Solvents of Low Nucleophilicity. VI. The Effects of Remote Substitutents in the Addition of Trifluoroacetic Acid to Aliphatic, Cyclic, and Bicyclic Alkenes[1a]

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A study of the rates of addition of trifluoroacetic acid to terminally substituted 1-alkenes was carried out for alkenes having chains of four to eleven carbon atoms. Among several inductive substituents examined, the cyano and trifluoroacetoxy groups were notable in giving significant rate depressions for all alkenes in the series, including the 11-substituted 1-undecenes. The more remote of these substituents are several carbon atoms farther removed from the reaction site than substituents previously observed to produce measurable inductive effects in aliphatic compounds. The rates of reaction are remarkably well correlated by the assumption that the substituent effect is attenuated by a constant factor per methylene group, although our attenuation factor (0.65) represents an unusually small attenuation with increasing distance. 5-Methoxy-1-pentene and, more notably, 5-halo-1-pentenes show deviations from the expected inductive effects attributable to substituent participation. Oxygen- and nitrogen-containing substituents show marked enhancement of inductive effects, attributable to hydrogen bonding of the substituent to trifluoroacetic acid. In order to assess the effect of substituents in systems of semirigid or rigid geometry we studied the addition of trifluoroacetic acid to several 4-vinylcyclo-hexanemethyl derivatives and bicyclo[4.3.0]non-3-en-8-yl derivatives. Rate effects similar to those found in the aliphatic series were observed, indicating that large rate effects are in fact characteristic of substituents which are remote from the reaction site.

Introduction

The effects of substituents as far removed as ten carbon atoms from the reaction site upon the rate of reaction of trifluoroacetic acid with terminally substituted 1-alkenes (eq. 1) have been reported by two of

$$CH_2=CH(CH_2)_{n-2}X + CF_3CO_2H \longrightarrow CH_3CH(CH_2)_{n-2}X \quad (1)$$
$$\underset{O_2CCF_3}{|}$$
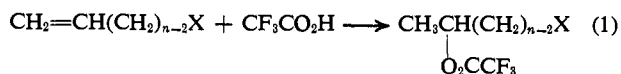
n = 5 to 11 (extended to n = 4 in the present study)

us in a preliminary communication.[2] Previously, similar large effects of moderately remote substituents had been reported.[3] These findings presented us with an unusual opportunity to extend studies of substituent effects to a wide variety of molecules containing substituents previously regarded as too remote to influence reactivity. Our initial task was to define the range of structures available for study. The present paper re-

ports such a study in which particular attention has been given to the attenuation of the substituent effect with distance for several substituents.

The concomitant variation of both the nature of the substituent and its distance from the reaction center involved determinations of the rates of reaction of more than 40 alkenes in the aliphatic series (*cf.* Table I).

Table I. Rates of Addition of Trifluoroacetic Acid to Alkenes $CH_2=CH(CH_2)_{n-2}X$, at 60°[a]

n	H	O_2CCF_3	CN	O_2CCH_3	Cl	OCH_3
4	1200[b]	0.263	...	2.62	2.85	4.57
5	1140	7.30	5.33	29.1	217	185
6	1470	45.6	23.8	90.0	175	205
7	1540	166	110	249	308	293
8	1680	377	298	582	708	568
9	1640	655	...	...	853	951
10	1840	1030	...	...	...	...
11	1590	1060	983	...	1250	...

[a] $k \times 10^6$, sec.$^{-1}$, X as indicated. [b] Calculated from rate constants measured at 0, 25, and 45°. The respective values of $k \times 10^6$ were 7.71, 80.6, and 407, from which the following activation parameters were calculated: $\Delta H^* = 14$ kcal./mole, $\Delta S^* = -28$ e.u. Additional rate constants ($k \times 10^6$, sec.$^{-1}$) are: 4-bromo-1-butene, 2.80; 5-bromo-1-pentene, 177; 6-bromo-1-hexene, 156; 4-penten-1-yl p-nitrobenzoate, 11.6; 5-hexen-1-yl p-nitrobenzoate, 59.8.

What was the justification for undertaking an extended study of homologous compounds? The initial rate results involving the addition of trifluoroacetic acid to substituted alkenes constituted a complex, and, at first, confusing picture, although several interpretations were eventually developed to explain the main features of the early studies, which involved principally 5-substituted 1-hexenes.[3] In the present work these novel features of our reaction system which include (1) an unusually slow falloff of the inductive effect with distance between the substituent and the reaction center, (2) substituent participation, including halogen participation, and (3) solvent enhancement of the inductive effect due to hydrogen bonding, are, we believe, convincingly disentangled. To this extent, substituent effects exhibited by reactions in trifluoroacetic acid may now be said to be understood, although the fundamental origin of substituent effects in general remains a subject of controversy.[4]

Procedure and Results

Synthesis. Fortunately, the substituted alkenes needed for our study are among the most readily available of difunctional compounds. The absence of previous extensive studies of inductive effects in carbonium

(1) (a) Supported in part by National Science Foundation Grants G-20904 and G-2917 and in part by a grant-in-aid from the Allied Chemical Corporation. (b) National Science Foundation undergraduate research participant.
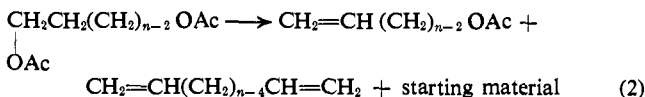(2) P. E. Peterson and C. Casey, *Tetrahedron Letters*, 1569 (1963).
(3) P. E. Peterson and G. Allen, *J. Am. Chem. Soc.*, **85**, 3608 (1963).
(4) S. Ehrenson, *Progr. Phys. Org. Chem.*, **2**, 195 (1964).

ion forming reactions in the aliphatic series may, in fact, reflect synthetic difficulties. Such studies might have used substituted secondary tosylates, CH_3-$CHOTs(CH_2)_{n-2}X$ whose synthesis is difficult compared to the synthesis of the alkene having the same carbon skeleton. For example, the synthesis of secondary alcohols *via* the substituted alkene, involving addition of HX to the double bond, is complicated by possible double-bond migration. Mixtures of products may ultimately be produced, as in the addition of trifluoroacetic acid to 6-chloro-1-hexene which gave a product containing considerable 6-chloro-3-hexyl trifluoroacetate.

In the case of substituted alkenes having a chain of 7, 8, 9, or 10 carbon atoms we resorted to partial acetate pyrolysis (eq. 2) as the key step in the syntheses, since there seemed to be no way to avoid the statistical loss associated with partial reaction of the symmetrical precursors available in these series. The course of

$$CH_2CH_2(CH_2)_{n-2} OAc \longrightarrow CH_2=CH (CH_2)_{n-2} OAc +$$
$$\overset{|}{OAc}$$

$$CH_2=CH(CH_2)_{n-4}CH=CH_2 + \text{starting material} \qquad (2)$$

reaction was followed by temperature-programmed gas chromatography, which enabled us to optimize the yield of monoacetate by repeated readjustment of the pyrolysis temperature. The monoacetates were used directly in rate studies and were also used as the source of other substituted alkenes.

For comparison with the aliphatic alkenes mentioned above, we synthesized two additional series of substituted alkenes having cyclic and bicyclic structures, respectively. Several 4-vinylcyclohexanemethyl derivatives were prepared from 4-vinylcyclohexanemethanol, which was obtained in only two steps (eq. 3 and 4),

$$\qquad (3)$$

$$\qquad (4)$$
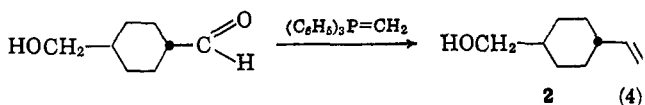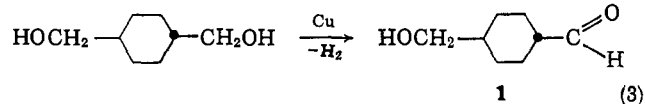
although in low yield. The dehydrogenation step 3 was carried out in the acetate pyrolysis apparatus, except that the packing was replaced with prereduced copper oxide wire.[5] Distillation in a spinning-band column gave the glassy monoaldehyde (which possibly solidified as a polymeric hemiacetal) which underwent a successful Wittig reaction, using Corey and Chaykovsky's modification.[6]

Bicyclo[4.3.0]non-3-ene derivatives were prepared by a sequence similar to that reported in the literature (Scheme I). In our work the starting *trans* diester 3 was obtained almost free of *cis* diester by careful spinning-band distillation, leading to a crystalline ditosylate of improved quality. The amount of *cis* diester initially present was shown by gas chromatography on a capillary column to represent the equilibrium concentration in the preparation of the *trans* diester by equilibration of the *cis* diester.

(5) *Cf.* E. Allison and R. Gorsich, *J. Chem. Educ.*, **32**, 209 (1955).

(6) (a) E. J. Corey and M. Chaykovsky, *J. Am. Chem. Soc.*, **84**, 866 (1962); (b) M. Chaykovsky and E. J. Corey, *J. Org. Chem.*, **28**, 254 (1963).

Scheme I. Synthesis of *Bicyclo[4.3.0.]non-3-enes*
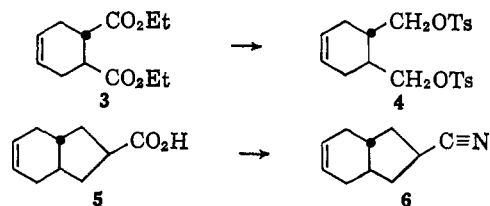
Product Studies. Based on previous work[3] the reaction of trifluoroacetic acid with the substituted alkenes of the present study may be assumed to proceed predominantly by ordinary Markovnikov addition, as in eq. 1, except for the reaction involving vinylcyclohexanes. In the latter reactions the rate-determining step might involve a hydride shift to give a tertiary carbonium ion, as shown for vinylcyclohexane itself (Scheme II).

Scheme II. Reaction of Vinylcyclohexane with Concomitant Hydrogen Shift
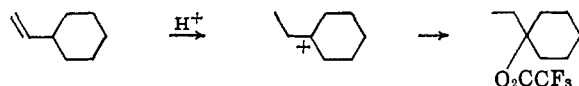
1-Ethylcyclohexyl trifluoroacetate would be the sole reaction product from this process, whereas a process involving no hydrogen participation or migration *via* a 1,2 shift in the initially formed ion would give this product only to the extent that double-bond rearrangement occurs (*cf.* Scheme III, which shows the result of double-bond migration).

Scheme III. Reaction of Vinylcyclohexane with Partial Double-Bond Migration
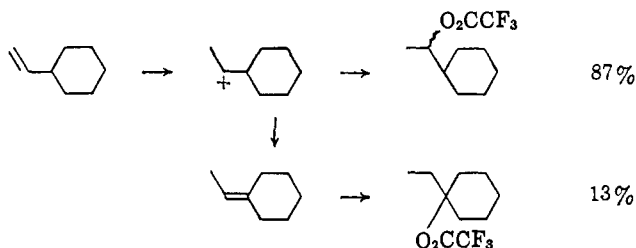
A gas chromatographic analysis of the reaction products gave the results shown in Scheme III. Only 13% of the tertiary trifluoroacetate is formed. This result is readily accommodated by Scheme III (involving double-bond migration); in any event hydrogen participation may be ignored in the interpretation of the rates of reaction of vinylcyclohexanes.[7]
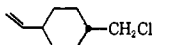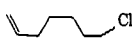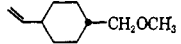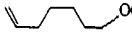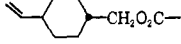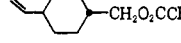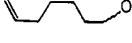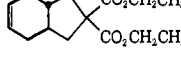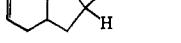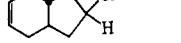
The products of reaction of 5-methoxy-1-pentene with trifluoroacetic acid are reported in a later section of this paper in which methoxyl participation is discussed. It may be finally remarked that 4-chloro-1-butene and 4-methoxy-1-butene were shown to give good yields of the expected addition products.

Rate Determination. Rates were measured by the iodine monobromide titrimetric method previously described[3] with the exception of the rate for hexenenitrile, which was measured gas chromatographically.

(7) In an analogous experiment, 3-methyl-1-butene gave 47% of 2-methyl-2-butyl trifluoroacetate and 53% of the normal addition product, 3-methyl-2-butyl trifluoroacetate. These results are again readily accommodated by reactions analogous to those in Scheme III. Since any tendency for hydrogen participation would be expected to be enhanced in these reactions, due to the low nucleophilicity of the solvent, our results suggest that hydrogen participation is generally unimportant.

A calculated correction which allowed for the effect of double-bond rearrangement during reaction was previously employed[3] for reactions of 5-substituted 1-hexenes. Rearrangement was found to be of less importance for the terminally substituted alkenes employed in the present study, and accordingly no correction was necessary. The results of our rate studies are reported in Tables I and II.

Table II. Relative Rates of Addition at 60.0° of Trifluoroacetic Acid to Cyclic and Bicyclic Alkenes, Compared to Aliphatic Analogs

Compd.	k_H/k_X	Compd.	k_H/k_X
(cyclohexane)—CH₂Cl	4.58ᵃ	(chain)—Cl	5.00ᶜ
(cyclohexane)—CH₂OCH₃	5.67ᵃ	(chain)—OCH₃	5.26
(cyclohexane)—CH₂O₂C—C₆H₄—NO₂	10.3ᵃ		
(cyclohexane)—CH₂O₂CCF₃	12.4ᵃ	(chain)—O₂CCF₃	9.28
(indane) CO₂CH₂CH₃ / CO₂CH₂CH₃	122ᵇ	(chain) CO₂CH₂CH₃ / CO₂CH₂CH₃	36.2ᵈ
(indane) CO₂H / H	30ᵇ		
(indane) CN / H	152ᵇ	(chain)—CN	61.8

ᵃ The k_H value was that measured for 4-vinylcyclohexane, 3120 (10^{-6}) sec.$^{-1}$. ᵇ The k_H value for cyclohexene, 2340 (10^{-6}), sec.$^{-1}$ was used for comparison since alkenes not bearing electron-attracting substituents exhibit only moderate variations in reaction rates: cf. P. E. Peterson and G. Allen, *J. Org. Chem.*, **27**, 1505 (1962). ᶜ Values of k_H and k_X are for 1-heptene and 7-chloro-1-heptene, respectively. ᵈ The preparation (from 5-bromo-1-pentene and malonic ester) and the rate determination were performed by Mr. Andrew Meyer. The k_H value for 1-hexene was used to calculate k_H/k_X.

Discussion

Attenuation of the Inductive Effect with Distance. Interpretation of the rate data for aliphatic compounds depends on the finding that the data for substituents showing no participation are well correlated by the assumption that the inductive effect, here defined as $\log k_H - \log k_X \equiv \Delta \log k$, falls off by a constant factor (ϵ) per methylene group. (k_H and k_X are the rate constants for the unsubstituted and substituted alkenes reacting according to eq. 1.) Accordingly

$$\Delta \log k_n = \epsilon^{n-m}(\Delta \log k_m) \qquad (5)$$

where n, m = numbers of carbon atoms in the alkenes whose inductive effects are compared ($n > m$). Taking the logarithm of both sides in eq. 5

$$\log \Delta \log k_n = \underbrace{(\log \epsilon)}_{} \underbrace{(n-m)}_{} + \underbrace{\log \Delta \log k_m}_{} \qquad (6)$$

$$cf. \qquad y = \quad m \quad x \quad + \quad b$$

As indicated in eq. 6 the variable, $\log \Delta \log k_n$, may be plotted as a linear function of the number of additional methylene groups, $(n - m)$, in compounds having a chain of n carbon atoms compared to the reference compounds having m carbon atoms. Alternatively, $\log \Delta \log k_n$ may be plotted against the number of

carbon atoms in the alkene carbon skeleton, (as shown in Figure 1 for alkenes having trifluoroacetoxy, cyano, and acetoxy substituents) since the latter number will differ from $n - m$ by a constant, in view of the fact that m is itself the constant number of carbon atoms in the arbitrary reference compounds.

The above-mentioned empirical approach to the attenuation of inductive effects is a familiar one.[8] Plotting of data in the above-mentioned linear form has likewise been employed previously.[9]

However, the attenuation of the inductive effect by a constant factor per methylene group was originally applied to a minimal number of methylene groups,[10] although ΔpK values of six cyano-substituted tertiary amines show an attenuation by a constant factor (0.53) per methylene group.[11] Furthermore, so far as we are aware, no physical model has ever been proposed from which an attenuation of this type has been derived. Since in our own work we encountered marked inductive effects over a notably extended range of distances, our expectation was that the previously used empirical approach to the attenuation of inductive effects would fail.

It is apparent from Figure 1 that no such failure is noted. However the attenuation factors observed throughout our study correspond to a remarkably small falloff of the inductive effect with distance, the values of Figure 1 (0.648, 0.663, and 0.657 for trifluoroacetates, cyanides, and acetates, respectively) being typical, compared to the more usual values of 0.3 to 0.5.[8]

The linearity of eq. 6 is remarkable in depending on only one variable (ϵ), the attenuation factor. However since the apparent success of eq. 6 could be an artifact of the $\log \Delta \log k$ treatment, which might appear to minimize small differences in inductive effects, an alternative empirical attenuation expression (eq. 7) was examined.

$$\Delta \log k_n = C(1/r)^\alpha \qquad (7)$$

Here r is the "distance" between the substituent and the reaction site, α is an arbitrary exponent, and C is a proportionality constant.

Taking logarithms of both sides

$$\log \Delta \log k_n = \alpha(\log 1/r) + \log C \qquad (8)$$

Although eq. 6 and 8 bear a superficial resemblance, linearity in eq. 8, in reality, depends on two variables instead of one, since the distance parameter, r, can only be simply represented as the number of atoms (or bonds) between the substituent and the reaction site, a number which may be counted in various ways. Although the cases $\alpha = 1$ and $\alpha = 2$ correspond to charge-charge and charge-dipole interactions, under appropriate simplified circumstances, the present intent is to attach no special physical significance to eq. 8. Plots of eq. 8, shown in Figure 2 for various values of r, indicate that the simpler eq. 6 is superior to eq. 8 for all values of the two variables, r and α, in eq. 8. Further-

(8) *Cf.* J. C. McGowan, *J. Appl. Chem.*, **10**, 312 (1960), for a discussion.

(9) H. Klootsterziel, *Rec. trav. chim.*, **82**, 508 (1963).

(10) G. E. K. Branch and M. Calvin, "The Theory of Organic Chemistry," Prentice-Hall, Inc., New York, N. Y., 1941, p. 204.

(11) G. W. Stevenson and D. Williamson, *J. Am. Chem. Soc.*, **80**, 5943 (1958).
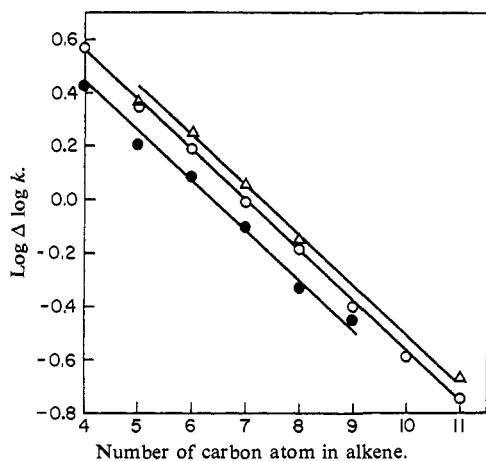
Figure 1. Plot of rate data for alkenes having cyano ($\triangle$), trifluoroacetoxy (O), and acetoxy ($\bullet$) substituents, based on the assumption that the substituent effect changes by a constant factor per methylene group. Slopes of the lines shown in Figures 1, 3, and 4 correspond to an attenuation factor, ϵ, of 0.65.
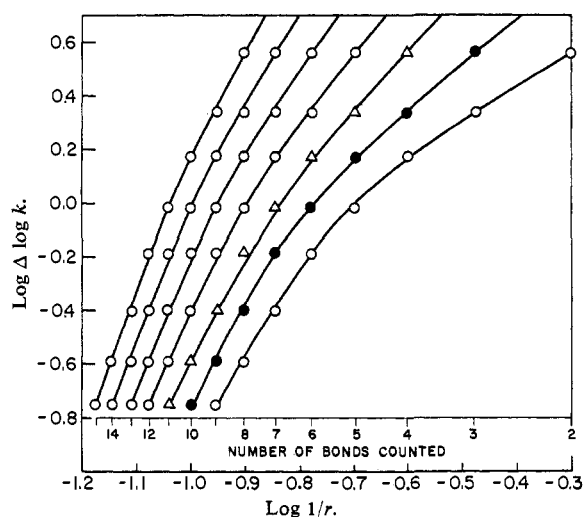

Figure 2. Plot of eq. 8 for ω-trifluoroacetoxy-1-alkene rate data. In Figure 2, in addition to log (1/r), numbers corresponding to bonds counted as follows (for a 4-substituted-1-butene), $\overset{1}{CH_2}=\overset{2}{CH}-\overset{3}{CH_2}-\overset{4}{CH_2}-X$, are shown and identified as triangular points, making the number of bonds identical with the number of atoms in the carbon skeleton for the curve of triangular points. However the solid circles would appear to illustrate the most appropriate count of the number of bonds between the substituent and the cationic reaction site, as in $CH_3-\overset{+}{CH}-\overset{1}{CH_2}-\overset{2}{CH_2}-\overset{3}{X}$. Open circles represent other "bond counts." Points on the same horizontal row represent rate data for the same compounds in each case.

more, apparent improvement in linearity of eq. 8 occurs when unrealistically large numbers of bonds are counted between the substituent and the reaction site. Under such circumstances the over-all "distance" variation is greatly decreased among the compounds considered, and the improved linearity is an artifact of using inadequate distance variation. In conclusion, it may be said that the usefulness of the empirical attenuation factor approach to the correlation of aliphatic inductive effects has been substantiated and extended by our work.
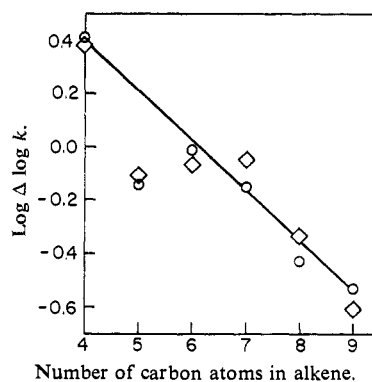

Figure 3. Plot of rate data for alkenes having methoxy ($\Diamond$) and chloro (O) substituents, based on the assumption that the substituent effect changes by a constant factor per methylene group.

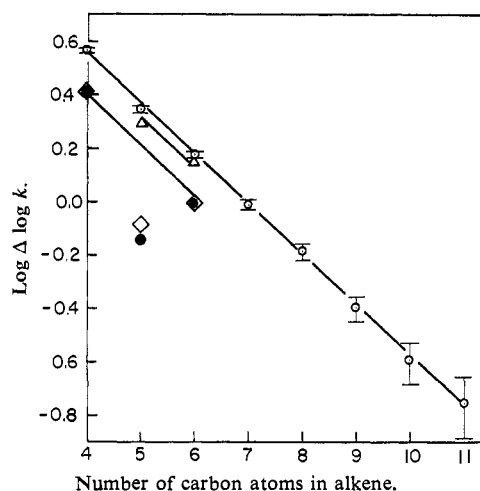Figure 4. Plot of rate data for alkenes having chloro ($\bullet$), bromo ($\Diamond$), p-nitrobenzoyloxy ($\triangle$), and trifluoroacetoxy (Φ) substituents, based on the assumption that the substituent effect falls off by a constant factor per methylene group.

Participation by Halogen and Methoxyl Groups. In Figure 3 log Δ log k is plotted vs. the length of the carbon skeleton for methoxy- and chloroalkenes having varying chain lengths. 5-Chloro-1-pentene and 5-methoxy-1-pentene are seen to react more rapidly than would be expected, based on the regular attenuation of the inductive effect with distance exhibited by the alkenes of Figure 1. Several lines of evidence now demonstrate that the acceleration can be ascribed to substituent participation, illustrated in eq. 9 for 5-chloro-1-pentene.
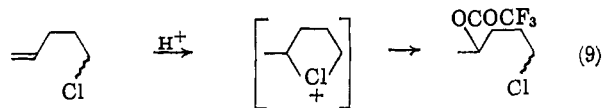
The intermediacy of a chloronium ion in a five-membered ring system (cf. eq. 9) was at first surprising, but independent demonstrations of 1,4-chlorine shifts in the addition of trifluoroacetic acid to 5-chloro-1-pentyne[12] and 5-chloro-1-hexene-2-d[13] provide strong confirmatory evidence for chloronium ion formation. In Figure 4 rate evidence for participation of bromine

(12) P. E. Peterson and J. E. Duddey, *J. Am. Chem. Soc.*, **85**, 2865 (1963).

(13) P. E. Peterson and E. V. P. Tao, *ibid.*, **86**, 4503 (1964).

closely paralleling that of chlorine is shown. In contrast to the effect of bromine in 2-bromocyclohexyl tosylate solvolysis in acetic acid, where bromine is nearly 1000 times as effective as chlorine in causing rate acceleration,[14] bromine, chlorine, and iodine[3] appear to exert similar effects in the 5-halo-1-alkene reactions with trifluoroacetic acid. Conceivably the angle strain associated with the five-membered rings containing the larger halogens counterbalances the expected rate enhancement expected for the more polarizable larger halogens. In all cases rate acceleration is moderate. Based on the deviation of the 5-chloro-1-pentene rate from the line defined by the other chloroalkenes (Figure 3), the rate of reaction of 5-chloro-1-pentene has been estimated to be 7.5 times the rate of the unaccelerated reaction.[13]

In Figure 4 the normal attenuation of the inductive effect of the trifluoroacetoxyalkenes is again shown for comparison. The additional space available in Figure 4 has been utilized to illustrate the possible effect of a $\pm 5\%$ error in the rate of reaction of *both* the trifluoroacetoxyalkenes and the unsubstituted alkenes. Similar "maximum" errors should be applicable to the other data of Figures 1 and 3 where error limits have been omitted for clarity. Finally, data for 5-penten-1-yl *p*-nitrobenzoate and 6-hexen-1-yl *p*-nitrobenzoate are included in Figure 4 to provide an additional example of normal attenuation of the inductive effect with distance.

Participation by methoxyl groups to form five-membered rings and possibly six-membered rings, which may be inferred from Figure 3, has a number of precedents in the literature.[15] Based on the rate for the unaccelerated reaction for 5-methoxy-1-pentene, calculated from the presumably normal rate for 4-methoxy-1-butene and the fall-off factor of 0.65 per methylene group, 5-methoxy-1-pentene shows a 6.1-fold rate acceleration, which may be compared to the 30-fold acceleration estimated for 5-methoxy-2-pentyl brosylate solvolysis in acetic acid.[15a] The products of reaction of 5-methoxy-1-pentene likewise indicate that a major reaction path involves the intermediacy of an oxonium ion intermediate (eq. 10).
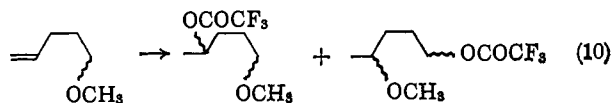
The ratio of methoxyl shift product to "normal" product is 30:70, which may be compared to the 40:60 ratio found in Winstein's brosylate solvolysis study.[15a]

Modification of σ_I Values by Trifluoroacetic Acid. The increase of the inductive effect of oxygen- and nitrogen-containing substituents as a result of strong hydrogen bonding to trifluoroacetic acid has been previously postulated, based on an empirical correlation of σ_I values with solvent shifts of the fluorine nuclear magnetic resonance frequencies of *meta*-substituted fluorobenzenes,[16] and also on earlier studies of the re-

activity of substituted fluoroalkenes with trifluoroacetic acid.[3] The major influence of such hydrogen bonding in our present study is shown in Figure 3 in which the inductive effect of the methoxyl group is seen to be raised to a value comparable to that of the chloro group.[17] The normal σ_I values are 0.25 for the methoxyl group and 0.47 for the chloro group.[16] A similar enhancement of the σ_I value of the acetoxyl group (normal $\sigma_I = 0.39$) compared to that of the chloro group may be seen from the nearly identical rate effects exerted by these substituents (*cf.* Table I). Based on these fairly extensive comparisons there can be no doubt that σ_I values in trifluoroacetic acid are modified so extensively as to require a re-evaluation of the effect of each substituent, compared to the substituent effects in normal solvents.

The n.m.r. studies of Taft and co-workers[16] already provide one new set of σ_I values whose possible relevance to reactions of aliphatic compounds can only be answered by extensive experiments similar to those in the present work. For the present, at least, we mercifully prefer to avoid an attempt to derive a best set of values applicable to reactivity (as opposed to n.m.r. solvent shift phenomena). Preliminary Hammett-Taft plots show, as would be expected, that the σ_I values for trifluoroacetic acid based on n.m.r. data give a notably better linear correlation than plots based on normal σ_I values.[18]

Cyclic and Bicyclic Compounds. In Table II rates of reaction of various cyclic and bicyclic alkenes are compared to rates for aliphatic compounds having substituents at comparable distances from the double bond, counting the shortest reaction path in each case. Marked similarities in inductive rate effects are noted between the two types of compounds, demonstrating that truly remote substituents *can* exert large effects.

Based on the limited data available, a useful empirical hypothesis is that substituent effects in the reactions studied are primarily a function of the smallest number of carbon atoms between the substituent and and the reaction site. (In the case of the bicycloheptenes the comparison is hindered slightly by the fact that cyclohexene is not the ideal unsubstituted analog.)

From a theoretical standpoint it could be postulated that opposing factors contribute to the similarities noted in the preceding paragraph. According to the Kirkwood-Westheimer formulation, large inductive effects are expected in the semirigid cyclohexane derivatives and in the rigid bicyclo[4.3.0]nonene derivatives as a consequence of the large cavity of low dielectric constant separating the substituent and the reaction site.[19] In the flexible aliphatic alkenes, however, the substituents and the reaction sites may be closer than is indicated by the number of carbon atoms separating them. Although many new experiments involving other solvents and reactants are suggested which may resolve such ambiquities, it is at present tempting to adopt a working hypothesis involving "Brownian" simplicity: that the moderate difference

(14) *Cf.* A. Streitwieser, *J. Am. Chem. Soc.*, **78**, 4935 (1956).
(15) (a) S. Winstein, E. Alfred, R. Heck, and R. Glick, *Tetrahedron*, **3**, 1 (1958); (b) S. Oae, *J. Am. Chem. Soc.*, **78**, 4032 (1956); (c) D. S. Noyce, B. R. Thomas, and B. N. Bastian, *ibid.*, **82**, 885, 1246 (1960).
(16) R. W. Taft, E. Price, I. R. Fox, I. C. Lewis, K. K. Anderson, and G. T. Davis, *ibid.*, **85**, 709 (1963).

(17) The values for methoxypentanes and methoxyhexanes are not applicable for comparison because of the participation effects previously discussed.
(18) E. Tao, Ph.D. Thesis, St. Louis University, 1965, available from University Microfilms, Ann Arbor, Mich.
(19) F. H. Westheimer and J. G. Kirkwood, *J. Chem. Phys.*, **6**, 513 (1938).

between the dielectric constants of the cavity, assumed to be 2,[19] and of the solvent[20] is negligible in our system, and, furthermore, that the aliphatic molecules are present predominantly in extended conformations. The effect of these conditions would be to make long-range inductive effects a predictable function of the number of atoms between the substituent and the reaction site.

Conclusion

Effects upon reactivity have been observed for substituents remarkably remote from the reaction site. The effects have been correlated within an empirical framework having good predictive value. Questions regarding the origin and nature of substituent effects have been largely deferred until comparisons can be drawn with effects in supposedly "familiar" solvents, for which, surprisingly, little information is available concerning substituent effects in carbonium ion reactions.

Experimental Section

ω-Substituted 1-Hexenes. The aliphatic alkenes Table I were purchased or synthesized by commonly used procedures, similar in many instances to those used in the synthesis of the cyclic and bicyclic compounds described below. New compounds gave satisfactory analyses for carbon and hydrogen. Several synthetic procedures are given in ref. 18.

trans-4-Hydroxymethylcyclohexane Carboxaldehyde (1). Cupric oxide wire was reduced in a slow stream of hydrogen.[5] In our hands it was impossible to avoid the development of a red-hot zone which passed down the tube. *trans*-1,4-Cyclohexane-1,4-dimethanol[21] was dropped into a Pyrex tube packed with the copper catalyst through which nitrogen was also passed. The tube temperature was maintained near 240° with adjustment as needed to give an optimum yield of monoaldehyde (*cf.* eq. 3) as judged from gas chromatography on a Carbowax 20M column at 220°. Distillation gave a fraction, b.p. 113–114° (0.5 mm.) containing only *trans*-4-hydroxymethylcyclohexane carboxaldehyde (1) and the starting diol, according to gas chromatographic analysis. This fraction gave a 2,4-dinitrophenylhydrazone, m.p. 193–194°.

Anal. Calcd. for $C_{14}H_{18}N_4O_5$; C, 52.17; H, 5.59. Found: C, 52.49; H, 5.58.

The formation of some *cis*-hydroxyaldehyde by epimerization of the aldehyde group during pyrolysis is not excluded in our study. Accordingly the compounds derived from the hydroxyaldehyde are most appropriately regarded as predominantly *trans*.

trans-4-Vinylcyclohexanemethyl Trifluoroacetate. Dimethyl sulfoxide (50 ml., predistilled from calcium hydride at 2 mm., 67°) was heated and stirred under argon for 40 min. with 1.32 g. (0.055 mole) of powdered sodium hydride. The resulting solution of methyl sulfinyl carbanion[6] was cooled in an ice bath, and 19.64 g. (0.55 mole) of methyltriphenylphosphonium bromide in dimethyl sulfoxide was added. *trans*-4-

Hydroxymethylcyclohexane carboxaldehyde (1.89, 0.013 mole, 95% pure) was added. The mixture was stirred for 36 hr. at 50°, poured into 150 ml. of water, and extracted repeatedly with pentane. Spinning-band distillation gave 0.61 g. (33%) of *trans*-4-vinylcyclohexanemethanol (2), b.p. 62° (0.6–0.7 mm) A portion of the alcohol (0.28 g., 0.002 mole) was converted to the trifluoroacetate by reaction with trifluoroacetic anhydride (0.63 g., 0.003 mole) in 10 ml. of ether. Hydrolysis of the excess anhydride, washing (potassium carbonate solution), drying (magnesium sulfate), and distilling (1.3 mm.) gave 0.2 g. (42%) of *trans*-4-vinylcyclohexanemethyl trifluoroacetate, bath temperature 80–120°.

Anal. Calcd. for $C_{11}H_{15}F_3O_2$: C, 55.92; H, 6.40. Found: C, 56.06; H, 6.45; double bonds, 101 mole %, based on extrapolation of the linear kinetic plot for addition of trifluoroacetic acid to time = zero.

trans-4-(Methoxymethyl)cyclohexylethene. *trans*-4-Vinylcyclohexanemethanol (0.61 g., 0.0043 mole) was dissolved in ether and 3 drops of concentrated fluoroboric acid[22] was added to the mixture cooled in a Dry Ice–acetone bath. Ether (130 ml.) containing 0.125 mole of diazomethane was added slowly, with 2 additional drops of fluoroboric acid. From the ether solution, 0.353 g. (53%) of *trans*-4-(methoxymethyl)-cyclohexylethene was obtained by short-path distillation at 2 mm. (bath temperature 90–130°).

Anal. Calcd. for $C_{10}H_{18}O$: C, 77.86; H, 11.76. Found: C, 77.99; H, 11.62; double bonds, 99.7 mole %.

trans-4-Vinylcyclohexanemethyl p-Nitrobenzoate. *trans*-4-Vinylcyclohexanemethanol (0.268 g., 0.0019 mole) was warmed with *p*-nitrobenzoyl chloride (0.43 g., 0.0023 mole) in 0.44 ml. of anhydrous pyridine. The product (0.27 g.) 49% after three crystallizations from methanol, had m.p. 60.5–61.5°.

Anal. Calcd. for $C_{16}H_{19}NO_4$: C, 66.42; H, 6.62. Found: C, 66.26; H, 6.55; double bonds, 106 mole %.

trans-4-(Chloromethyl)cyclohexylethene. Thionyl chloride (0.6 g., 0.005 mole) was heated with a stirred solution of *trans*-4-vinylcyclohexanemethanol (0.70 g., 0.005 mole) in pyridine (0.4 g.) at 90–100° for 7 hr. Isolation by an extraction procedure and short-path distillation gave 0.2 g. (28.5%) of *trans*-4-(chloromethyl)cyclohexylethene (2 mm., bath temperature 80–100°).

Anal. Calcd. for $C_9H_{15}Cl$: C, 68.12; H, 9.52. Found: C, 67.98; H, 9.48; double bonds, 100 mole %.

trans-Diethyl Δ^4-Tetrahydrophthalate (3). *cis*-Diethyl Δ^4-tetrahydrophthalate[23] (226 g., 1 mole) was refluxed with a solution obtained from 30.6 g. of sodium dissolved in 280 ml. of absolute ethanol. Gas chromatographic analysis (150-ft. Apeazon L capillary column, 130°) indicated the approximate 88:12 *trans* to *cis* equilibrium mixture is reached after 1 hr. Final isolation of a product enriched in the *trans* isomer was accomplished by distillation in a 36-in. spinning-band column at a 20:1 reflux ratio. The combined early fractions, 113 g. (50%) contained approximately 92%

(19)
(20) D. Dannhauser and R. H. Cole, *J. Am. Chem. Soc.*, 74, 6105 (1952), report the dielectric constant of trifluoroacetic acid to be 8.42 at 20°.
(21) We are indebted to Eastman Chemical Products, Inc., Kingsport, Tenn., for a generous sample of the *trans* isomer, available by crystallizing the commercially available mixture.

(22) The procedure is essentially that of M. Neeman, M. C. Caserio, J. D. Roberts, and W. S. Johnson, *Tetrahedron*, 6, 36 (1959).
(23) A. C. Cope and E. C. Herrick, *J. Am. Chem. Soc.*, 72, 983 (1950).

of the *trans* isomer. The previously reported synthesis involved the esterification of *trans*-4-cyclohexene-1,2-dicarboxylic acid.[24]

trans-Bicyclo[4.3.0]non-3-ene-8-carboxamide. *trans*-Diethyl Δ^4-tetrahydrophthalate was reduced to the known diol.[24] which was converted to ditosylates **4** (Scheme I) (50% yield, based on diol, after one crystallization from methanol, m.p. 91–93°; lit.[24] m.p. 94–95.5°). Diethyl-*trans*-bicyclo[4.3.0]non-3-ene-8,8-diethyl dicarboxylate was prepared from the ditosylate, hydrolyzed to the dicarboxylic acid, and decarboxylated to *trans*-bicyclo[4.3.0]non-3-ene-8-carboxylic acid (**5**) by the previously employed methods.[24] The monocarboxylic acid (3.5 g.) was refluxed with 17 ml. of thionyl chloride for 20 min., and the mixture was added dropwise to ice-cooled, concentrated ammonium hydroxide. Attempted crystallization from water gave an oil which solidified (1.85 g., 54%), m.p. 140–160°. Crystallization from a more dilute solution in water gave an analytical sample of *trans*-bicyclo[4.3.0]non-3-ene-8-carboxamide, m.p. 170–171°.

Anal. Calcd. for $C_{10}H_{15}NO$: C, 72.69; H, 9.15. Found: C, 72.55; H, 8.96.

(24) D. C. Ayres and R. A. Raphael, *J. Chem. Soc.*, 1779 (1958).

8-Cyano-trans-bicyclo[4.3.0]non-3-ene (**6**). A previously recommended method for amide dehydration was used.[25] Benzenesulfonyl chloride (1.94 g., 0.011 mole) was added to a stirred mixture of crude *trans*-bicyclo[4.3.0]non-3-ene-8-carboxamide (1.85 g., 0.011 mole) at such a rate that the temperature did not exceed 70°. The reaction was strongly exothermic, following an induction period. The resulting slurry was stirred with ether. The ether layer was washed with 4 ml. of 6 N hydrochloric acid and water. The dried ether layer gave 1.0 g. of product, b.p. 80–85° (0.9 mm.), which appeared to be contaminated with the amide starting material (infrared absorption at 1650 cm.$^{-1}$). Redistillation through a microspinning-band column gave 0.16 g. of 8-cyano-*trans*-bicyclo[4.3.0]non-3-ene (**6**) (Scheme I), b.p. 52–58° (0.6 mm.).

Anal. Calcd. for $C_{10}H_{13}N$: C, 81.58; H, 8.90. Found: C, 81.12; H, 8.91.

The same compound has been prepared by a different method and reported in a preliminary communication without experimental details.[26]

(25) C. R. Stephens, E. J. Bianco, and F. J. Pilgrim, *J. Am. Chem. Soc.*, 77, 1701 (1955).
(26) H. B. Henbest and B. Nicholls, *Proc. Chem. Soc.*, 225 (1958).

Solvents of Low Nucleophilicity. VII. Solvolysis of Unbranched Secondary Alkyl Tosylates in Acetic, Formic, and Trifluoroacetic Acids[1]

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Rates of solvolysis of secondary propyl, butyl, pentyl, hexyl, and heptyl tosylates in formic and trifluoroacetic acids were determined and compared with reported rates in acetic acid. An unusually high sensitivity to electron release by alkyl groups is found for the solvolyses in trifluoroacetic acid. Values of ρ_I were -15.7, -7.79, and -5.72 for reactions in trifluoroacetic, formic, and acetic acids, respectively.

A remarkably large portion of the organic chemical literature currently deals with secondary tosylate solvolyses. Not surprisingly, relatively little attention has been given to comparison of unbranched secondary aliphatic tosylates. The rewards to be gained in this somewhat restricted area are exemplified by Pritzkow and Schoppler's study of the rates of acetolysis of heptyl and octyl tosylates (among others).[3] 2-Heptyl tosylate and 2-octyl tosylate solvolyzed at almost identical rates ($k = 4.81$ and 4.64, respectively), while the four other secondary tosylates in the heptyl and octyl series constituted a faster reacting group having

rate constants which varied only from 9.22 to 10.14. The average 2.05-fold rate increase in the second group of compounds, compared to the first, was attributed to the stronger electron release of the larger alkyl groups compared to that of methyl groups. Logarithms of the acetolysis rates of the tosylates, R_1R_2CHOTs, were well correlated with the sum of the σ^*-values of R_1 and R_2, but the ρ^* value (-2.58) was different from that (-3.49) found by Streitwieser in an earlier correlation which encompassed tosylates having strong electron-attracting substituents.[4]

Since a knowledge of secondary tosylate solvolysis rates in trifluoroacetic acid was needed in connection with our studies of long-range inductive effects,[5] we undertook, with some reluctance the measurement of rates for all of the unbranched propyl, butyl, pentyl, hexyl, and heptyl compounds. In addition, the solvolysis rates in formic acid were obtained. These rate studies, with the acetic acid solvolysis studies from the literature, constitute a continuation of our program of comparing the properties of the weakly nucleophilic

(4) A. Streitwieser, *J. Am. Chem. Soc.*, 78, 4935 (1956).
(5) (a) P. E. Peterson and C. Casey, *Tetrahedron Letters*, 1569 (1963); (b) P. E. Peterson and G. Allen, *J. Am. Chem. Soc.*, 85, 3608 (1963); (c) P. E. Peterson and E. Tao, *ibid.*, 86, 4503 (1964).