9.1	9.98

[a]See footnote a, Table 2.

[b]See footnote b, Table 2.

[c]See footnote d, Table 2.

leaving group removes a β proton in the solvolysis of ionizable cyclohexyl compounds. Although there is not nearly enough evidence concerning the solvolytic behavior of secondary derivatives, the data accumulated so far argue that ion-pair intermediates in these systems are indeed reasonable (90-93). This means that we are justified in considering elimination reactions from the solvolysis of secondary systems as being E_1 processes. The data from the solvolysis of cyclohexyl derivatives, however, do not furnish any insight into the mechanism of the E_1 reaction since the details of this solvolysis reaction are by no means well understood.

We also solvolyzed 2-pentyl p-nitrobenzenesulfonate and p-toluenesulfonate in acetic acid and 20% acetic acid - 80% nitrobenzene, the data are presented in Table 24. Again, the ratio of olefin to acetate is the same within experimental error for the different leaving groups, implying that either the difference in the leaving groups is not great enough to show a difference in the amount of olefin or that the leaving group does not participate in the removal of a β hydrogen. If the difference in sulfonate leaving groups was large enough and if the leaving group was involved in the E_1 elimination, we should have observed a change. Our analysis shows a much higher yield of olefins than that reported by Brown (94,95) which distinctly shows the improvement in quantitative analysis over the last few years and points out the disadvantage of relying on data obtained by earlier methods. It is noteworthy that the ratio of olefin to acetate is less in these solvolyses than in the corresponding solvolyses of cyclohexyl derivatives, but yet much greater than the ratio of cyclohexene to cyclohexyl acetate from the solvolysis of 5-hexenyl derivatives (Table 19).

Several investigators have presented data that support the removal of a proton from a cationic intermediate by the leaving group or solvent affected by the leaving group. Cram (96) observed large differences in the ratios of different elimination products from 2-phenyl-2-butyl substrates with

Table 24. Solvolysis of 2-pentyl sulfonates at 100° in acetic acid and 20% acetic acid - 80% nitrobenzene[a]

Solvent (No. of runs)	Reaction Time, hrs.	% Recovery[c]	Analysis[b] A, Pentenes[d]	Analysis[b] B, Pentyl Acetates[e]	A/B
2-Pentyl p-Nitrobenzenesulfonate					
Acetic Acid (3)	12	96	43.0	57.0	0.75
20% Acetic Acid - 80% Nitrobenzene (3)	12	92	64.9	35.1	1.85
2-Pentyl p-Toluenesulfonate					
Acetic Acid (3)	36	90	43.5	56.5	0.77
20% Acetic Acid - 80% Nitrobenzene (3)	36	95	65.9	34.1	1.93

[a]See footnote a, Table 2.

[b]See footnote b, Table 2.

[c]See footnote d, Table 2.

[d]1- and 2-pentenes not separated.

[e]1- and 2-pentyl acetates not separated.

different leaving groups and felt that the leaving group, in proportion to its basicity, assisted the removal of a proton from the carbonium ion intermediate. Solvolysis of erythro- and threo-3-deuterio-2-butyl p-toluenesulfonates produced olefin by predominantly cis-elimination in nitrobenzene and predominantly trans-elimination in acetamide (97), and was explained in terms of an intimate association of the leaving group with the carbonium ion with loss of a proton to either the leaving group (cis-elimination) or the solvent (trans-

elimination); although, considering the large difference in solvents, this evidence could also be explained by solvent removal of a proton and does not demand leaving group assistance. In contrast to Hughes and Ingold's classic experiments which defined the mechanism of the E_1 reaction (98), Winstein and Cocivera (99) have reported a gradual change in the relative amount of olefin produced during the solvolysis of t-butyl and t-amyl substrates with different leaving groups and in solvents of varying nucleophilicity. Smith (100) has more recently found that the elimination over substitution ratio for the ethanolysis of various 2-phenyl-2-propyl substrates depends on the leaving group.

For solvolysis of tertiary systems it is known that the rate determining step is formation of intermediate ion pairs (101). However, it is not definitely known whether removal of a β proton occurs from this ion pair or from a solvent separated ion pair. Once the leaving group is separated from the cation by a molecule of solvent removal of a hydrogen in an E_1 fashion becomes an intermolecular process. Thus, in the arguments which support removal of a β hydrogen by the leaving group there is the assumption that this is an intramolecular elimination, a condition for which there appears to be no evidence.

The base added to neutralize the strong acid produced in the solvolysis of 5-hexenyl p-nitrobenzenesulfonate appears

Table 25. Acetolysis of 5-hexenyl p-nitrobenzenesulfonate at 100° with sodium acetate, urea, or tetramethylurea present to neutralize the arenesulfonic acid produced[a]

Base (No. of runs)	Reaction Time, hrs.	% Recovery[b]	% Open / % Cyclic Products	A/B
Sodium Acetate (2)	12	88	4.07	0.46
Urea (3)	12	82	1.19	0.45
Urea (4)	50	90	1.21	0.42
Tetramethylurea (2)	24	88	1.25	0.38

[a] [RONs] = .01 M, [Base] = 0.2 M.

[b] See footnote d, Table 2.

to have no effect on the ratio of cyclohexene to cyclohexyl acetate. In Table 25 is presented data for acetolysis of 5-hexenyl p-nitrobenzenesulfonate with sodium acetate, urea, and tetramethylurea used as bases. As seen from this table the ratio of cyclohexene to cyclohexyl acetate is not a function of the base even though when sodium acetate is used considerable direct displacement occurs. If removal of a β proton from a carbonium ion by the most basic component in the mixture was important, then there should have been some difference in the cyclohexene to cyclohexyl acetate ratio when the added base was changed. If the leaving group or the solvent is responsible for removal of a proton then there should be no effect of the added base. These data also show that tetramethylurea is an effective base in solvolysis reactions, and

because it is a liquid and soluble in nonpolar media its use is advocated when urea would be insoluble in the solvolyzing media. Newman (102) has used tetramethylurea in the esterification of t-butyl alcohol and found its use promoted better yields of ester than when urea was used.

In addition to the data showing the insensitivity of the cyclohexene to cyclohexyl acetate ratio from the solvolysis of 5-hexenyl p-nitrobenzenesulfonate to added base, it is known that the products from the acetolysis of cyclohexyl p-nitrobenzenesulfonate show the same insensitivity (41). However, because the details of the mechanism for solvolysis of cyclohexyl derivatives are not well understood it is impossible to relate these data to the removal of a proton by either the leaving group or the solvent.

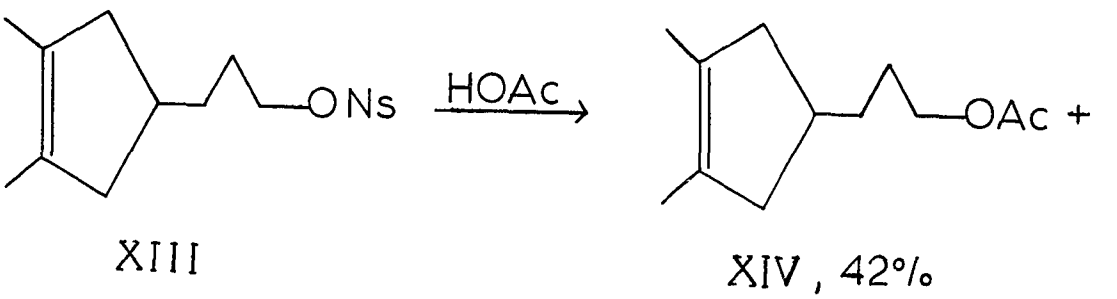
An alternate to the approach we have used to determine whether or not a β proton is removed by the leaving group would be to drastically change the leaving group. Cogdell (103) has worked out a procedure for deamination of alkyl amines in acetic acid. However, he found only low yields and no cyclic products when 5-hexenyl amine was deaminated in acetic acid. Use of less reactive leaving groups such as halides or benzoates is not satisfactory since the leaving group anion is the most nucleophilic substance in the mixture, and trapping of the cyclohexyl cation intermediate, XII, by this anion is likely to be the preferred reaction. Solvolysis of this

cyclohexyl derivative would lead to a higher ratio of cyclohexene to cyclohexyl acetate than would occur if the trapping of the cation intermediate did not occur. In the acetolysis of 5-hexenyl bromide or iodide such a trapping reaction probably gives the higher ratio of cyclohexene to cyclohexyl acetate that is observed (Table 21), and for this reason less reactive leaving groups cannot be used. When 5-hexenyl p-nitrobenzenesulfonate was solvolyzed in acetic acid solution to which was added one equivalent of sodium iodide (there was a 200 molar excess of acetic acid), 5-hexenyl iodide was quantitatively recovered.

Thus, although many chemists believe that the removal of a β proton in an E_1 reaction is by the leaving group, definitive evidence is still lacking. There appears to be no simple way to determine if solvent or the leaving group removes a proton from the cationic intermediate formed in the solvolysis of 5-hexenyl derivatives. Since we find no change in the ratio of olefin to acetate with sulfonate esters we cannot state that solvent alone removes the β proton. In spite of the enormous amount of research on solvolytic reactions that has been carried out many fundamental questions remain unanswered.

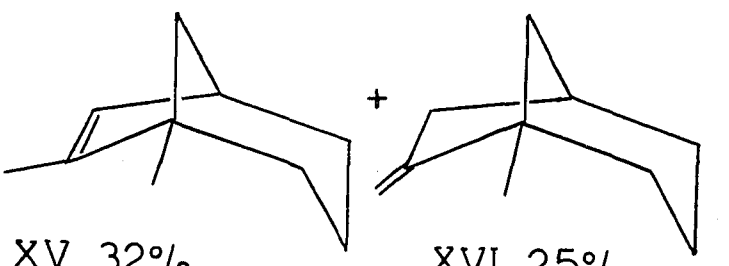
Solvolysis of 6-Heptenyl p-Nitrobenzenesulfonate in Solvents of Low Nucleophilicity

When 2-(3-cyclopentenyl)ethyl p-nitrobenzenesulfonate, III, is acetolyzed in the presence of sodium acetate only exo-norbornyl acetate is produced, the rate acceleration over its saturated analog being a factor of 90 (27,30). In contrast, 3-(3-cyclopentenyl)propyl p-nitrobenzenesulfonate solvolyzes in acetic acid without cyclization and without acceleration by the double bond (36). However, 3-(3,4-dimethyl-3-cyclopentenyl)propyl p-nitrobenzenesulfonate, XIII, does undergo acetolysis three times faster than a saturated model compound, yielding, in the presence of sodium acetate, the corresponding acetate, XIV, and two bicyclic olefins,



XIII

XIV, 42%



XV, 32%

XVI, 25%

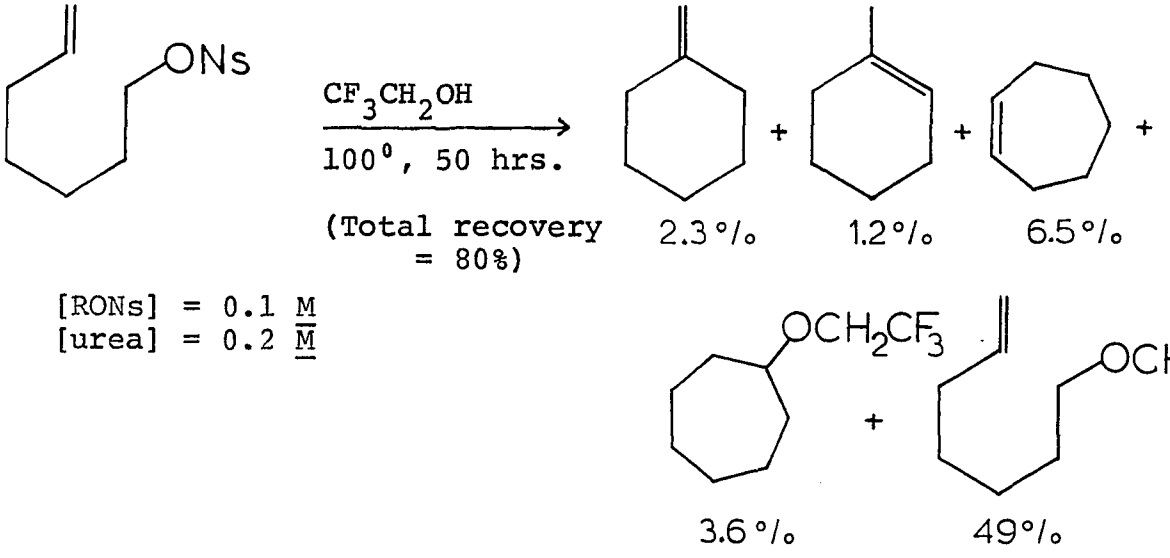
1,7-dimethylbicyclo[3.2.1]octene-6, XV, and 1-methyl-7-methylenebicyclo[3.2.1]octane, XVI (36). Thus, the effect of an increase by one methylene group in the length of the chain between an ionizing center and an actively participating double bond is to substantially decrease the ability of the double bond to participate in the solvolysis reaction.

For solvolyses of 6-heptenyl p-nitrobenzenesulfonate it has been reported that acetolysis in the presence of sodium acetate yields only 6-heptenyl acetate (38), and we have found that acetolysis of this 6-heptenyl derivative using urea as the base produces no detectable amount of cyclic products. Even when 6-heptenyl p-nitrobenzenesulfonate was solvolyzed in formic acid only 1% of a cyclic product (cycloheptyl formate) was formed (39).

Of the solvents we have used for the solvolysis of 5-hexenyl p-nitrobenzenesulfonate 2,2,2-trifluoroethanol and trifluoroacetic acid give the highest amount of cyclic products. Since both of these solvents lead to no appreciable amount of direct displacement it was not possible to tell which solvent was the more nucleophilic. Solvolysis of 6-heptenyl p-nitrobenzenesulfonate in the trifluoroethanol and in trifluoroacetic acid offers the possibility of determining which solvent is the more reactive as well as giving an estimate of the reactivity of the 6,7-double bond in olefinic cyclizations and, possibly, allowing observation of the distribution of 6- and

7-membered ring cyclic products.

The yields of products from the solvolysis of 6-heptenyl p-nitrobenzenesulfonate in 2,2,2-trifluoroethanol containing urea are as indicated. The absolute yield of the cyclic products, methylenecyclohexane, 1-methylcyclohexene, cyclo-



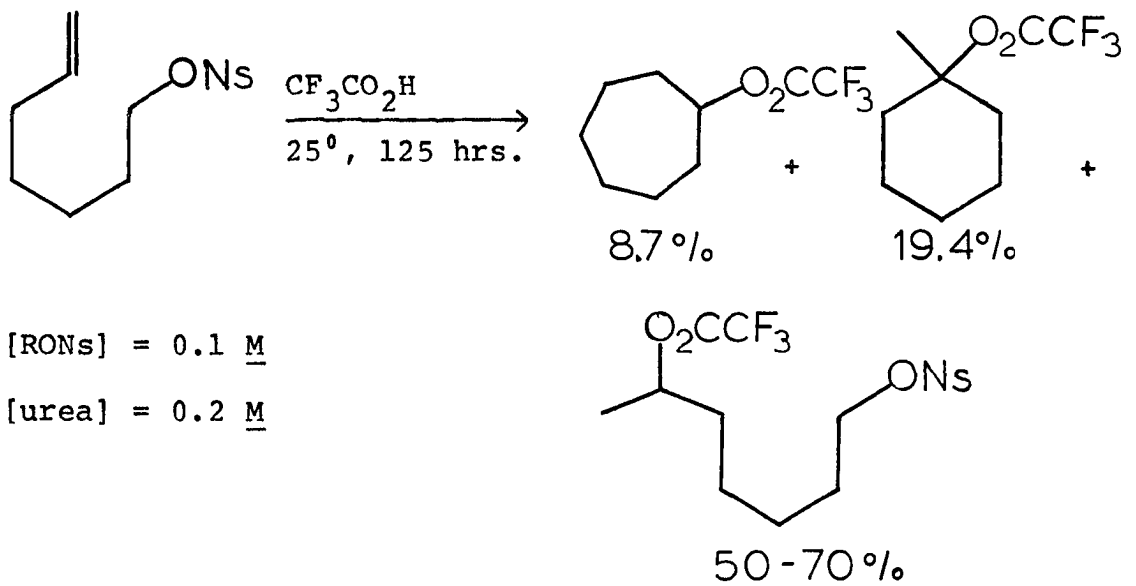
Unknown Olefin No. 1 - 3.9%

Unknown Olefins Nos. 2 and 3 - 10.7%

Unknown Ether No. 1 - 2.3%

heptene, and cycloheptyl 2,2,2-trifluoroethyl ether, as determined by g.l.p.c. analysis, is 14% (17% relative yield). A quantity of 49% of the open product, 6-heptenyl 2,2,2-trifluoroethyl ether, identified by an n.m.r. spectrum of the products, was obtained. The unknown olefins are tentatively identified as acyclic heptadienes. The unknown ether may be a cyclic product, either cyclohexylmethyl or 1-methylcyclohexyl 2,2,2-trifluoroethyl ether.

Solvolysis of 6-heptenyl p-nitrobenzenesulfonate in trifluoroacetic acid under the same conditions as those used for solvolysis of the 5-hexenyl sulfonate derivative gave three products as indicated. The cyclic products, cycloheptyl



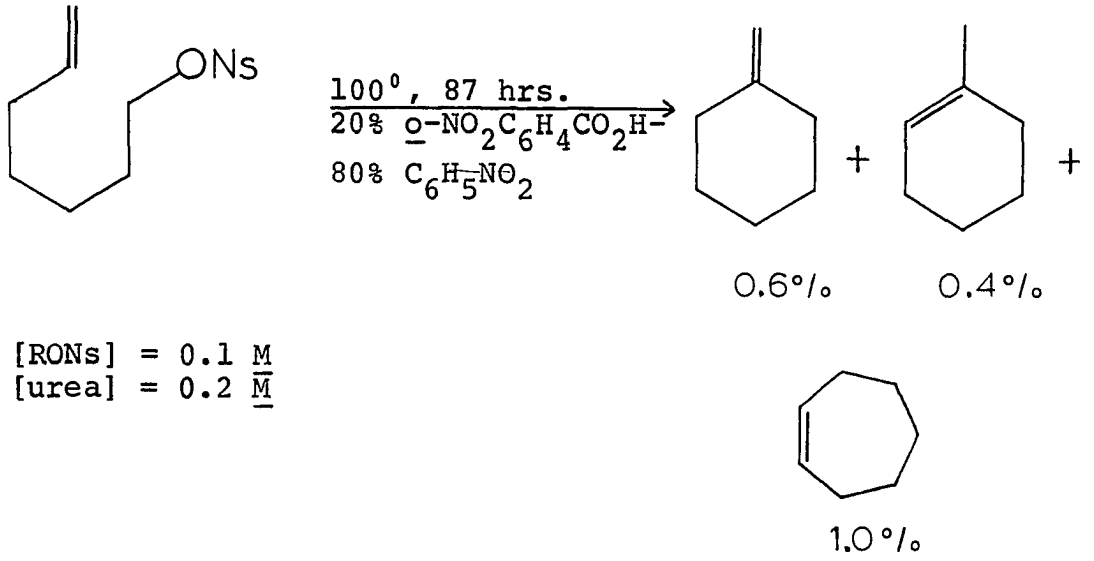
and 1-methylcyclohexyl trifluoroacetates, were identified by an n.m.r. spectrum of the solvolysis products and by g.l.p.c. analysis after basic hydrolysis to the corresponding alcohols. The presence of the open product, produced by addition of trifluoroacetic acid into the 6,7-double bond, was confirmed by n.m.r. No 1,6-ditrifluoroacetoxyheptane was found.

The fact that more cyclic products are produced in trifluoroacetic acid than in 2,2,2-trifluoroethanol as well as the absence of products from direct displacement when trifluoroacetic acid was used means that trifluoroacetic acid is

less nucleophilic than the trifluoroethanol. This is expected if nucleophilicity of fluorinated derivatives follows the same trend as the corresponding hydrogenated compounds; that is, since acetic acid is less nucleophilic than ethanol (15) it is reasonable that trifluoroacetic acid would be less nucleophilic than 2,2,2-trifluoroethanol. However, trifluoroacetic acid is a strong acid, and because of this the undesirable olefin addition reaction occurs. Thus in trifluoroacetic acid three processes may occur, nucleophilic attack by the double bond or by trifluoroacetic acid, and electrophilic addition into the double bond. Since we did not observe any product from nucleophilic attack by trifluoroacetic acid we cannot give an exact number to the relative nucleophilicity of trifluoroacetic acid. However, we can set an upper limit on the reactivity of this solvent, assuming that open product from nucleophilic attack was formed but was outside of the limits of detection. That is, assuming that less than 5% relative yield of 1,6-ditrifluoroacetoxyheptane compared to 95% cyclic products formed we can set an upper limit to the nucleophilicity of this solvent. Only when the imposed olefin addition reaction is eliminated can one hope to obtain an accurate number for the relative solvent nucleophilicity of trifluoroacetic acid.

We have detected cyclic products when 6-heptenyl p-nitrobenzenesulfonate is solvolyzed in 80% nitrobenzene - 20%

o-nitrobenzoic acid. As indicated, approximately 2% cyclic products are formed, and, since no further effort was made to identify cyclic or open benzoate esters this 2% of cyclic



[RONs] = 0.1 M
[urea] = 0.2 M

Unknown olefin No. 1 and 2 - 4.1%
Unknown olefin No. 3 - 0.5%

products must be set as a lower limit of the amount of cyclic products produced. However, since the ratio of cyclohexene to cyclohexyl o-nitrobenzoate from the solvolysis of 5-hexenyl p-nitrobenzenesulfonate (Table 12) favored the olefin by a factor of three, no more than 1% of cyclic benzoate esters would be expected in this solvolysis of the 6-heptenyl derivative.

Using the data from the solvolysis of 5-hexenyl and 6-heptenyl p-nitrobenzenesulfonates in 20% o-nitrobenzoic acid - 80% nitrobenzene as a bridge between the 5-hexenyl and 6-heptenyl derivatives we can crudely estimate the relative

reactivity of 2,2,2-trifluoroethanol and trifluoroacetic acid with respect to acetic acid. In Table 26 is listed the ratio of % open to % cyclic products from the solvolysis of 5-hexenyl and 6-heptenyl p-nitrobenzenesulfonates in various solvents and solvent mixtures. As shown, the trifluoroethanol is 46 times less nucleophilic than acetic acid and trifluoroacetic acid is at least 100 times less nucleophilic than 2,2,2-trifluoroethanol.

An interesting observation is that the major portion of the cyclic products from the solvolysis of 6-heptenyl p-nitrobenzenesulfonate in 2,2,2-trifluoroethanol contain 7-membered instead of 6-membered rings, while the corresponding solvolysis in trifluoroacetic acid produces mainly 6-membered ring products. Predominant formation of 7-membered ring products is unexpected if one considers the additional strain of 7-membered rings compared to 6-membered rings. Compared to acetolysis of cyclopentylmethyl derivatives which shows a substantial rate acceleration (38, 104) over a model compound and gives predominantly ring expanded cyclohexyl products (38, 105), solvolysis of cyclohexylmethyl derivatives leads to predominantly 6-membered ring products (105-107) and shows no rate acceleration (104), both results indicative of the relative ease of formation of 5-, 6-, and 7-membered rings. However, formally the 7-membered rings arise from a secondary cation whereas the 6-membered rings arise from a primary cation.

Table 26. Relative reactivity of various solvents and solvent mixtures

Solvent	% Open/% Cyclic Products from $CH_2=CH(CH_2)_{n-2}ONs$ Solvolyses		Relative Reactivity[a]
	n = 6	n = 7	
Acetic Acid[b]	1.21	-	46
20% Acetic Acid - 80% Nitrobenzene[b]	0.65	-	25
Formic Acid (97%)[c]	0.46	>99	18
20% o-Nitrobenzoic Acid - 80% Nitrobenzene[d]	0.17	32	6.5
2,2,2-Trifluoroethanol	0.00	4.9[e]	1.0
Trifluoroacetic Acid	0.00	<0.05[f]	<0.01

[a]Calculated by assuming that the products from the solvolysis of 6-heptenyl p-nitrobenzenesulfonate measure solvent nucleophilicity as do the products from the solvolysis of the 5-hexenyl derivative. The relative reactivity was then calculated using the data from the solvolyses in 20% o-nitrobenzoic acid - 80% nitrobenzene to bridge the 5- and 6-alkenyl derivatives, and using a relative reactivity of 1.00 for solvolyses in 2,2,2-trifluoroethanol.

[b]Experimental data taken from Table 2.

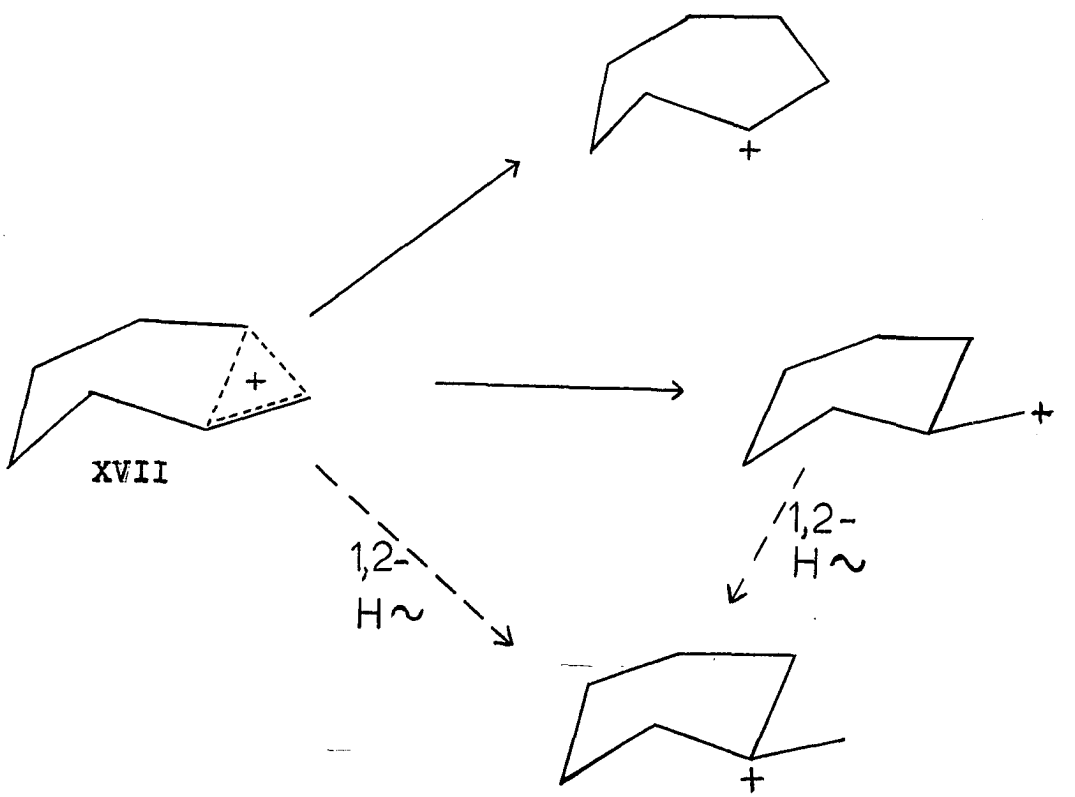
[c]Experimental data taken from Table 13 for solvolysis of the 5-hexenyl derivative. For formolysis of the 7-heptenyl sulfonate used the data of Johnson and coworkers (39).

[d]Experimental data taken from Table 12 for 5-hexenyl sulfonate solvolysis. Assumed a 3% relative yield of cyclic products from solvolysis of the higher homolog.

[e]Relative yield of cyclic products taken to be 17% and is probably low.

[f]Assumed a relative yield of cyclic products of 95% and of open product of 5%. These values were used excluding the olefin addition reaction. The value of open product set at 5% arbitrarily may be high.

Thus, there should be a competition between formation of 6- and 7-membered ring compounds from the solvolysis of 6-heptenyl derivatives which is dependent on the solvolytic conditions used. On the one hand, formation of cyclohexyl products is favored over production of cycloheptyl derivatives because of product stability. On the other hand, the cycloheptyl cation is more stable than the cyclohexylmethyl cation. Another factor, a 1,2-hydride shift, may be important in this solvolysis if 6-membered ring products arise from the 1-methylcyclohexyl cation produced directly from XVII or indirectly from the cyclohexylmethyl cation.



Olefinic cationic cyclizations to 7-membered rings have recently been reported by Marshall and Anderson (108) and Goldsmith and Clark (109). These workers treated unsaturated aldehydes or epoxides with Lewis acids in benzene. In these cases, cyclization to a 7-membered ring was favored by the presence of a 6-methyl group which resulted in a tertiary carbonium ion during cyclization to a 7-membered ring. The almost quantitative yields of 7-membered ring products observed by Marshall and Anderson (108) must be a consequence of the conformational rigidity of their starting materials; the 7-membered chains which cyclized were fused to 5-membered rings.

EXPERIMENTAL

Materials

Instrumentation

N.m.r. spectra were taken with a Varian model A-60 spectrometer using tetramethylsilane as an internal standard. Infrared (i.r.) spectra were obtained with a Perkin-Elmer Model 21 recording spectrometer. Mass spectra were obtained with an Atlas MAT model CH 4 spectrometer. Melting points were taken on a Thomas Hoover capillary melting point apparatus and are uncorrected. Boiling points are uncorrected. Elemental Analyses were performed by Spang Microanalytical Laboratory, Ann Arbor, Michigan.

G.l.p.c. measurements were carried out on an Aerograph model 202 gas chromatograph (Wilkins Instrument and Research, Inc.) fitted with dual thermal conductivity detectors. Use was made of 5-ft. columns of 20% silicone SE-30 on Chromasorb W, 7-ft. columns of 20% glyceryl tripropionate, 6-ft. columns of 20% Carbowax 20 M, 20% diisodecylphthalate, 20% didecyl phthalate, 20% β,β'-oxydipropionitrile, 20% Ucon 50-Hb-2000, 5-ft. columns of 20% silicone SE-30, and 4-ft. columns of 20% 1,2,3-tris-(2-cyanoethoxy)propane and 20% diethylene glycol succinate, all on Chromosorb P.

Solvents

A listing of the commercial source of the solvents used in the solvolysis reactions is given in Table 27. Ethyl

Table 27. Solvents and commercial sources

Solvent	Commercial Source
Acetic Acid	Baker, Mallinckrodt, Fisher
Triacetin	Baker
γ-Butyrolactone	Aldrich
Methyl Benzoate	Matheson, Coleman, and Bell
Ethyl Ether	Baker
Benzyl Ether	Aldrich
Anisole	Matheson, Coleman, and Bell
Phenyl Ether	Matheson, Coleman, and Bell
Phenyl Sulfide	Eastman
Tetrahydrofuran	Matheson, Coleman, and Bell
Carbon Tetrachloride	Matheson, Coleman, and Bell
Chloroform	Mallinckrodt
1,1,2,2-Tetrachloroethane	Matheson, Coleman, and Bell
o-Dichlorobenzene	Matheson, Coleman, and Bell
Trichloroethylene	Matheson, Coleman, and Bell
Acetophenone	Matheson, Coleman, and Bell
Benzil	Matheson, Coleman, and Bell
Acetonitrile	Eastman
Benzonitrile	Matheson, Coleman, and Bell
Nitromethane	Matheson, Coleman, and Bell
Nitrobenzene	Eastman
Triphenyl Phosphite	Eastman
Hexamethylphosphoramide	Eastman
Trimethyl Phosphate	Aldrich

Table 27 (Continued)

Solvent	Commercial Source
Triphenyl Phosphate	Eastman
Tris-(Tetrahydrofurfuryl) Phosphate	Aldrich
Sulfolane	Aldrich
Butyl Sulfone	Phillips Petroleum
Methyl Phenyl Sulfone	Aldrich
Vinyl Sulfone	Aldrich
1,4-Butanesultone	Aldrich
Dimethyl Sulfoxide	Matheson, Coleman, and Bell
Benzene	Fisher
Furan	Matheson, Coleman, and Bell
N,N-Dimethylformamide	Matheson, Coleman, and Bell
Tripentyl Borate	Eastman
Pyridine-N-Oxide	Aldrich
Acetone	Mallinckrodt
2,4-Pentanedione	Matheson, Coleman, and Bell
Methyl Methanesulfonate	Eastman
Tetramethyl Orthosilicate	Aldrich
o-Nitrotoluene	Matheson
2-Nitro-m-Xylene	Aldrich
p-Nitrotoluene	Matheson, Coleman, and Bell
2,4-Dinitrotoluene	Aldrich
2,6-Dinitrotoluene	Aldrich
m-Dinitrobenzene	Matheson, Coleman, and Bell

Table 27 (Continued)

Solvent	Commercial Source
1-Chloro-2-Nitrobenzene	Eastman
1-Chloro-4-Nitrobenzene	Eastman
o-Nitroanisole	Aldrich
m-Nitroanisole	Eastman
p-Nitroanisole	Aldrich
2,4-Dinitroanisole	Eastman
Formic Acid (97+%)	Aldrich
Benzoic Acid	Mallinckrodt
p-Nitrobenzoic Acid	Matheson, Coleman, and Bell
o-Nitrobenzoic Acid	Eastman
Phenol	Mallinckrodt
o-Methoxybenzoic Acid	Matheson
Chloroacetic Acid	Baker
2,2,2-Trifluoroethanol	Halocarbon Products
Trifluoroacetic Acid	Eastman
Pivalic Acid	Eastman

stearate was prepared from stearic acid and excess ethanol in the presence of sulfuric acid (110), b.p. 132-133° at 0.1 mm., m.p. 32-33° (lit. (111) m.p. 33.6°). p-Methyl anisole was kindly donated by L. B. Young who prepared the ether from the corresponding phenol with dimethyl sulfate (112). Deuteroacetic acid was prepared by Paul Nave who treated acetic anhydride with deuterium oxide and thoroughly removed the excess heavy water and acetic anhydride.

Several of the materials listed in Table 27 were further purified. The stabilizing ethanol in reagent grade chloroform was removed using the method of Fieser (113). Solvolyses in which chloroform was used as the nonhydroxylic solvent were run within one week after purification. 1,1,2,2-Tetrachloroethane, nitrobenzene, triphenyl phosphite, trimethyl phosphate, o-nitrotoluene, 2-nitro-m-xylene, and o-nitroanisole were distilled before use. Hexamethylphosphoramide was purified by distillation over calcium hydride. Dimethyl sulfoxide was distilled under reduced pressure and stored over Linde molecular seives no. 4A. Sulfolane was distilled over calcium hydride and kept under nitrogen. p-Nitrotoluene, 2,4-dinitrotoluene, 2,6-dinitrotoluene, m-dinitrobenzene, 1-chloro-2-nitrobenzene, 1-chloro-4-nitrobenzene, m-nitroanisole, p-nitroanisole, and 2,4-dinitroanisole were all recrystalized before use.

Reagents

Table 28 lists the commercial source for many of the materials other than solvents used in this study. Samples of methylenecyclopentane and 1-methylcyclopentene were generously donated by Gary Jewitt. Cyclohexene was distilled and kept under nitrogen. The substituted benzenesulfonyl chlorides were recrystallized from ether-pentane immediately before use. Pentyl acetate was distilled. 2,4,6-Trimethylbenzenesulfonyl chloride was prepared from 1,3,5-trimethylbenzene and chlorosulfonic acid in 90% yield according to the method of Newton (114), m.p. 55.0-55.4^0 (lit. (115) m.p. 50-53^0). 2-Pentanol was prepared in 42% yield from n-butyraldehyde and methylmagnesium iodide by the method of Coburn (116), b.p. 118-119^0 (lit. (94) b.p. 118-118.5^0 at 749 mm.).

Carboxylate esters

Hexyl acetate was prepared from hexanol and acetic anhydride (117), b.p. 58-59^0 at 10 mm. (lit. (118) b.p. 169^0 at 760 mm.). 5-Hexenyl acetate was prepared by W. S. Trahanovsky. Cyclopentylmethyl acetate was prepared from the corresponding alcohol and acetic anhydride (117), b.p. 65-66^0 at 10 mm. (lit. (118) b.p. 169.2^0 at 760 mm.). The acetate ester of cyclohexanol was prepared in the same manner (117), b.p. 50^0 at 8 mm. (lit. (119) b.p. 172^0 at 752 mm.). 1-Methylcyclopentyl acetate was prepared in 64% yield by the method of Hammond and Nevitt (120), b.p. 48.5^0 at 9 mm. (lit. (121) b.p. 66-70^0 at 30 mm.).

Table 28. Reagents and commercial sources

Reagent	Commercial Source
Cyclohexene	Eastman
Cyclohexanol	Matheson, Coleman, and Bell
5-Hexen-1-ol	Columbia, Peninsular
p-Nitrobenzenesulfonyl Chloride	Eastman
2,4-Dinitrobenzenesulfonyl Chloride	Eastman
o-Nitrobenzenesulfonyl Chloride	Eastman
m-Nitrobenzenesulfonyl Chloride	Eastman
p-Bromobenzenesulfonyl Chloride	Matheson, Coleman, and Bell
Benzenesulfonyl Chloride	Mallinckrodt
p-Toluenesulfonyl Chloride	Matheson, Coleman, and Bell
p-Methoxybenzenesulfonyl Chloride	Aldrich
Methanesulfonyl Chloride	Matheson, Coleman, and Bell
Hexanol	Eastman
Pentyl Acetate	Matheson, Coleman, and Bell
Urea	Matheson, Coleman, and Bell
Butyl Acetate	Matheson, Coleman, and Bell
Ethyl Acetate	Matheson, Coleman, and Bell
Cyclopentylcarbinol	K and K
Calcium Hydride	Fisher
1,5-Hexadiene	Aldrich
Pyridine	Baker, Fisher
1-Methylcyclopentanol	Columbia
2,6-Lutidine	Eastman

Table 28 (Continued)

Reagent	Commercial Source
Tetramethylurea	Baker
1-Methylcyclohexene	Aldrich
Methylenecyclohexane	Aldrich
Cycloheptene	Aldrich
1-Methylcyclohexanol	Aldrich
Cyclohexylcarbinol	Aldrich
Cycloheptanol	Aldrich
1,3,5-Trimethylbenzene	Matheson, Coleman, and Bell
p-Nitrobenzenesulfonic Acid	Eastman
Hydrochloric Acid (37.7%)	Baker
Methyl Iodide	Baker
n-Butyraldehyde	Eastman
Acetic Anhydride	Eastman
Acetyl Chloride	Matheson, Coleman, and Bell

Methyl acetate was prepared according to the method of Sarel and Newman (122), b.p. 55° (lit. (118) b.p. 57.3°). Preparation of 2-pentyl acetate was effected by the usual method (117), b.p. 130-131° (lit. (94) b.p. 131-131.5°). Cycloheptyl acetate, b.p. 78-80° at 11 mm. (lit. (123) b.p. 76-78° at 11 mm.) and 6-heptenyl acetate, b.p. 87-90° at 18 mm. (lit. (124) b.p. 82° at 18 mm.) were prepared by Larry Krueger in our laboratories. Cyclohexylmethyl acetate was prepared from cyclohexylmethanol and acetic anhydride (117), b.p. 80° at 8 mm. (lit. (122) b.p. 108° at 40 mm.). Only a poor yield of 1-methylcyclohexyl acetate was obtained when 1-methylcyclohexene was treated with acetic acid and a catalytic amount of sulfuric acid, b.p. 68-70° at 10 mm. (lit. (121) b.p. 75-76° at 17 mm.).

Cyclohexyl pivalate, b.p. 88-89° at 22 mm., and 5-hexenyl pivalate, b.p. 88° at 20 mm., were prepared by W. S. Trahanovsky. The n.m.r. spectrum of both esters exhibits a resonance due to the t-butyl group at 1.15δ (singlet).

Anal. Calcd. for cyclohexyl pivalate, $C_{11}H_{20}O_2$: C, 71.70; H, 10.94. Found: C, 71.57; H, 10.93.

Anal. Calcd. for 5-hexenyl pivalate, $C_{11}H_{20}O_2$: C, 71.70; H, 10.94. Found: C, 71.49; H, 11.02.

Formate esters were prepared from the corresponding alcohols and 97% formic acid using catalytic amounts of p-toluenesulfonic acid. The mixture of alcohol and acids in a

flask fitted with a reflux condenser was heated on a steam bath for less than 30 hours. Cyclohexyl formate, b.p. 48.0-48.5° at 8 mm. (lit. (125) b.p. 154-155° at 701 mm.), was prepared in 61% yield. Preparation of 5-hexenyl formate using this method also produced some 1,5-hexyl diformate. Distilled 5-hexenyl formate was obtained in 52% yield, b.p. 49.0-49.5° at 8 mm. Cyclopentylmethyl formate was prepared in 51% yield, b.p. 53.5-54.0° at 9 mm. This method was inadequate for preparation of 1-methylcyclopentyl formate. Only a low yield (<10%) of product was obtained, and the material collected from distillation at 41.5-42.0° (10 mm.) contained approximately 20% of the starting alcohol. The n.m.r. spectra of these formate esters all show a singlet at 7.85-7.95δ due to the formate proton, 5-hexenyl formate shows a triplet centered at 4.1δ for the methylene hydrogens next to the formate group, and cyclopentylmethyl formate shows its characteristic methine doublet at 4.0δ. The formate ester of 1-methylcyclopentanol shows n.m.r. resonance at 1.56δ for the methyl group, whereas the corresponding singlet for the alcohol appears at 1.28δ.

Anal. Calcd. for 5-hexenyl formate, $C_7H_{12}O_2$: C, 65.60; H, 9.44. Found: C, 65.77; H, 9.37.

Cyclohexyl and cycloheptyl trifluoroacetates were prepared from cyclohexene and cycloheptene, respectively, with trifluoroacetic acid in a slight excess using Peterson's method (61). Cyclohexyl trifluoroacetate, b.p. 80° at 38 mm., and

cycloheptyl trifluoroacetate, b.p. 70-71° at 10 mm., were obtained in 19% and 48% yield, respectively. The n.m.r. spectrum of cycloheptyl trifluoroacetate is shown in Figure 7.

Anal. Calcd. for cyclohexyl trifluoroacetate, $C_8H_{11}O_2F_3$: C, 48.98; H, 5.65. Found: C, 49.36; H, 5.95.

2,2,2-Trifluoroethyl ethers

Cyclohexyl and cycloheptyl 2,2,2-trifluoroethyl ethers were prepared from the corresponding cyclic olefins with 2,2,2-trifluoroethanol and catalylic amounts of p-nitrobenzenesulfonic acid. In a sample procedure 5.0 ml. of cyclohexene (50 mmoles.) was mixed with 10 ml. of the fluorinated alcohol (110 mmoles.), 0.2 g. of p-nitrobenzenesulfonic acid added, and the mixture kept at 75°. The trifluoroethanol and cyclohexene were not originally miscible at 75° but after 2 hours the mixture became homogeneous. After 30 hours the deep brown colored solution was cooled, ether added, and extracted with water. The organic layer was passed through anhydrous magnesium sulfate and the ether evaporated under reduced pressure. The resultant orange liquid was distilled to give 4.3 g. of colorless cyclohexyl 2,2,2-trifluoroethyl ether (21 mmoles., 42% yield), b.p. 146-147°. Cycloheptyl 2,2,2-trifluoroethyl ether was prepared by this method in 26% yield, b.p. 63-64° (10 mm.). 1-Methylcyclohexyl 2,2,2-trifluoroethyl ether could not be prepared by this procedure; only a high-boiling oil was formed. In Figures 8 and 9 is shown the n.m.r.

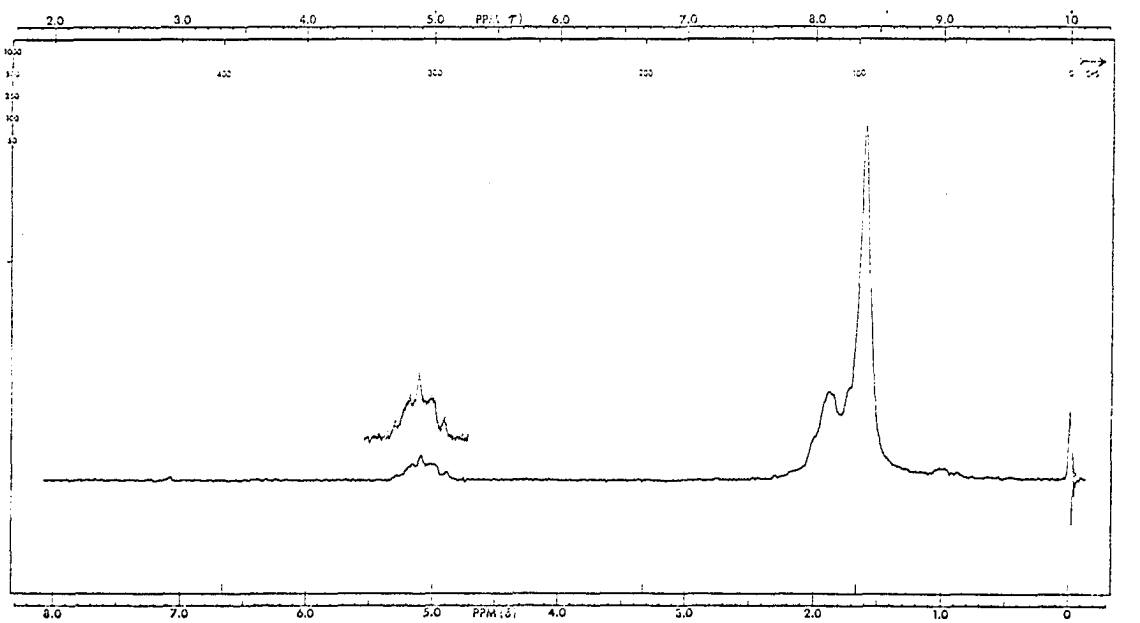
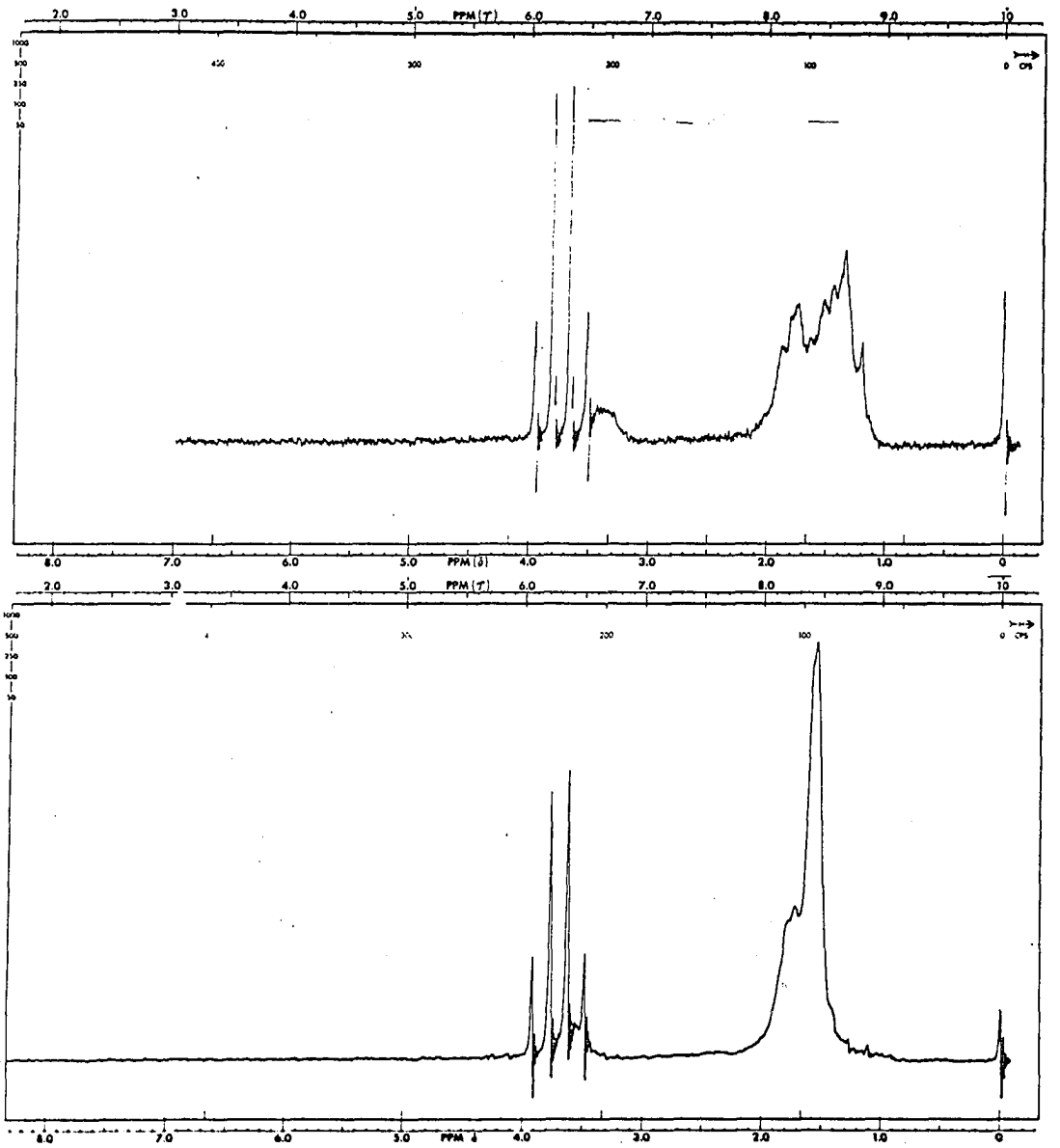


Figure 7. N.m.r. spectrum of cycloheptyl trifluoro-acetate

Figure 8. N.m.r. spectrum of cyclohexyl 2,2,2-trifluoroethyl ether

Figure 9. N.m.r. spectrum of cycloheptyl 2,2,2-trifluoroethyl ether


2.0
3.0
4.0
5.0
PPM(τ)
6.0
7.0
8.0
9.0
10
8.0
7.0
6.0
5.0
PPM(δ)
4.0
3.0
2.0
1.0
0
PPM(τ)
PPM δ

spectrum of cyclohexyl and cycloheptyl 2,2,2-trifluoroethyl ethers. Integration of the spectra indicated that these ethers were pure within the limits of this n.m.r. technique, and g.l.p.c. analysis of each ether showed only one compound.

Anal. Calcd. for cyclohexyl 2,2,2-trifluoroethyl ether, $C_8H_{13}OF_3$: C, 52.74; H, 7.19. Found: C, 53.19; H, 7.31.

Anal. Calcd. for cycloheptyl 2,2,2-trifluoroethyl ether, $C_9H_{15}OF_3$: C, 55.09; H, 7.71. Found: C, 56.19; H, 7.90.

Sulfonate esters

Preparation of hexyl p-nitrobenzenesulfonate was previously reported (38). The 5-hexenyl sulfonate esters used in this study were prepared according to a single procedure. To a constantly stirred solution of 5-hexen-1-ol (approximately 0.050 mole) in 50 ml. of dry pyridine (for preparation of 5-hexenyl 2,4-dinitrobenzenesulfonate, dry 2,6-lutidine was used[2]) contained in a stoppered flask and cooled to -15°

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[2]When pyridine was used no 5-hexenyl 2,4-dinitrobenzenesulfonate was obtained. Low yields (10-20%) of a white solid melting at 195-196° were obtained, however, when the reaction solution was poured into 10% hydrochloric acid solution and starting alcohol was recovered. The high melting solid was not soluble in ether, carbon tetrachloride, or benzene but was soluble in hot water, nitromethane, and other dipolar aprotic solvents. Spectra and an elemental analysis obtained by Richard Ehlers in this laboratory point to the structure of this solid as being pyridinium 2,4-dinitrobenzenesulfonate. Nunn and Ralph (126) have shown that alkylation of 2,6-lutidine by methyl 2,4-dinitrobenzenesulfonate can occur even at 0°. When pyridine is used alkylation may proceed at a very fast rate making isolation of the sulfonate ester almost impossible.

was added a 10% excess of the desired sulfonyl chloride. After a period of time dictated by the sulfonyl chloride used (120 min. for benzenesulfonyl chloride, 90 min. for toluenesulfonyl chloride, and 40 min. for the remaining sulfonyl chlorides) the reaction mixture was poured into a solution of cold 10% hydrochloric acid, and the aqueous solution was washed three times wtih ether. The combined ether extracts were washed three times with 10% hydrochloric acid and twice with a saturated sodium bicarbonate solution. The etheral solution was then passed through anhydrous magnesium sulfate and the majority of the ether removed under reduced pressure. If the ester produced was a solid at room temperature crystallization was effected by adding pentane to the ether - ester solution. Recrystallized 5-hexenyl p-nitrobenzenesulfonate prepared in this way was obtained in 86% yield, m.p. 40.1-40.7^0 (lit. (38) m.p. 40-41^0). White, flakey crystals of 5-hexenyl 2,4-dinitrobenzenesulfonate were easily prepared in 49% yield, m.p. 47.5-48.0^0.[3] The methanesulfonate ester of 5-hexen-1-ol was purified by distillation at 0.4 mm., b.p. 95-98^0.

The remaining 5-hexenyl derivatives were purified by re-

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[3]The more tedious method of Nunn and Chadbourne (127) was also tried, giving a 58% yield of a yellow-brown solid. This material was found extremely difficult to purify. The preferred method for preparation of 2,4-dinitrobenzenesulfonate esters is, therefore, that reported above.

crystalization at -77°.[4] The ester was dissolved in a minimal amount of a 1:1 mixture of ether-pentane, protected from moisture by use of a calcium chloride drying tube, and cooled at -77° until solid had formed. The ether-pentane solution was then removed and the solid warmed to room temperature. Ether-pentane was again added and the process repeated until a sample of sufficient purity could be obtained, usually after five recrystalizations. Any ether-pentane remaining after recrystalization was removed under reduced pressure (usually 0.1 mm.) in a vacuum desiccator. The yields obtained and the integration of the n.m.r. peaks are given in Table 29. The integration of n.m.r. peaks was by necessity the best indication of the purity of these esters since, except for 5-hexenyl 2,4,6-trimethylbenzenesulfonate, the elemental analyses obtained did not give adequate correspondance between the cal-

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[4]Distillation of sulfonate esters, especially substituted nitrobenzenesulfonate esters, is extremely hazardous. At 0.8 mm. pressure a solution of less than 5 g. of 5-hexenyl o-nitrobenzenesulfonate in a flask fitted with a short-path distillation apparatus was heated with the use of an oil bath to remove any unreacted 5-hexen-1-ol which might have been present. With the oil bath temperature less than 150° an explosion took place which, fortunately, caused only destruction of the apparatus.

culated and found percent of the element.[5]

Anal. Calcd. for 5-hexenyl p-bromobenzenesulfonate, $C_{12}H_{15}O_3S$ Br: C, 45.15; H, 4.74; S, 10.04. Found: C, 45.71; H, 4.87; S, 10.02.

Anal. Calcd. for 5-hexenyl 2,4,6-trimethylbenzenesulfonate, $C_{15}H_{22}O_3S$: C, 63.80; H, 7.86; S, 11.35. Found: C, 63.86; H, 7.77; S, 11.35.

Anal. Calcd. for 5-hexenyl methanesulfonate, $C_7H_{14}O_3S$: C, 47.17; H, 7.92; S, 17.99. Found: C, 47.32; H, 8.01; S, 19.51.

As can be seen from Table 29 the integration of n.m.r. peaks shows that the purity of these esters is as high as can be detected by n.m.r. methods (generally considered to be ±5%). Solvolyses of these esters with the exception of 5-hexenyl p-nitrobenzenesulfonate, in whcih case periodic checks were made on its purity, were performed within one week after their preparation. The esters were stored in a refrigerator at times when they were not used. In Figure 10 the n.m.r. spectrum of 5-hexenyl benzenesulfonate is presented as an example of the type of spectra obtained for the sulfonate esters listed in Table 29.

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[5]The time required to obtain an elemental analysis even on a rush order was generally greater than one week. Sulfonate esters are not extremely stable and storage of these compounds during their transit to Spang Microanalytical Laboratory could not have been the best.

Table 29. Yields and integrated areas of n.m.r. signals for various 5-hexenyl sulfonate derivatives

Derivative, X = $CH_2=CH-(CH_2)_3-CH_2OSO_2-X$	% Yield[a]
2,4-Dinitrobenzene	49.0
o-Nitrobenzene	40.5
p-Nitrobenzene	86.3
m-Nitrobenzene	59.8
p-Bromobenzene	65.7
Benzene	95.1
p-Toluene	58.3
p-Methoxybenzene	26.2
2,4,6-Trimethylbenzene	60.7
Methane	86.1

[a]Purified derivative.

[b]Position of signal independent of leaving group.

[c]Position of methylene protons adjacent to vinyl group is not completely separated from normal aliphatic proton resonances.

[d]Signal position dependent on the leaving group and at least qualitatively reflects the rate of solvolysis. Since these spectra were all taken in carbon tetrachloride at about the same sample concentration, the differences are not due to solvent shift or concentration differences. Rather, this signal dependancy on the leaving group seems to reflect the charge density on the methylene group. The triplet spanned about 0.3 p.p.m.

[e]Methylene and methoxy protons not separated.

Integrated Area				
$-(CH_2)_3-$[b,c] 1.1-2.3δ	$-CH_2OSO_2X$[d] (Signal Position, c.p.s.)	$CH_2=CH-$[b] 4.7-6.2δ	Leaving Group Signals: Aromatic	Leaving Group Signals: $-CH_3$
6.0	2.0 (260)	3.0	3.0	-
6.1	1.9 (252)	2.8	4.1	-
5.9	1.9 (245)	3.0	4.1	-
6.2	1.9 (248)	3.1	3.9	-
6.0	2.0 (240)	3.0	4.1	-
5.9	1.9 (239)	3.1	5.1	-
6.2	1.9 (237)	3.0	3.9	3.0
6.0	2.0[e] (236)	3.0	4.0	3.0[e]
6.0	2.0 (232)	2.9	2.0	9.1
5.9	2.0 (239)	3.0	-	3.1

The mass spectrum of 5-hexenyl methanesulfonate was obtained. The molecular ion peak was very weak at 178 m/e. Peaks observed which were greater than 20% of the intensity of the base peak were m/e 109, 97, 82, 81, 67, 55, 54 (base peak), and 41. A fragment at m/e 83 which might correspond to either a 5-hexenyl or cyclohexyl cation was observed but only in 10% relative intensity. Several of the peaks observed here can be explained by known fragmentation and rearrangement patterns of alkyl alkanesulfonates (128).

Cyclohexyl p-nitrobenzenesulfonate was prepared in 65% yield using the procedure of Streitwieser and Schaeffer (43), m.p. 76.5-77.5^0 (lit. (38) m.p. 78-79^0). Cyclohexyl p-toluenesulfonate was prepared in 35% yield by the same procedure used for the preparation of 5-hexenyl sulfonate esters, m.p. 42.5-43.5^0 (lit. (129) m.p. 43.5-44.0^0).

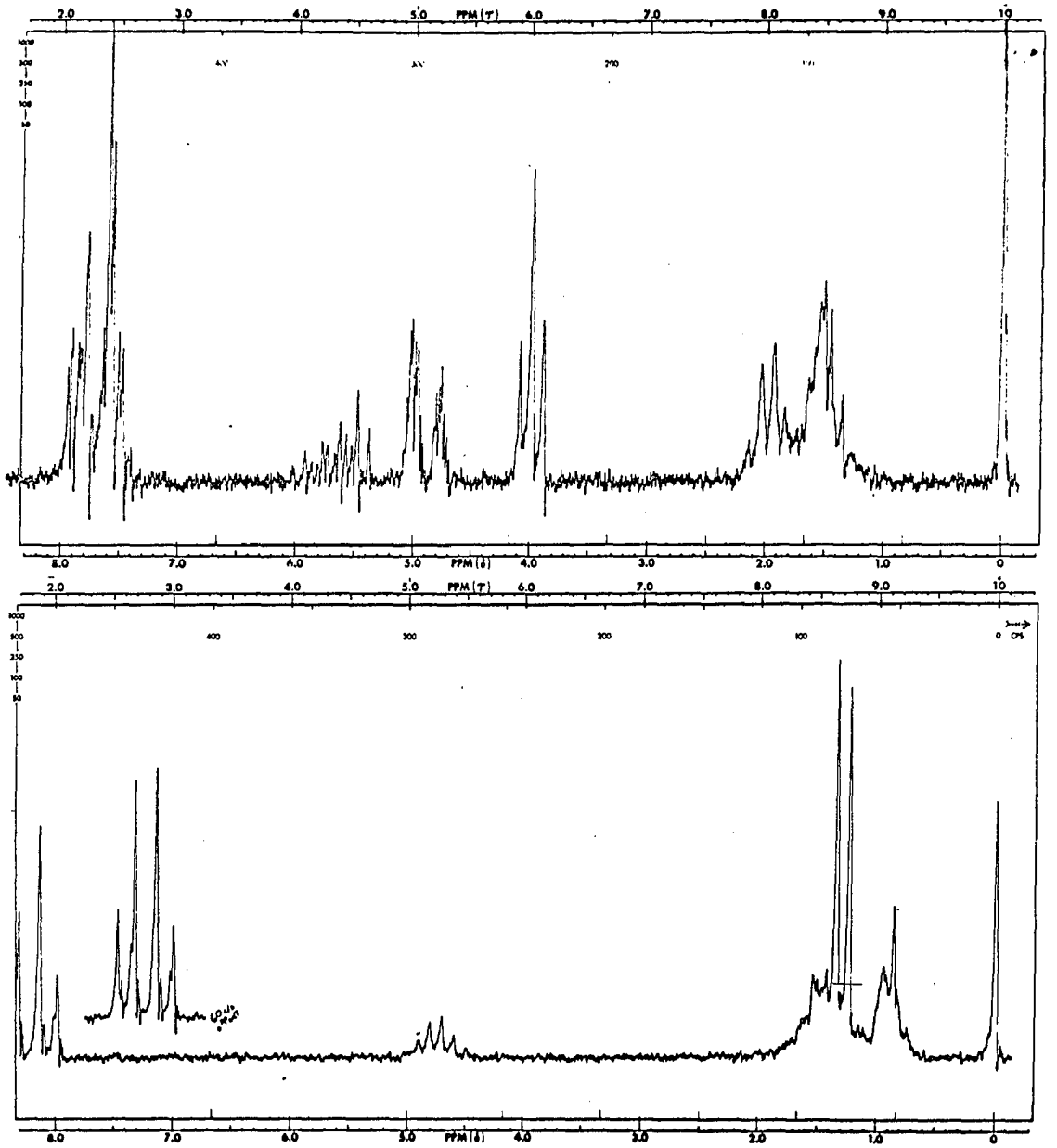
The p-nitrobenzenesulfonate ester of 2-pentanol was obtained in 56% yield using the procedure described previously, m.p. 60.3-60.8^0. The n.m.r. spectrum of this ester is shown in Figure 11. 2-Pentyl p-toluenesulfonate was prepared in an identical manner using a reaction time of three hours to obtain a 68% yield of the faintly yellow colored oil.

Anal. Calcd. for 2-pentyl p-nitrobenzenesulfonate, $C_{11}H_{15}NO_5S$: C, 48.31; H, 5.53; S, 11.75. Found: C, 47.67; H, 5.32; S, 11.94.

Anal. Calcd. for 2-pentyl p-toluenesulfonate, $C_{12}H_{18}O_3S$:

Figure 10. N.m.r. spectrum of 5-hexenyl benzenesulfonate

Figure 11. N.m.r. spectrum of 2-pentyl p-nitrobenzene-sulfonate


PPM (τ)
PPM (δ)
PPM (τ)
PPM (δ)

C, 59.47; H, 7.49; S, 13.23. Found: C, 59.35; H, 7.41; S, 13.11.

6-Heptenyl p-nitrobenzenesulfonate was prepared in 65% yield using the above procedure, m.p. 43.5-43.9° (lit. (39) m.p. 46.5-47.5°).

5-Hexenyl halides

5-Hexenyl bromide was prepared in 31% yield from 5-hexenyl p-nitrobenzenesulfonate by treatment with sodium bromide in acetone for twenty hours (130). Distillation of the crude 5-hexenyl bromide produces a clear liquid, b.p. 43-44° at 8 mm. (lit. (131) b.p. 47° at 17 mm.). The mass spectrum of 5-hexenyl bromide distinctly showed molecular ions at 162 and 164 m/e. Peaks observed which were greater than 20% of the intensity of the base peak were m/e 136 and 134 (equal intensity), 122 and 120 (equal intensity), 123 and 121 (nearly equal intensity), 83, 82, 67, 55 (base peak), 54, and 41.

Treatment of 5-hexenyl methanesulfonate with potassium iodide in anhydrous acetonitrile for 20 hours at 85° afforded a 38% yield of 5-hexenyl iodide after distillation, b.p. 64.0-64.5° at 8 mm. An n.m.r. spectrum of 5-hexenyl iodide is shown in Figure 12.

Anal. Calcd. for 5-hexenyl iodide, $C_6H_{11}I$: C, 34.31; H, 5.28; I, 60.41. Found: C, 34.15; H, 5.63; I, 60.09.

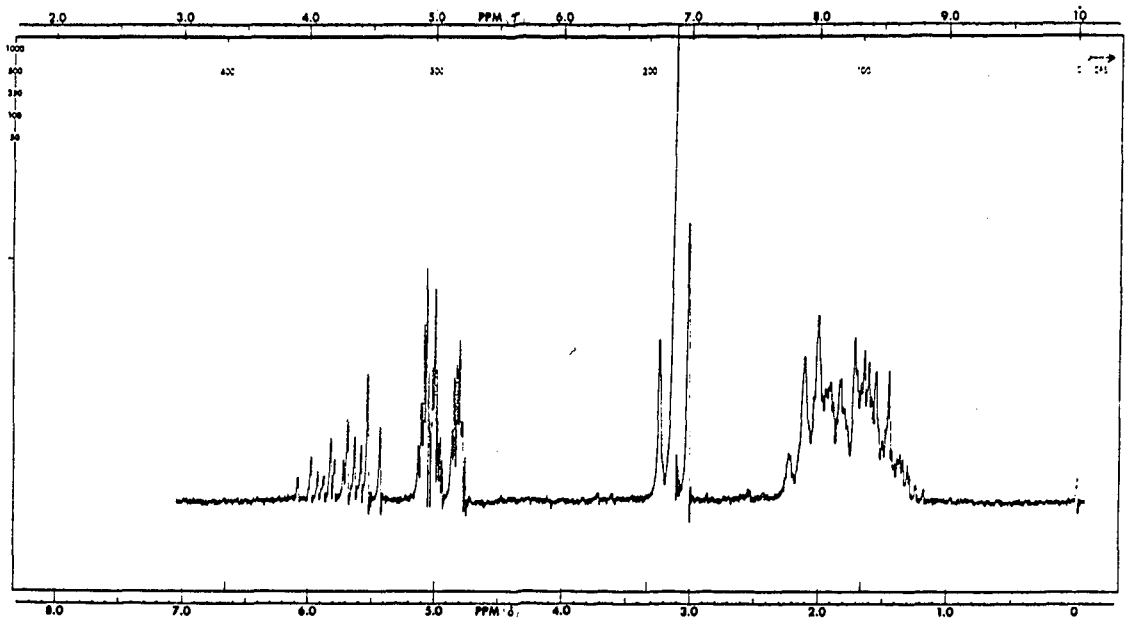


Figure 12. N.m.r. spectrum of 5-hexenyl iodide

6-Hepten-1-ol

The title compound was prepared by a six-step synthesis from 5-hexen-1-ol in approximately 40% overall yield. 5-Hexen-1-ol was converted into its methanesulfonate ester in nearly quantitative yield by the usual method. Conversion of the methanesulfonate ester to 5-hexenyl nitrile was effected in refluxing 70% aquous acetonitrile by adding two equivalents of potassium cyanide to the ester. Refluxing was continued for 24 hours whereupon after cooling and adding ether the solution was washed with water. The organic layer was separated, passed through anhydrous magnesium sulfate, and the ether removed under reduced pressure. The remaining liquid was then treated with 1.1 equivalents of potassium hydroxide in 50% aquous ethanol and heated on a steam bath for 26 hours. After cooling an excess of hydrochloric acid was added and the slightly acidic solution poured through ice into ethyl ether. After shaking the lower aquous layer was removed, the organic layer passed through anhydrous magnesium sulfate, and the ether removed under reduced pressure. Methyl 6-heptenoate was prepared from 6-heptenoic acid by treatment with thionyl chloride followed by dropwise addition of the acid chloride into methanol. The ester was then reduced with lithium aluminum hydride by a procedure similar to that of Sroog and coworkers (132). Distillation of the resultant liquid gave 6-hepten-1-ol, b.p. 75-76^0 at 11 mm. (lit. (133) b.p. 105^0 at 20 mm.).

Product Studies

General procedure

To weighed quantities of the compound to be solvolyzed and urea were added 1.00 ml. of the hydroxylic solvent and 4.00 ml. of nonhydroxylic solvent, if they were liquids at room temperature. If solvolyses were run using only hydroxylic solvent, 5.00 ml. of this solvent was added. When necessary the mixture was warmed slightly to help make it homogeneous and transferred to a constricted tube which was then sealed at atmospheric pressure. After the mixture was heated for a definite period of time, the mixture was cooled and the tube was opened. A measured amount (about 17 mg.) of an internal standard, pentyl acetate,[6] ether,[7] and saturated sodium chloride solution were added and the ether layer was separated after shaking, washed with saturated sodium chloride solution and

[6]The internal standard was hexyl acetate when tripentyl borate was used as the inert solvent.

[7]For solvolyses of 2-pentyl derivatives, benzene was added instead of ether. For solvolyses in 2,2,2-trifluoroethanol, pentane was used; ethyl ether retains the trifluoroethanol making analysis of the products difficult if not impossible.

saturated sodium bicarbonate solution.[8] The volume of ether was kept small so that no concentration step was necessary prior to g.l.p.c. analysis. The etheral solution was dried over anhydrous magnesium sulfate and then passed through a cotton filter into a sample vial. Prior to g.l.p.c. analysis approximately 0.2 g. of anhydrous magnesium sulfate was added to the sample vial to ensure dryness.[9]

If the nonhydroxylic solvent was a solid at room temperature, a weighed quantity equivalent to 4.0 ml. of the solid (calculated from the density of the compound at room temperature unless otherwise stated) was placed in a constricted tube and the acetic acid solution of the substrate and base was added to the tube. The mixture was treated as above except that after the standard was added, the solid solution plus the tube was placed in a flask fitted with a reflux condenser. Ether was added and the mixture was heated to reflux for at least one hour. After cooling, the ether solution was decanted into a separatory funnel and the residue washed four

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[8]For runs in which pivalic acid was used washing several times with sodium bicarbonate was not sufficient to remove all of the acid. Washing twice with a mixture of saturated sodium carbonate-dilute sodium hydroxide did adequately remove all of the acid. This method is to be preferred for removal of a carboxylic acid with a higher pK_a than acetic acid.

[9]Without inclusion of this last step, quantitative g.l.p.c. analysis was almost impossible in some solvent mixtures.

times with ether. The ether solutions were combined and treated as described above.

If the hydroxylic solvent was a solid at room temperature, a weighed quantity equivalent to 1.0 ml. of the solid (also calculated from the density of the compound at room temperature) plus weighed amounts of the compound to be solvolyzed and urea were placed in a constricted tube and 4.0 ml. of the nonhydroxylic solvent was added. The mixture was then treated as above for solutions of liquids.

After g.l.p.c. analysis of the olefinic components of the products from the solvolysis of 5-hexenyl p-nitrobenzenesulfonate in 80% nitrobenzene - 20% o-nitrobenzoic acid the low boiling compounds, olefins and ether, were removed under reduced pressure. To the remaining nitrobenzene solution of o-nitrobenzoate esters was added 5 ml. of 10% alcoholic potassium hydroxide and the mixture heated on a steam bath for 8 hours. After cooling ether was added, the solution washed with water, and dried over anhydrous magnesium sulfate. The resultant solution was then treated with excess pyridine and acetyl chloride (122), worked up as usual, and analyzed by g.l.p.c. for 5-hexenyl and cyclohexyl acetates.[10]

[10]Lithium aluminum hydride reductions are not applicable to preparation of solvolysis products for g.l.p.c. analysis when nitrobenzene is used as a solvent. Being in such a large excess, nitrobenzene is preferentially reduced.

The products from the solvolysis of 5-hexenyl and 6-heptenyl p-nitrobenzenesulfonate in trifluoroacetic acid were treated with 10% aquous sodium hydroxide at room temperature as described by Cope and Peterson (62) after preliminary analysis of the trifluoroacetate esters. It was found that pentyl acetate is also hydrolyzed under these conditions which indicates that analysis of the alcohols instead of the esters may be feasible in certain cases using the mild conditions described by Cope and Peterson.

In Table 30 is listed individual data from the solvolysis of 5-hexenyl p-nitrobenzenesulfonate in several solvents and solvent mixtures. The average deviation of the data in this table gives an indication of the precision of g.l.p.c. analysis obtained in this study.

Thermal conductivities and extraction ratios

The yields of the products were determined in all but a few cases by g.l.p.c. The areas of the product peaks were compared to the area of the standard peak, and the absolute yields of the products based on the average of at least three g.l.p.c. traces were calculated by use of experimentally determined relative thermal conductivity and extraction ratios. The values of these ratios are shown in Table 31. It was assumed that all olefinic products, including 1-methylcyclopentene, 1-methylcyclohexene, methylenecyclohexane, and cycloheptene, had a thermal conductivity equal to that of cyclohexene.

Table 30. Individual data from the solvolysis of 5-hexenyl p-nitrobenzenesulfonate at 100° in several solvents and solvent mixtures

Solvent		RONs mole/l.	Urea mole/l.	Reaction Time, hrs.	% Recovery
Acetic Acid		0.098	0.206	50	89
		0.099	0.212	50	89
		0.101	0.218	50	92
		0.102	0.244	50	89
	Average	0.100 ±0.002	0.220 ±0.012	50	90±1
20% Acetic Acid - 80% Nitrobenzene		0.098	0.208	50	85
		0.103	0.204	50	87
	Average	0.100 ±0.002	0.206 ±0.002	50	86±1
20% Acetic Acid - 80% 1-Chloro-4-Nitrobenzene		0.099	0.195	50	79
		0.107	0.228	50	80
		0.099	0.210	50	80
		0.098	0.204	50	81
	Average	0.101 ±0.003	0.209 ±0.009	50	80±1
Deuteroacetic Acid		0.100	0.218	24	79
		0.103	0.204	24	82
		0.100	0.204	24	81
	Average	0.101 ±0.001	0.209 ±0.006	24	81±1

Analysis			
1-Methyl-cyclo-pentene	Cyclo-hexene	Cyclohexyl Acetate	5-Hexenyl Acetate
1.0	13.2	31.3	54.5
0.8	13.3	31.1	54.8
1.0	13.1	31.2	54.7
0.9	13.1	30.9	55.1
0.9±0.1	13.2±0.1	31.1±0.1	54.8±0.2
2.2	39.6	18.7	39.5
2.2	39.5	18.7	39.6
2.2±0.05	39.6±0.1	18.7±0.05	39.5±0.1
1.7	29.9	17.9	50.5
1.7	29.3	16.8	52.2
1.7	30.8	16.5	51.0
1.7	32.2	16.4	49.7
1.7±0.05	30.6±1.0	16.9±0.5	50.8±0.8
0.2	6.8	22.2	70.8
0.2	6.5	22.4	70.9
0.2	6.5	22.2	71.1
0.2±0.05	6.6±0.1	22.3±0.1	70.9±0.2

Table 31. Thermal conductivities and extraction ratios of various compounds relative to pentyl acetate

Compound	Relative Thermal Conductivity[a]	Extraction Ratio[a]
Cyclohexene[b]	0.655	1.00[c]
5-Hexenyl Acetate[b]	1.096	1.00[c]
Cyclohexyl Acetate[b]	0.848	1.00[c]
5-Hexenyl Formate	0.953	-[d]
Cyclohexyl Formate	0.828	-[d]
5-Hexenyl Pivalate	1.248	-[d]
Cyclohexyl Pivalate	1.166	-[d]
Cyclohexyl Trifluoroacetate	1.043	1.00
Cyclohexyl 2,2,2-trifluoroethyl Ether[e]	1.128	1.18
Hexyl Acetate	0.961	-[d]
5-Hexenyl Iodide	1.000	-[d]
Pentenes[f]	0.604	-[d]
2-Pentyl Acetate	0.991	-[d]

[a]To calculate the thermal conductivity - extraction ratio multiply the two values. The numbers obtained were the average of at least three determinations. The average deviation was usually less than 0.5% of the value reported.

[b]The values reported here are for the thermal conductivities relative to pure pentyl acetate. Some early analyses were performed using pentyl acetate which contained approximately 5% pentanol. The values obtained for the relative thermal conductivity were then, cyclohexene, 0.690; cyclohexyl acetate, 0.894; and 5-hexenyl acetate, 1.155. Since the same pentyl acetate was used both for determination of thermal conductivities and for product analyses, no error was introduced into the values for actual yield of products.

[c]Extraction ratios were determined in acetic acid, 20% acetic acid - 80% nitrobenzene, and 20% acetic acid - 80% sulfolane. In all cases the extraction ratios were within 1% of being 1.00 and were assumed to be equal to 1.00 for all solvent mixtures.

[d]Assumed to be 1.00.

[e]Values are for workup using pentane as the solvent.

[f]Mixture of 1- and 2-pentenes.

Acetate products other than those given in Table 31 were assumed to have a thermal conductivity of 1.00. 5-Hexenyl bromide was assumed to have the same thermal conductivity as 5-hexenyl iodide. Ether products from the solvolysis of 6-heptenyl p-nitrobenzenesulfonate in 2,2,2-trifluoroethanol were given the thermal conductivity of the cyclohexyl trifluoroethyl ether.

Product analysis by n.m.r.

When solvolysis products were to be analyzed by n.m.r. methods, a minimal amount of carbon tetrachloride was substituted for ether and the mixture worked up as described above. After drying over anhydrous magnesium sulfate a standard was added, usually naphthalene, and dissolved in the mixture. The solution was then transferred to an n.m.r. tube and analyzed quantitatively by comparing the integral ratio per proton for product signal and standard signal.

Product Identification

Acetolysis of 5-hexenyl, hexyl, and cyclohexyl derivatives

Product identification was carried out, unless otherwise specified, by comparison of g.l.p.c. retention times and by peak enhancement of the product peaks by authentic samples. Pertinant gas chromatographic information is displayed in Table 32. Due to the small fraction of 1-methylcyclopentene formed during solvolysis of 5-hexenyl derivatives, this product could

Table 32. Calibration of gas chromatographic columns for products from the acetolysis of 5-hexenyl, hexyl, and cyclohexyl derivatives

Sample	Carbowax 20 M[a]	Ucon 50-Hb-2000[b]
1,5-Hexadiene	2.80	4.1
Unknown Number 1	3.20	5.5
Methylenecyclopentane	4.25	7.4
1-Methylcyclopentene	4.25	7.4
Cyclohexene	5.60	9.2
5-Hexenal	13.1	-
5-Hexenyl Bromide	15.5	-
Unknown Number 2	15.8	-
1-Methylcyclopentyl Acetate	16.2	-
Hexyl Acetate	16.8	-
Unknown Number 3	16.8	-
5-Hexenyl Acetate	17.5	-
Methyl 5-Hexenyl Sulfide	17.7	-
Cyclopentanemethyl Acetate	18.1	-
5-Hexenyl Iodide	18.0	-
Cyclohexyl Acetate	18.1	-
5-Hexen-1-ol	18.3	-
Pentyl Acetate	14.3	-
Methyl Acetate	5.6	-[g]
Ethyl Acetate	7.6	-
Butyl Acetate	13.4	-

[a]Injector temperature was 180°. Column temperature was 60° for 7 min., then programmed 10°/min. Helium flow was 40 ml./min.

[b]Injector temperature was 180°. Column temperature was 65°. Helium flow was 40 ml./min.

[c]Injector temperature was 200°. Column temperature given with retention times. Helium flow was 40 ml./min.

[d]Injector temperature was 175°. Column temperature was 41°. Helium flow was 45 ml./min.

[e]Injector temperature was 110°. Column temperature was 92°. Helium flow was 48 ml./min.

[f]Injector temperature was 175°. Column temperature was 155°. Helium flow was 60 ml./min.

[g]Comes under ether. Retention time is less than 3 min.

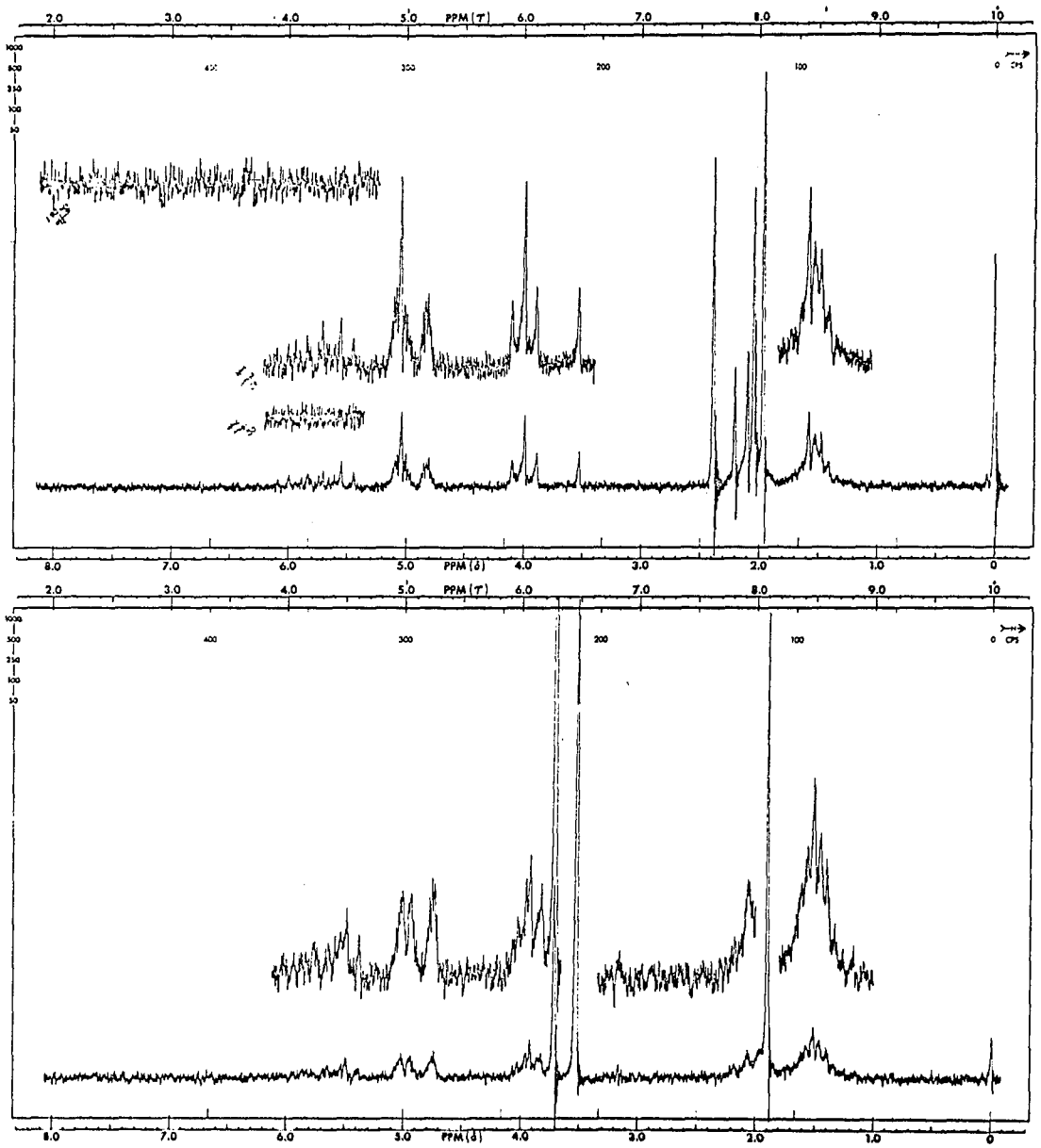
Retention Time, min.			
Diiso-decyl Phthalate[c]	β,β'-Oxy-dipropio-nitrile[d]	Glyceryl Tri-propionate[e]	Didecyl Phthalate[f]
-	-	-	-
-	-	-	-
2.9 (78°)	6.20	5.40	-
2.9 (78°)	5.60	5.10	-
3.6 (78°)	8.0	6.45	1.35
-	-	-	-
-	-	-	-
-	-	-	-
-	-	-	-
-	-	-	-
-	-	-	-
11.1 (150°)	-	-	6.45
-	-	-	-
14.4 (150°)	-	-	-
-	-	-	8.85
13.6 (150°)	-	-	8.05
-	-	-	-
5.60 (150°)	-	-	3.85
-	-	5.80	-
-	-	-	-
-	-	-	-

only be identified by g.l.p.c. Its presence was confirmed by retention times and peak enhancement on five different columns. Unknowns number 1,2, and 3 are present in the majority of acetolyses of 5-hexenyl derivatives. In acetic acid with urea as the base unknowns number 1,2, and 3 are formed in approximately 1.0, 0.4, and 0.6%, respectively. It is reasonable that unknown number 1 is a hexadiene which might have resulted from acid catalyzed isomerization of 1,5-hexadiene by the sulfonic acid before it was neutralized by urea; or, possibly, the tentatively identified hexadiene resulted from elimination after a hydride shift to the 1-position concurrent with removal of the sulfonate leaving group. The retention time of this unknown is only slightly greater than 1,5-hexadiene. A peak having the same retention time as 1,5-hexadiene was found in only one run of the acetolysis of 5-hexenyl p-nitrobenzenesulfonate using sodium acetate as the base. 1-Methylcyclopentyl and cyclopentylmethyl acetates if produced at all were present in trace quantities and could not be confirmed. Unknown number 2 may be an acyclic acetate isomeric with 5-hexenyl acetate formed by a route similar to that of unknown number 1. Unknown number 3 could possibly be hexyl acetate, which has the same retention time, and might arise from trace amounts of hexanol in the 5-hexen-1-ol used to prepare the sulfonate esters. In our analyses it was possible to detect less than 0.1% of a product.

The products from the solvolysis of 5-hexenyl p-nitrobenzenesulfonate in dimethyl sulfoxide - acetic acid were identified by g.l.p.c. and/or n.m.r. analysis. N.m.r. analysis showed the absence of cyclohexene, cyclohexyl acetate, and cyclopentylmethyl acetate, all of which were possible products as indicated by g.l.p.c. analysis. 5-Hexenal was produced from the p-nitrobenzenesulfonate ester of 5-hexen-1-ol by Maurice Gately in our laboratories using the usual conditions for the Kornblum reaction (47). Using this material the presence of the aldehyde as one of the products from the solvolysis reaction was confirmed by g.l.p.c. analysis. Dimethyl sulfide was identified by its characteristic odor and from an n.m.r. spectrum of the reaction products. A sample of 5-hexenyl p-nitrobenzenesulfonate was solvolyzed in 80% dimethyl sulfoxide - 20% acetic acid for 50 hours, the solution extracted in the usual way with a minimal volume of carbon tetrachloride, and an n.m.r. spectrum taken; the spectrum is shown in Figure 13. Singlets at 1.98δ and 2.4δ are due to acetate and dimethyl sulfide, respectively. No aldehyde proton was observed. Since only a minor amount of the aldehyde is formed it is practically impossible to detect this product by n.m.r. The vinyl protons, the methylene protons centered at 4.0δ and the singlet at 3.55δ integrate to 6.0:3.0:0.5. G.l.p.c. analysis shows the ratio of 5-hexenyl acetate to 5-hexen-1-ol to be approximately 5 to 1. Therefore, the singlet

Figure 13. N.m.r. spectrum of the products from the solvolysis of 5-hexenyl p-nitrobenzenesulfonate in 80% dimethyl sulfoxide - 20% acetic acid

Figure 14. N.m.r. spectrum of the products from the solvolysis of 5-hexenyl p-nitrobenzenesulfonate in 80% trimethyl phosphate - 20% acetic acid

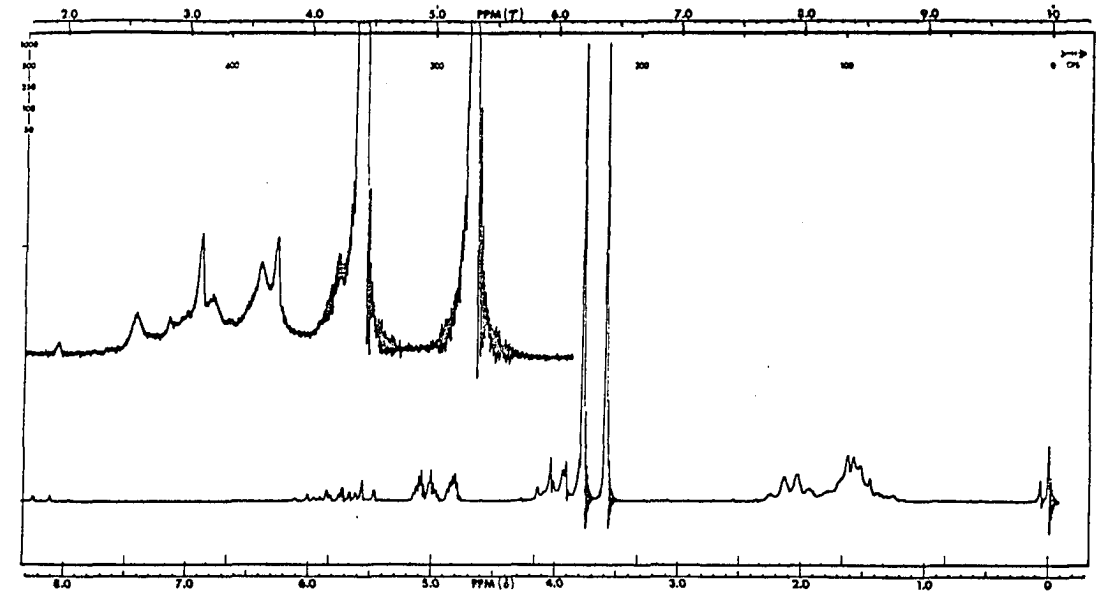

2.0
3.0
4.0
5.0
PPM (τ)
6.0
7.0
8.0
9.0
10
400
300
200
100
0 CPS
8.0
7.0
6.0
5.0
PPM (δ)
4.0
3.0
2.0
1.0
0

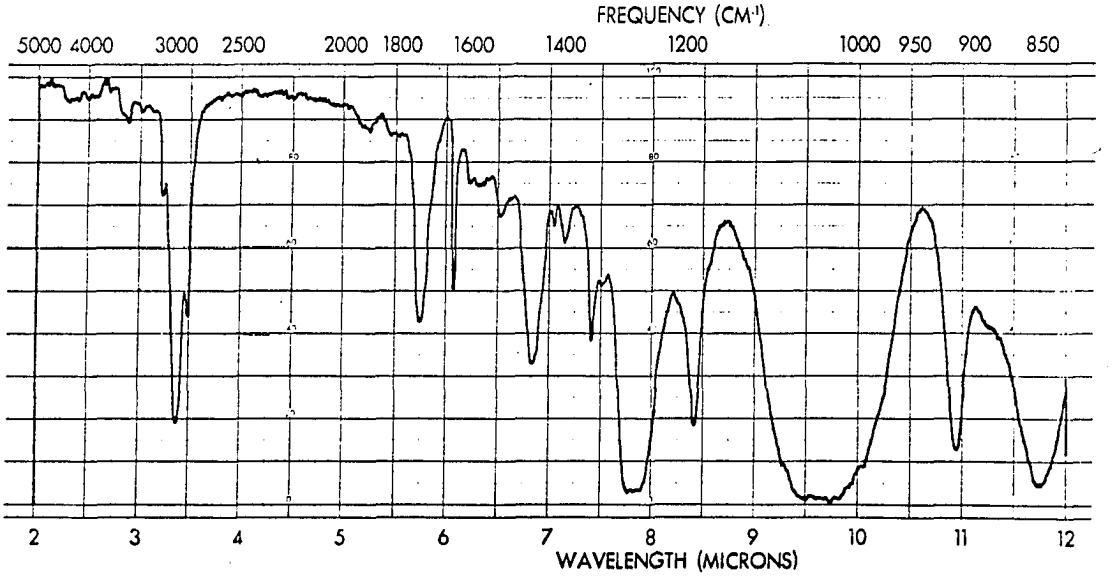
at 3.55δ could not be the hydroxyl proton and is more likely due to methyl acetate. From Figure 13 75% of the vinyl proton resonance can be accounted for as coming from 5-hexenyl acetate and 5-hexen-1-ol, leaving 25% of the 5-hexenyl moiety unaccounted for. If 5-hexenyl methyl sulfide is the remaining product, signals at 2.04, 2.10, and 2.2δ can be accounted for, the methylene triplet being centered at 2.04δ partially obscured by the singlet at 1.98δ.

In addition to g.l.p.c. analysis of the products from the solvolysis of 5-hexenyl p-nitrobenzenesulfonate in 20% acetic acid - 80% trimethyl phosphate, n.m.r. analysis was used to confirm the presence of methyl acetate and 5-hexenyl dimethyl phosphate. Figure 14 shows the n.m.r. spectrum of solvolysis products after extraction with a minimal volume of carbon tetrachloride. Sharp singlets at 1.95 and 3.60δ which integrate closely 1:1 strongly indicate the presence of methyl acetate. Production of this product was also confirmed by g.l.p.c. analysis. Upon removal of all low boiling products under reduced pressure a clear, slightly discolored oil remains. The n.m.r. and i.r. spectra of this liquid are shown in Figures 15 and 16, respectively. These spectra are most reasonably interpreted as those of 5-hexenyl dimethyl phosphate. The absence of any suitable resonance at 5.8δ (cyclohexene vinyl protons) in Figure 14 indicates cyclohexene is not present in any appreciable amount. No g.l.p.c. peaks or n.m.r.

Figure 15. N.m.r. spectrum of 5-hexenyl dimethyl phosphate

Figure 16. I.r. spectrum of 5-hexenyl dimethyl phosphate


2.0
3.0
4.0
5.0
PPM (τ)
6.0
7.0
8.0
9.0
10
8.0
7.0
6.0
5.0
PPM (δ)
4.0
3.0
2.0
1.0
0


FREQUENCY (CM-1)
5000 4000
3000
2500
2000
1800
1600
1400
1200
1000
950
900
850
2
3
4
5
6
7
8
9
10
11
12
WAVELENGTH (MICRONS)

signals were observed that would correspond to 5-hexenyl methyl ether. Although trimethyl phosphate is quite soluble in aqueous solutions and can be removed from the solvolysis products in this way, 5-hexenyl dimethyl phosphate is more soluble in diethyl ether or carbon tetrachloride and can be separated from trimethyl phosphate by simply washing with water.

From the solvolysis of 5-hexenyl p-nitrobenzenesulfonate in 20% acetic acid - 80% γ-butyrolactone significant amounts of two compounds were observed during g.l.p.c. analysis which were not present in the γ-butyrolactone solvent. Approximately 0.3 minutes after cyclohexyl acetate comes off the Carbowax 20M column a broad peak which tails is seen in an amount twice that of cyclohexyl acetate. A product with the same retention time is also observed for the corresponding solvolysis of hexyl p-nitrobenzenesulfonate. Another product is observed approximately 4 minutes after γ-butyrolactone comes off the column at 225°. This compound is produced in roughly the same yield as cyclohexyl acetate.

In triphenyl phosphite - acetic acid mixtures approximately 1% 1,5-hexadiene is formed in the solvolysis of 5-hexenyl p-nitrobenzenesulfonate. Other unidentified products were observed in this case as well as from solvolyses in benzil-acetic acid and in dibenzyl ether - acetic acid.

Formolysis of 5-hexenyl p-nitrobenzenesulfonate

For authentic samples of the possible formolysis products, retention times were observed as shown in Table 33.[11] 1,5-Hexadiene was not observed, nor were any compounds containing 5-membered rings. The structure of the unknown olefin may correspond to a hexadiene. However, this olefin does not have the same retention time as unknown number 1 in Table 32 and is observed only when Carbowax 20M columns are used. Because cyclopentylmethyl formate has the same retention time as does cyclohexyl formate on two different columns, its presence or absence could not be definitely determined. The fact that no other products containing 5-membered rings were formed, however, points to its absence.

Solvolysis of 5-hexenyl p-nitrobenzenesulfonate in pivalic acid, mixed carboxylic acids, and acetolysis of 2-pentyl derivatives

For authentic samples of the solvolysis products, retention times were observed as shown in Table 34. Pentenes were assumed to contain the same composition of 1- and isomeric 2-pentenes as found by Brown (94). 2-Pentyl acetate was

[11] 1,5-Hexyl diformate was not identified in this way. Knowing this product to be present from n.m.r. analysis of the solvolysis products a peak was observed by g.l.p.c. analysis and was assigned 1,5-hexyl diformate. The odor of this compound was characteristically that of an ester.

Table 33. Calibration of gas chromatographic columns for products from the formolysis of 5-hexenyl p-nitrobenzenesulfonate

Sample	Retention Time, min.			
	Glyceryl Tri-propionate[a]	Didecyl Phthalate[b]	SE-30[c]	Carbowax 20 M[d]
1,5-Hexadiene	2.55	-	5.65	2.40 (75°)
Unknown Olefin	-[e]	-	-[e]	3.20 (75°)
1-Methylcyclopentene	3.35	-	7.70	3.20 (75°)
Cyclohexene	4.15	1.55	9.75	4.30 (75°)
1-Methylcyclopentyl Formate	-	5.80	-	3.10 (151°)
5-Hexenyl Formate	-	5.65	-	3.40 (151°)
Cyclohexyl Formate	-	7.60	-	4.40 (151°)
Cyclopentylmethyl Formate	-	7.60	-	4.40 (151°)
1,5-Diformatohexane	-	-	-	2.70 (230°)
Pentyl Acetate	-	4.60	-	2.30 (151°)

[a]Injector temperature was 150°. Column temperature was 92°. Helium flow was 50 ml./min.

[b]Injector temperature was 175°. Column temperature was 151°. Helium flow was 50 ml./min.

[c]Injector temperature was 175°. Column temperature was 30°. Helium flow was 90 ml./min.

[d]Injector temperature was 203°. Column temperature given with retention times. Helium flow was 25 ml./min.

[e]Not observed in quantity seen on Carbowax 20 M columns. Probably comes under the ether peak.

not separable from 3-pentyl acetate on Carbowax 20 M columns. When mixtures of formic acid - acetic acid or formic acid - pivalic acid were used for the solvolysis of 5-hexenyl p-nitrobenzenesulfonate, 1,5-disubstituted hexane was observed by n.m.r. analysis. It was not determined whether this product represented a mixture of esters or was composed entirely of 1,5-hexyl diformate.

Solvolysis of 5-hexenyl p-nitrobenzenesulfonate in 2,2,2-trifluoroethanol and trifluoroacetic acid

Pertinent gas chromatographic information concerning the products from the solvolysis of 5-hexenyl p-nitrobenzenesulfonate in 2,2,2-trifluoroethanol is shown in Table 35. Cyclohexyl 2,2,2-trifluoroethyl ether, formed in this solvolysis, was further identified from an n.m.r. spectrum of the products after removal of the low-boiling compounds, olefins and ethyl ether, under reduced pressure. The spectrum of the cyclohexyl 2,2,2-trifluoroethyl ether formed in the solvolysis reaction was identical to that shown in Figure 8. The 5-membered ring olefin was assumed to be methylenecyclopentane and not 1-methylcyclopentene because of the low acidity of the solvent (65); in trifluoroethanol acid catalyzed conversion of methylenecyclopentane to 1-methylcyclopentene is improbable. Unknown number 1 is actually at least two compounds as shown by g.l.p.c. analysis at lower column temperatures.

For the products from the solvolysis of 5-hexenyl

Table 34. Calibration of gas chromatographic columns for products from the solvolysis of 5-hexenyl p-nitrobenzenesulfonate in pivalic acid and mixed carboxylic acids and from the acetolysis of 2-pentyl derivatives

Sample	Retention Time, min.		
	Didecyl Phthalate[a]	Carbowax 20 M[b]	Carbowax 20 M[c]
Unknown Number 1	2.40 (100°)	-	-
1-Methylcyclopentene	3.05 (100°)	-	-
Cyclohexene	3.55 (100°)	-	-
5-Hexenyl Formate	3.40 (175°)	3.85	-
Cyclohexyl Formate	4.55 (175°)	5.00	-
5-Hexenyl Acetate	4.35 (175°)	4.50	-
Cyclohexyl Acetate	5.35 (175°)	5.45	-
5-Hexenyl Pivalate	8.00 (175°)	-	-
Cyclohexyl Pivalate	9.90 (175°)	-	-
Pentyl Acetate	2.80 (175°)	2.60	4.75 (120°)
Pentenes	-	-	1.45 (50°)
2-Pentyl Acetate	-	-	3.15 (120°)
3-Pentyl Acetate	-	-	3.15 (120°)

[a]Injector temperature was 175°. Column temperature given with retention times. Helium flow was 50 ml./min.

[b]Injector temperature was 190°. Column temperature was 153°. Helium flow was 50 ml./min.

[c]Injector temperature was 180°. Column temperature given with retention times. Helium flow was 40 ml./min.

Table 35. Calibration of gas chromatographic columns for products from the solvolysis of 5-hexenyl p-nitrobenzenesulfonate in 2,2,2-trifluoroethanol

Sample	Retention Time, min. Carbowax 20 M[a]
Methylenecyclopentane	3.20 (75°)
Cyclohexene	4.30 (75°)
Unknown Number 1[b]	1.50 (110°)
Unknown Number 2	1.80 (110°)
Unknown Number 3	2.15 (110°)
Cyclohexyl 2,2,2-Trifluoroethyl Ether	2.70 (110°)
Pentyl Acetate	3.70 (110°)

[a]Injector temperature was 180°. Column temperature given with retention times. Helium flow was 50 ml./min.

[b]Actually two products. At lower column temperatures two peaks are observable.

p-nitrobenzenesulfonate in trifluoroacetic acid gas chromatographic information is given in Table 36. Cyclohexyl trifluoroacetate was further identified by an n.m.r. spectrum of the solvolysis mixture and through conversion of the trifluoroacetate products to the corresponding alcohols by basic hydrolysis (62). Peaks number 1 and 2 may correspond to cyclic products or may be due to partial decomposition of cyclohexyl trifluoroacetate in the injector port during g.l.p.c. analysis, since after basic hydrolysis the unknown products did not correspond to either 1-methylcyclopentanol or cyclopentylcarbinol. However, peaks number 3 and 4, observed after hydrolysis, may be unreacted trifluoroacetate. Another product, peak number 5, was also observed after hydrolysis.

Table 36. Calibration of gas chromatographic columns for products from the solvolysis of 5-hexenyl p-nitrobenzenesulfonate in trifluoroacetic acid

Sample	Retention Time, min.	
	Carbowax 20 M[a]	Carbowax 20 M[b]
Peak Number 1	1.80	-
Peak Number 2	2.00	-
Cyclohexyl Trifluoroacetate	2.65	-
Pentyl Acetate	4.70	2.05
Peak Number 3	-	1.00
Peak Number 4	-	1.15
Peak Number 5	-	4.95
1-Pentanol	-	3.10
Cyclohexanol	-	6.65
5-Hexen-1-ol	-	6.65
1-Methylcyclopentanol	-	3.10
Cyclopentylcarbinol	-	7.90

[a]Injector temperature was 150°. Column temperature was 110°. Helium flow was 40 ml./min.

[b]Injector temperature was 215°. Column temperature was 129°. Helium flow was 40 ml./min.

In addition, 5-trifluoroacetohexyl-1-p-nitrobenzenesulfonate was formed in this solvolysis. This product was identified from the n.m.r. spectrum of the solvolysis products: the characteristic A_2B_2 pattern of the p-nitrobenzenesulfonate group, distinctly visible and centered at 8.2δ, the triplet at 4.1δ for the methylene group attached to the leaving group, and a doublet centered at 1.35δ for the methyl hydrogens adjacent to the methine group in the 5-position. The methine hydrogen for this product is buried under the signal for the

methine hydrogen of cyclohexyl trifluoroacetate. The spectrum of 5-trifluoroacetohexyl-1-p-nitrobenzenesulfonate closely resembles the spectrum of the higher homolog shown in Figure 19.

Solvolysis of 6-heptenyl p-nitrobenzenesulfonate in 2,2,2-trifluoroethanol and in 20% o-nitrobenzoic acid - 80% nitrobenzene

Products from the solvolysis of 6-heptenyl p-nitrobenzenesulfonate were observed by g.l.p.c. analysis as shown in Table 37. Unknowns 1,2, and 3 are probably acyclic heptadienes. For authentic samples of cyclic olefins retention times showed complete separation on five different columns. Unknowns 5 and 6 were observed from the solvolysis in 2,2,2-trifluoroethanol and may be the cyclic products, cyclohexylmethyl and 1-methylcyclohexyl 2,2,2-trifluoroethyl ethers. 6-Heptenyl 2,2,2-trifluoroethyl ether was not independently prepared but was identified from an n.m.r. spectrum of the solvolysis products plus the pentyl acetate standard, shown in Figure 17. Only the olefinic products were identified when 6-heptenyl p-nitrobenzenesulfonate was solvolyzed in 20% o-nitrobenzoic acid - 80% nitrobenzene.

Solvolysis of 6-heptenyl p-nitrobenzenesulfonate in trifluoroacetic acid

Analysis of the products from the solvolysis of 6-heptenyl derivatives in trifluoroacetic acid presents some difficulty.

Table 37. Calibration of gas chromatographic columns for products from the solvolysis of 6-heptenyl p-nitrobenzenesulfonate in 2,2,2-trifluoroethanol and in 20% o-nitrobenzoic acid - 80% nitrobenzene

Sample	Carbowax 20 M[a]
Unknown Number 1[f]	2.35 (93°)
Unknown Number 2[f]	-
Unknown Number 3	2.65 (93°)
Methylenecyclohexane	3.30 (93°)
1-Methylcyclohexene	4.10 (93°)
Cycloheptene	4.80 (93°)
Unknown Number 4[g]	5.20 (93°)
Cyclohexene	3.70 (93°)
Pentyl Acetate	1.65 (125°)
6-Heptenyl 2,2,2-Trifluoroethyl Ether	1.45 (125°)
Cycloheptyl 2,2,2-Trifluoroethyl Ether	2.15 (125°)
Unknown Number 5	1.10 (125°)
Unknown Number 6	-

[a]Injector temperature was 180°. Column temperature given with retention times. Helium flow was 70 ml./min.

[b]Injector temperature was 175°. Column temperature was 75°. Helium flow was 60 ml./min.

[c]Injector temperature was 185°. Column temperature was 95°. Helium flow was 55 ml./min.

[d]Injector temperature was 165°. Column temperature was 48°. Helium flow was 55 ml./min.

[e]Injector temperature was 175°. Column temperature given with retention times. Helium flow was 65 ml./min.

[f]Only observed on didecyl phthalate columns.

[g]Only observed from solvolysis of 6-heptenyl p-nitrobenzenesulfonate in 20% o-nitrobenzoic acid - 80% nitrobenzene.

Retention Time, min.			
Ucon 50-Hb-2000[b]	Glyceryl Tripropionate[c]	1,2,3-Tris-(2-Cyanoethoxy)-Propane[d]	Didecyl Phthalate[e]
3.10	4.30	2.00	1.90 (120^0)
-	-	-	2.40 (120^0)
3.40	4.65	2.00	2.80 (120^0)
5.35	5.80	2.70	3.45 (120^0)
6.50	6.90	3.65	4.00 (120^0)
7.75	8.10	4.50	4.65 (120^0)
-	-	-	-
-	-	-	-
8.95	-	-	2.80 (165^0)
-	-	-	3.15 (165^0)
-	-	-	4.75 (165^0)
-	-	-	2.50 (165^0)
-	-	-	5.80 (165^0)

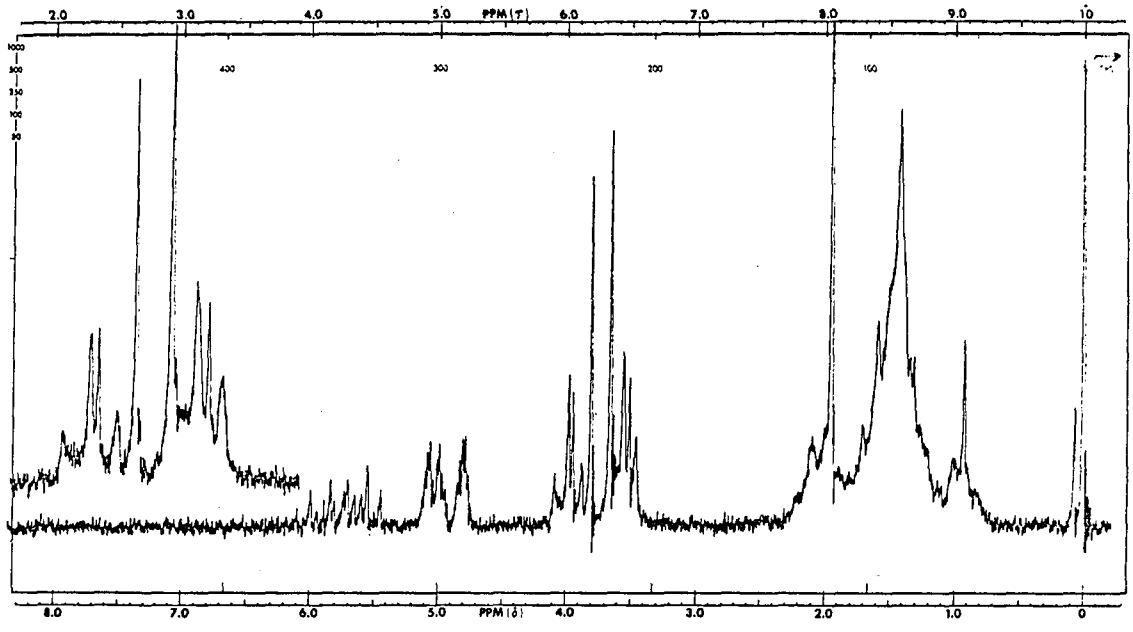


Figure 17. N.m.r. spectrum of 6-heptenyl 2,2,2-trifluoroethyl ether formed in the solvolysis of 6-heptenyl p-nitrobenzenesulfonate with 2,2,2-trifluoroethanol, plus pentyl acetate added as a standard

Cycloheptyl and 1-methylcyclohexyl trifluoroacetates are not stable to the conditions used for g.l.p.c. analysis. When injected into the gas chromatograph, cycloheptyl trifluoroacetate shows a peak with a retention time identical to that of methylenecyclohexane. Although cycloheptanol is stable under the conditions used for g.l.p.c. analysis, 1-methylcyclohexanol is not and partially decomposes. Therefore, since quantitative analysis was not feasible by g.l.p.c. the products were analyzed by n.m.r. methods quantitatively and the results qualitatively confirmed by g.l.p.c.

The products from the solvolysis of 6-heptenyl p-nitrobenzenesulfonate were worked up in the usual way using pentane as the solvent. Pentane was used because 6-trifluoroacetoheptyl-1-p-nitrobenzenesulfonate is quite soluble in ethyl ether and carbon tetrachloride and obstructs the n.m.r. signals due to cycloheptyl trifluoroacetate. Pentane was removed under reduced pressure and a minimal amount of carbon tetrachloride added. To this solution a measured amount of naphthalene was added as a standard. An n.m.r. spectrum was taken and is shown in Figure 18. The spectrum clearly shows signals due to 6-trifluoroacetoheptyl-1-p-nitrobenzenesulfonate and does show the methine hydrogen of cycloheptyl trifluoroacetate which, however, comes at the same position as the methine hydrogen of the open-chain trifluoroacetate. Subtracting the integral due to the open trifluoro-

acetate from the total integral at 5.0δ gives the integral due to cycloheptyl trifluoroacetate, which when compared to the standard gives the actual yield of this cyclic product. When the integral due to cycloheptyl trifluoroacetate and 6-trifluoroacetohexyl-1-p-nitrobenzenesulfonate is subtracted from the total integral of the normal aliphatic signal a large portion of the aliphatic signal is unaccounted for. If the singlet at 1.49δ is due to 1-methylcyclohexyl trifluoroacetate, which is reasonable from comparison of the n.m.r. spectra similar compounds, then the entire spectrum integral can be explained.

The aqueous solution resulting after extraction with pentane was washed twice with ethyl ether, the organic solution passed through anhydrous magnesium sulfate, and the ether removed under reduced pressure to give a light colored solid. This solid was dissolved in a minimal amount of carbon tetrachloride and an n.m.r. spectrum taken. The spectrum of this solid is shown in Figure 19 which confirms the structure of this compound as being 6-trifluoroacetoheptyl-1-p-nitrobenzenesulfonate. The integration of n.m.r. signals is as expected for this sulfonate ester.

The presence of cycloheptyl and 1-methylcyclohexyl products was confirmed by basic hydrolysis of the trifluoroacetates to the corresponding alcohols. Retention times for authentic samples were observed as shown in Table 38. The

Figure 18. N.m.r. spectrum of the products from the solvolysis of 6-heptenyl p-nitrobenzenesulfonate in trifluoroacetic acid, plus naphthalene added as a standard

Figure 19. N.m.r. spectrum of 6-trifluoroacetoheptyl-1 p-nitrobenzenesulfonate

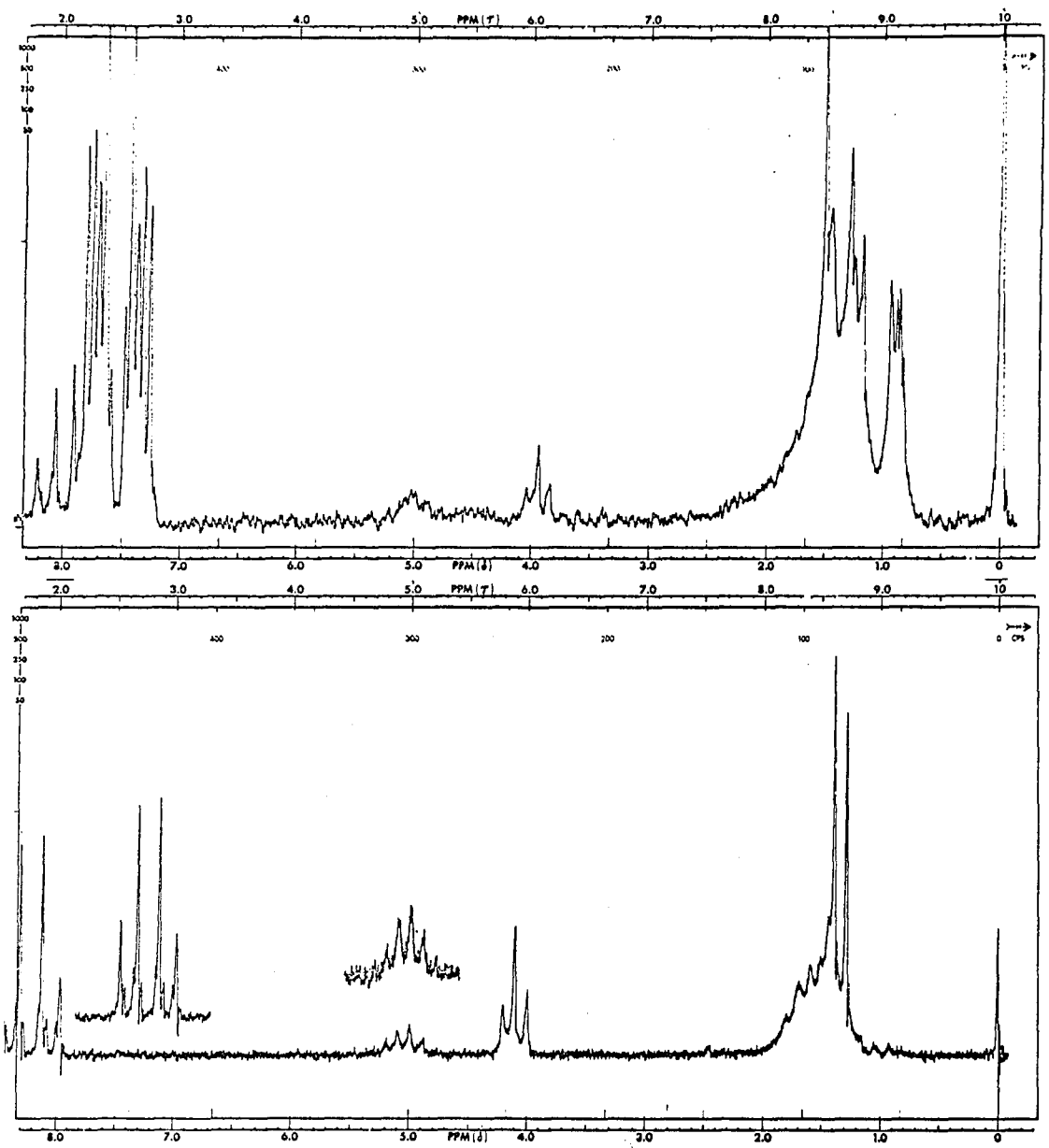

2.0
3.0
4.0
5.0
PPM (τ)
6.0
7.0
8.0
9.0
10
8.0
7.0
6.0
5.0
PPM (δ)
4.0
3.0
2.0
1.0
0

Table 38. Calibration of gas chromatographic columns for products from the solvolysis of 6-heptenyl p-nitrobenzenesulfonate in trifluoroacetic acid

Sample	Retention Time, min.		
	Carbowax 20 M[a]	Didecyl Phthalate[b]	Diethylene Glycol Succinate[c]
1-Methylcyclohexanol	2.35	1.85	1.50
Cycloheptanol	5.55	8.20	3.40
Cyclohexylcarbinol	5.60	7.90	3.05
Cycloheptyl Trifluoroacetate	1.50	-	-

[a]Injector temperature was 205°. Column temperature was 156°. Helium flow was 45 ml./min.

[b]Injector temperature was 195°. Column temperature was 170°. Helium flow was 45 ml./min.

[c]Injector temperature was 185°. Column temperature was 150°. Helium flow was 45 ml./min.

presence of cycloheptanol and 1-methylcyclohexanol from the solvolysis mixture was detected on three different columns. The peak area of 1-methylcyclohexanol was at least twice as large as that of cycloheptanol confirming the quantitative analysis by n.m.r. which showed that the 7-membered ring cyclic product was formed in 9% yield and the 6-membered ring in 19% yield. Cyclohexylcarbinol was not detected by either n.m.r. or g.l.p.c. analysis. At no time was a product corresponding to 1,6-hexyl ditrifluoroacetate found during either n.m.r. or g.l.p.c. analysis even though this product was carefully looked for.

SUMMARY

Acetolysis of 5-hexenyl p-nitrobenzenesulfonate in the presence of the base urea has been previously shown to lead to open product, 5-hexenyl acetate, and cyclic products, cyclohexyl acetate, cyclohexene, and 1-methylcyclopentene. These two sets of products may be considered to be the result of a) external nucleophilic attack by the solvent, acetic acid, to give open product and b) internal nucleophilic attack by the olefin to give cyclic products. The yields of products from the solvolysis of 5-hexenyl p-nitrobenzenesulfonate and other 5-hexenyl derivatives in binary solvent mixtures were determined. For solvolyses in 20% acetic acid - 80% nonhydroxylic solvent mixtures polar solvents, such as nitrobenzene, lead to the greatest amount of cyclization while nonpolar solvents decrease the yield of cyclic products relative to acetic acid. When the percent composition of acetic acid - nonhydroxylic solvent mixtures is varied an increase in the yield of cyclic products can be explained as specific solvation of acetic acid. Variation of the hydroxylic component of binary solvent mixtures indicates that hydrogen bonding is a major determinant in effecting changes in the amount of cyclic products formed and that the carboxylic acid dimer is more nucleophilic than the monomer. When the leaving group is varied changes in the yield of cyclic products occur which must be due

to the effect of the leaving group on the transition states leading to open and cyclic products since the leaving group is in both ground states. These results are analyzed and discussed with respect to solvent nucleophilicity. The mechanism for formation of cyclohexene from 5-hexenyl derivatives is also dealt with.

Solvolysis of 6-heptenyl p-nitrobenzenesulfonate in 2,2,2-trifluoroethanol led to a 14% recovered yield of cyclic products, cycloheptyl 2,2,2-trifluoroethyl ether, cycloheptene, methylenecyclohexane, and 1-methylcyclohexene. Solvolysis of this same sulfonate ester in trifluoroacetic acid gave 19% 1-methylcyclohexyl trifluoroacetate, 9% cycloheptyl trifluoroacetate, 50-70% 6-trifluoroacetoheptyl-1 p-nitrobenzenesulfonate, and no product of direct displacement by trifluoroacetic acid. The nucleophilic reactivity of 2,2,2-trifluoroethanol was calculated to be 46 times less than acetic acid while that of trifluoroacetic acid was at least 100 times less than 2,2,2-trifluoroethanol.

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