

Chemical Effects of Steric Strains. XVI. Rates of Reaction of Sodium Borohydride with α -Phenylacetones. Nature of the Driving Force in the Fast Solvolyses of 2,2,2-Triphenylethyl Tosylate and Related Derivatives¹

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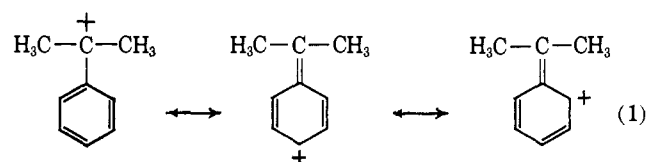
The rates of reaction of sodium borohydride in isopropyl alcohol with a number of phenyl- and methyl-substituted acetones were determined in order to compare the effect of structure on the rate of reaction with the effect of structure on the rate of acetolysis of the corresponding 2-propyl sulfonate esters. The observed relative rates at 50° (2-propanone, 1.00; 1-phenyl-2-propanone, 1.6; 1,1-diphenyl-2-propanone, 0.19; 1,1,1-triphenyl-2-propanone, 0.0051; 3-phenyl-2-butanone, 0.23; and 3-phenyl-3-methyl-2-butanone, 0.034) parallel in inverse order the rates of acetolysis of the brosylates at 50° (2-propyl, 1.00; 1-phenyl-2-propyl, 0.319; 1,1-diphenyl-2-propyl, 1.8; 1,1,1-triphenyl-2-propyl, 417; 3-phenyl-2-butyl, 1.1,1.3; and 3-phenyl-3-methyl-2-butyl, 73). The two sets of rate data yield a reasonably good linear free energy correlation. In the case of the ketones it is proposed that the observed effects of structure on reactivity are primarily the result of the steric and inductive influences of the substituents. The similarity of the structural effects in the two series suggests that similar influences may account for the observed reactivities in the secondary brosylates. This would mean that phenyl bridging may play a much less important role in the observed rates than has been considered in the past. It is suggested that relief of steric strain may be a major factor in the highly reactive derivatives, 1,1,1-triphenyl-2-propyl and 3-phenyl-3-methyl-2-butyl sulfonate esters, with participation of importance primarily in providing a mechanism for relief of steric strain.

The present investigation was initiated in an effort to attain a better understanding of the factors providing the driving force in the fast solvolyses of β,β,β -triphenylethyl chloride,^{5,6} β,β,β -triphenylethyl tosylate,⁷ and related derivatives.

The replacement of a methyl group in *t*-butyl chloride (k_1 0.086×10^{-6} sec.⁻¹⁸) by the phenyl group in

t-cumyl chloride (k_1 394×10^{-6} sec.⁻¹⁹) causes the rate of ethanolysis at 25° to increase by a factor of 4600.

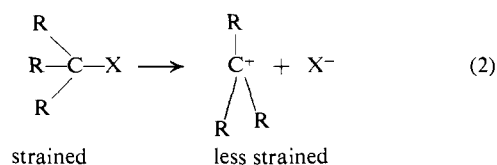
The enhanced rate of *t*-cumyl chloride is attributed to the greater ability of the phenyl group to supply electron density to the electron-deficient center of the carbonium ion and thereby stabilize it (eq. 1).



Although the transition state for the solvolysis does not contain a fully developed carbonium ion, it is assumed to contain a partially formed carbonium ion with an electronic deficiency which can be stabilized by the phenyl substituent.

An energy profile of the reaction path is indicated in Figure 1. This represents a case of rate enhancement resulting from "classical" resonance.

In 1946 it was proposed that rate enhancements should be observed in solvolytic reactions of strained systems on the basis that partial or complete relief of strain in the transition state should provide a potent driving force for the ionization step^{10,11} (eq. 2).



For example, neopentylidimethylcarbinyl chloride (k_1 190×10^{-6} sec.⁻¹¹²) and dineopentylmethylcarbinyl chloride (k_1 5300×10^{-6} sec.⁻¹¹³) undergo solvolysis in 80% aqueous ethanol at rates that are 21 and 580 times that of *t*-butyl chloride (k_1 9.1×10^{-6} sec.⁻¹¹²).

In Figure 2 is shown a representative energy profile for the solvolysis of a strained tertiary halide, such as neopentylidimethylcarbinyl chloride. The higher energy of the initial state will evidently result in a lower energy of activation and an enhanced rate.

The fast rates of solvolysis of β,β,β -triphenylethyl chloride^{5,6} and tosylate,⁷ of camphene hydrochloride,¹⁴

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(2) Gulf Research and Development Co. Fellow, 1959-1960.

(3) Research assistant, 1957-1959, on Grants G 6273 and G 2752 supported by the National Science Foundation.

(4) Postdoctorate research associate, 1960-1961, on Project No. AT-(11-1)-170 supported by the Atomic Energy Commission.

(5) J. C. Charlton, I. Dostrovsky, and E. D. Hughes, *Nature*, **167**, 986 (1951).

(6) C. K. Ingold, "Structure and Mechanism in Organic Chemistry," Cornell University Press, Ithaca, N. Y., 1953, pp. 513, 514.

(7) (a) S. Winstein, B. K. Morse, E. Grunwald, K. C. Schreiber, and J. Corse, *J. Am. Chem. Soc.*, **74**, 1113 (1952); (b) S. Winstein, M. Brown, K. C. Schreiber, and A. H. Schlesinger, *ibid.*, **74**, 1140 (1952); (c) S. Winstein, C. R. Lindegren, H. Marshall, and L. L. Ingraham, *ibid.*, **75**, 147 (1953).

(8) A. H. Fainberg and S. Winstein, *ibid.*, **78**, 2770 (1956).

(9) Y. Okamoto, T. Inukai, and H. C. Brown, *ibid.*, **80**, 4972 (1958).

(10) H. C. Brown, *Science*, **103**, 385 (1946).

(11) F. Brown, T. D. Davies, I. Dostrovsky, O. J. Evans, and E. D. Hughes, *Nature*, **167**, 988 (1951).

(12) H. C. Brown and R. S. Fletcher, *J. Am. Chem. Soc.*, **71**, 1845 (1949).

(13) H. C. Brown and H. L. Berneis, *ibid.*, **75**, 10 (1953).

(14) F. Brown, E. D. Hughes, C. K. Ingold, and J. F. Smith, *Nature*, **168**, 65 (1951).

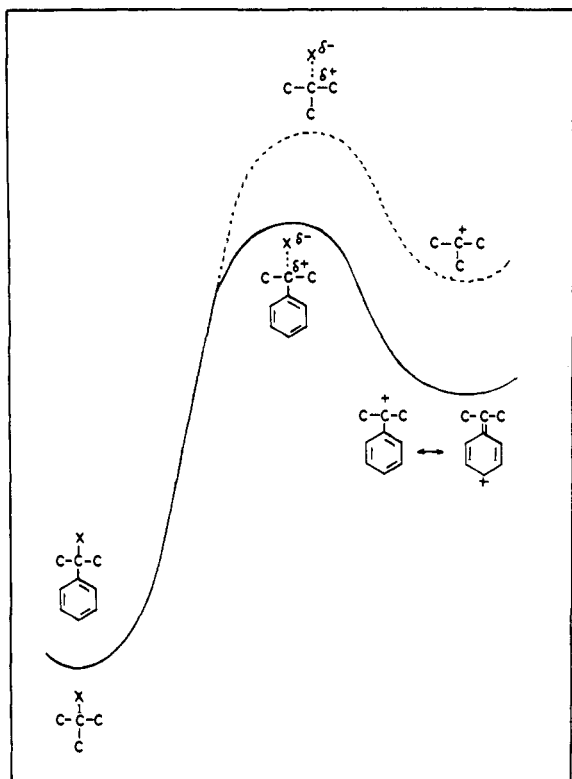


Figure 1. Energy profile for the reaction path for the solvolysis of *t*-butyl and *t*-cumyl derivatives.

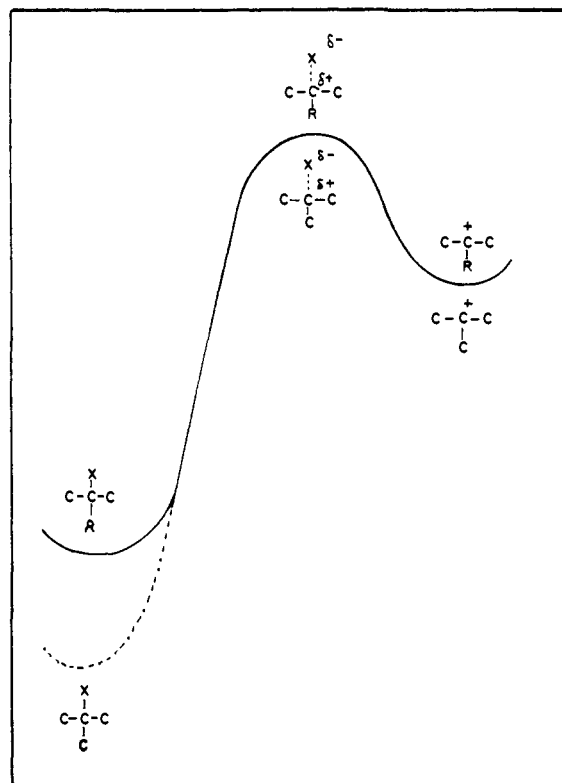
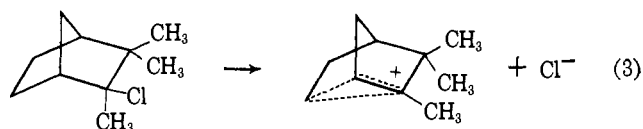


Figure 2. Energy profile for the reaction path involving the solvolysis of *t*-butyl and neopentyl dimethylcarbinyl derivatives (R is the bulky neopentyl group).

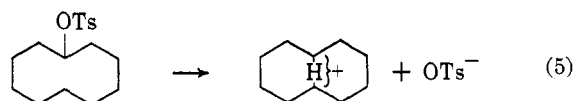
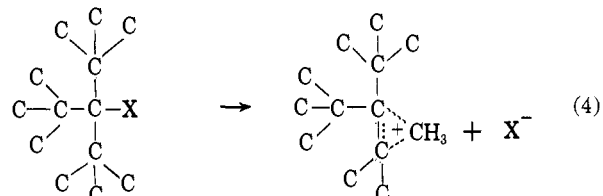
of tri-*t*-butylcarbinyl *p*-nitrobenzoate,¹⁵ and of cyclodecyl tosylate¹⁶ all involve molecules with strained initial states, with relief of strain evident in the ionization stage. However, the possibility that carbonium ions might possess nonclassical structures was explored intensively in the 1950's,¹⁷ and these enhanced rates were interpreted primarily in terms of the enhanced stability of the transition state, provided by nonclassical resonance, rather than to the relief of strain.

For example, the high rate of solvolysis of camphene hydrochloride was attributed not to relief of strain accompanying the separation of chloride ion from its highly crowded environment, but to the driving force provided by the formation of a nonclassical (synartetic, mesomeric) cation (eq. 3; Figure 3).

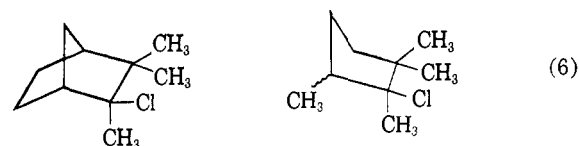


Similarly, it was suggested that the formation of a methyl-bridged tri-*t*-butylcarbinyl cation provides driving force for the observed enhanced rates of solvolysis of tri-*t*-butylcarbinyl derivatives^{15,18} (eq. 4).

The high rate of solvolysis of cyclodecyl tosylate was attributed to the formation of a stabilized bridged cyclodecyl cation¹⁶ (eq. 5).



In the case of camphene hydrochloride we have pointed out that the rate of ethanolysis at 25° (k_1 1160×10^{-6} sec.⁻¹) is of the same order of magnitude as that of the related 1,2,2,5-tetramethylcyclopentyl chloride (k_1 202×10^{-6} sec.⁻¹)¹⁹ (eq. 6). Conse-



quently, there would appear to be no need to attribute the observed rate to any unusual stabilization of the cation from camphene hydrochloride.

(15) P. D. Bartlett and M. Stiles, *J. Am. Chem. Soc.*, **77**, 2806 (1955).

(16) R. Heck and V. Prelog, *Helv. Chim. Acta*, **38**, 1541 (1955).

(17) For a detailed review, with leading references, see A. Streitwieser, Jr., "Solvolytic Displacement Reactions," McGraw-Hill Book Co., Inc., New York, N. Y., 1962.

(18) P. D. Bartlett, *J. Chem. Educ.*, **30**, 22 (1953).

(19) H. C. Brown and F. J. Chloupek, *J. Am. Chem. Soc.*, **85**, 2322 (1963).

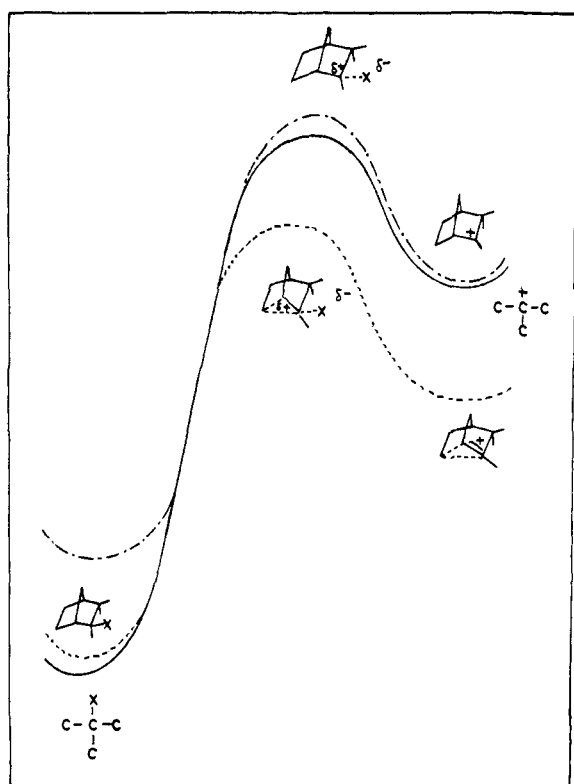


Figure 3. Energy profiles for the reaction path for the solvolysis of camphene hydrochloride to illustrate alternative interpretations based on (a) relief of steric strain or (b) formation of a stabilized nonclassical cation.

The rate of acetolysis of cyclodecyl tosylate is unusually high; it represents the maximum in rate for the cycloalkyl tosylates examined, from C-4 through C-17.^{16,20} If this enhanced rate is the result of steric strain accompanying the crowding of all of the carbon-hydrogen moieties in the cyclic system, we should expect an inverse relationship for a reaction involving addition to the carbonyl group.²¹ Indeed, it is observed that the rate of reaction of sodium borohydride with cyclodecanone is very slow and represents the minimum in the observed rate constants for the cycloalkanones.²² In other words, it appears that those factors (relief of steric strain) which favor the transformation from the tetrahedral *p*-toluenesulfonate to the trigonal carbonium ion resist the related conversion from the corresponding trigonal ketone into tetrahedral carbinol. Moreover, several approaches involving the use of isotopes have led Prelog to the conclusion that the proposed bridged cyclodecyl cation is not a significant intermediate in the solvolytic reactions of cyclodecyl tosylate.²³

In the case of β,β,β -triphenylethyl derivatives, the question of the relative importance of steric and electronic factors in the observed enhanced rates of solvolysis is in a much less certain state. With regard to this derivative, Ingold has stated, "However, steric acceleration can scarcely be supposed to apply to the question of a primary chloride. . . . Thus the ascrip-

tion of the observed acceleration to a release of bonding energy in the transition state seems secure."²⁶ Similarly, Streitwieser has stated, "The acetolysis of β,β,β -triphenylethyl tosylate is 4000 times faster than that of neopentyl tosylate. The rate ratio of the corresponding chlorides in formic acid is 60,000. The high relative rate is reasonably attributed only to anchimeric assistance by a neighboring phenyl group."²⁴

On the other hand, Winstein has indicated that the enhanced rate must involve both steric and electronic contributions, "While we believe the large rate trends observed involve participation and the driving forces have mainly the electronic origin discussed, nevertheless the observed rates (involving participation) can be influenced by steric effects to an extent we still have to assess. If steric strain is relieved by migration from C_β to C_α , there can be an enhancement of rate of a reaction involving participation. To put it another way, participation may provide a mechanism for relief of steric strain."^{27a}

Accordingly, it appeared desirable to undertake a study with the objective of attaining a more precise understanding of the relative importance of relief of steric strain vs. phenyl bridging in the transition state in facilitating the solvolysis of β,β,β -triphenylethyl and related derivatives. The question then arose as to which of several experimental approaches might provide data to assist in answering the question. One possibility was to undertake the synthesis of β,β,β -tricyclohexylethyl tosylate and to determine the magnitude of the rate enhancement anticipated for the solvolysis of this derivative. Unfortunately, it appeared that the experiment might prove ambiguous in view of the proposals that bridging by saturated alkyl groups may be a major factor in enhanced solvolysis rates of sterically crowded structures.^{18,25}

Consequently, we decided to rely on the experimental approach previously utilized to investigate the question of the factor, steric or nonclassical, which was responsible for the enhanced solvolysis rate exhibited by cyclodecyl tosylate.²² If the observed rates in the β,β,β -triphenylethyl tosylates and related derivatives were primarily the result of the steric and inductive influence of the phenyl substituents, we should expect to find similar effects, in inverse order, influencing the rates of reaction of the corresponding aldehydes or ketones with sodium borohydride. On the other hand, if phenyl bridging were providing a major portion of the driving force, this factor should be absent from the borohydride reaction and no simple parallelism should be observed.

Results

The technique utilized to follow the rate of reaction of sodium borohydride with carbonyl derivatives was that previously described.²⁶ Initially we had hoped to determine the rates of reaction of sodium borohydride with (a) acetaldehyde, (b) α -phenylacetaldehyde, (c), α,α -diphenylacetaldehyde, and (d) α,α,α -triphenylacetaldehyde for comparison with the rates of acetolysis of (a) ethyl, (b) β -phenylethyl, (c) β,β -diphenylethyl, and

(20) H. C. Brown and G. Ham, *J. Am. Chem. Soc.*, **78**, 2735 (1956).

(21) H. C. Brown, R. S. Fletcher, and R. B. Johannesen, *ibid.*, **73**, 212 (1951).

(22) H. C. Brown and K. Ichikawa, *Tetrahedron*, **1**, 221 (1957).

(23) V. Prelog and J. G. Traynham, "Molecular Rearrangements," P. de Mayo, Ed., McGraw-Hill Book Co., Inc., New York, N. Y., 1963.

(24) Ref. 17, p. 151.

(25) S. Winstein and H. Marshall, *J. Am. Chem. Soc.*, **74**, 1120 (1952).

(26) H. C. Brown, O. H. Wheeler, and K. Ichikawa, *Tetrahedron*, **1**, 214 (1957).

Table I. Second-Order Constants for the Reaction of Sodium Borohydride with Acetone and Representative α -Phenyl Derivatives

Ketone	Temp., °C.	Rate constant, 10 ⁴ l. mole ⁻¹ sec. ⁻¹	E _{act} , kcal. mole ⁻¹	log A	ΔH^* , kcal. mole ⁻¹	ΔS^* , e.u.
2-Propanone ^a	50.0	207 ^b	9.3	4.59	8.8	-39.1
1-Phenyl-2-propanone	0.0	21.3				
	15.0	55.9				
	25.0	91.6				
	50.0	320 ^b	9.4	4.88	8.8	-38.4
3-Phenyl-2-butanone	0.0	2.16				
	25.0	9.53				
	50.0	47.8	10.8	4.99	10.2	-37.8
1,1-Diphenyl-2-propanone	15.0	6.77				
	25.0	11.4				
	45.0	32.3				
	50.0	40.1	9.5	4.01	8.9	-42.3
3-Methyl-3-phenyl-2-butanone	25.0	1.19				
	37.5	3.24				
	50.0	6.98	13.5	5.96	12.9	-33.4
1,1,1-Triphenyl-2-propanone	25.0	0.129				
	40.0	0.452				
	50.0	1.01	15.9	6.78	15.3	-29.7

^a Ref. 26. ^b Calculated from rate constants at other temperatures.

(d) β,β,β -triphenylethyl tosylate. Unfortunately, the rates of reaction of sodium borohydride with the less substituted aldehydes are too fast to measure.²⁷ Accordingly, we decided to work with the less reactive methyl ketones.

The rate constants and derived data for the individual ketones are summarized in Table I.

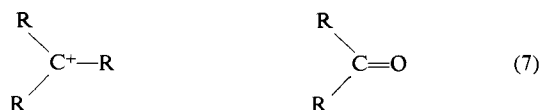
The rate constants were calculated for 50° as a common temperature, since this was the temperature previously utilized for comparison of the relative rates of acetolysis of the sulfonate esters under consideration.⁷

Rate data for all of the sulfonate esters of interest in this investigation were available in the literature, with one exception. We synthesized 1,1,1-triphenyl-2-propyl tosylate and determined its first-order constants ($\times 10^5$ sec.⁻¹) for acetolysis to be 1.73 at 16.0°, 5.28 at 25.0°, and 18.5 at 35.0°. These values lead to a calculated rate constant of 9.75×10^{-4} sec.⁻¹ at 50.0°, with ΔH^* 21.6 kcal. mole⁻¹ and ΔS^* -5.6 e.u.

Discussion

Carbonium ions, in most cases, are fugitive intermediates which are difficult to study by direct physical or chemical observation.²⁸ Consequently, it is not a simple matter to subject to direct test the many proposals for the formation of hydrogen-bridged, alkyl-bridged, and phenyl-bridged carbonium ions which have appeared in recent years.¹⁷

The essential idea behind the experimental approach adopted in the present investigation is that it may be possible to utilize ketones as relatively stable models for carbonium ions (eq. 7).



(27) Previously we had successfully measured the rate for a less active aldehyde, benzaldehyde, only by adopting special techniques and working at low temperatures.²⁶

(28) The recent study of the 1,2-di-*p*-anisylborbornyl cation represents a noteworthy advance in our ability to investigate carbonium ions: P. von R. Schleyer, D. C. Kleinfelter, and H. G. Richey, Jr., *J. Am. Chem. Soc.*, **85**, 479 (1963).

For example, the relatively fast rates of solvolysis of 1-methyl-1-chlorocyclopentane and cyclopentyl tosylate are attributed to the relief of strain accompanying the loss of one of the opposed bonds in the cyclopentyl derivative.²¹ Confirming this interpretation is the observation that the rate of reaction of cyclopentanone is relatively slow.²² On the other hand, the rates of solvolysis of 1-methyl-1-chlorocyclohexane and cyclohexyl tosylate are relatively slow. This is attributed to the strain-free staggered arrangement of bonds in the cyclohexane molecule, so that conversion to a carbonium ion with some bond opposition is resisted.²¹ In line with this interpretation is the fast rate of reaction of cyclohexanone with borohydride.²²

It has not yet proved possible to achieve linear free energy correlations in aliphatic derivatives, such as have proven so successful in the aromatic series.²⁹ However, a limited correlation of this kind was observed for the cyclanones from C-5 through C-10 involving the rate constants for the borohydride reactions and the corresponding constants for the acetolysis of the tosylates. The higher ring derivatives deviate, presumably because of their much greater flexibility.

A linear correlation of this kind has recently been proposed for the rate of acetolysis of various tosylates and the infrared frequencies of the carbonyl groups in the corresponding ketones.³⁰

For convenience in following the discussion, the relative rates of acetolysis of the primary tosylates are presented in Table II along with the rates of reaction of the corresponding ketones with sodium borohydride.

β -Phenylethyl tosylate undergoes acetolysis at a rate that is roughly one-third of the rate of ethyl tosylate. It has been considered that phenyl participation is not important in this derivative, and the lower rate arises from the electron-withdrawing inductive effect ($-I$) of the phenyl substituent. The modestly enhanced rate of β,β -diphenylethyl tosylate has been attributed to phenyl bridging, such bridging becoming sufficiently important as to overcome the unfavorable inductive

(29) L. P. Hammett, "Physical Organic Chemistry," McGraw-Hill Book Co., Inc., New York, N. Y., 1940.

(30) C. S. Foote, *J. Am. Chem. Soc.*, **86**, 1853 (1964). P. von R. Schleyer, *ibid.*, **86**, 1854, 1856 (1964).

Table II. Relative Rates of Acetolysis of the β -Phenylethyl Tosylates and the Relative Rates of Reaction of the Corresponding Methyl Ketones with Borohydride

Tosylate	Relative rate of acetolysis at 50° ^a	Ketone	Relative rate of reaction with NaBH ₄ at 50°
CH ₃ CH ₂ OTs	1.00	CH ₃ CCH ₃	1.00
C ₆ H ₅ CH ₂ CH ₂ OTs	0.35	$\begin{array}{c} \text{O} \\ \\ \text{C}_6\text{H}_5\text{CH}_2\text{CCH}_3 \end{array}$	1.6
(C ₆ H ₅) ₂ CHCH ₂ OTs	2.6	$\begin{array}{c} \text{O} \\ \\ (\text{C}_6\text{H}_5)_2\text{CHCCH}_3 \end{array}$	0.19
(C ₆ H ₅) ₃ CCH ₂ OTs	378	$\begin{array}{c} \text{O} \\ \\ (\text{C}_6\text{H}_5)_3\text{CCCH}_3 \end{array}$	0.0051

^a Data from ref. 7.

effect of the two phenyl groups. Finally, there is observed a large rate enhancement in the case of β,β,β -triphenylethyl tosylate. In this case phenyl bridging has been considered to be very important, although there is some difference of opinion as to whether relief of steric strain plays any significant role in the observed rate increase.^{6,7,24}

In the case of the borohydride reaction, the presence of an α -phenyl substituent increases the rate by nearly a factor of two. Here also we attribute the increase to the electron-withdrawing inductive effect ($-I$) of the phenyl substituent. (It is evident that the separation of the negatively charged tosylate ion will be affected in an opposite manner by substituents than will the approach of the borohydride anion to the carbonyl group.) In the case of α,α -diphenylacetone, the rate exhibits a decrease by a factor of five, in spite of the combined inductive influence of the two phenyl substituents. We attribute the decreased rate to the large steric influence of the two substituents which is sufficient to overcome their favorable electronic effect. Finally, there is observed a very large decrease in the case of α,α,α -triphenylacetone, a decrease by a factor of 191. Such a large sudden decrease in rate is the kind commonly associated with large steric effects, and there appears to be no reason to doubt that steric influences must be responsible here.

The observed effects of phenyl substituents on rate in the two series are entirely analogous, yet two different explanations are being used for the observed rate changes.

It is appropriate to inquire whether we can find a single explanation for the observed rates.

One possibility to consider is that there is phenyl bridging in the ketones. However, the ultraviolet and infrared spectra show no anomalies which can be associated with bridging of a phenyl group to the carbonyl group. Thus the carbonyl frequencies (for solutions in carbon disulfide) of 1-phenyl- (1726 ± 3 cm.⁻¹), 1,1-diphenyl- (1718 ± 3 cm.⁻¹), and 1,1,1-triphenylpropane (1727 ± 3 cm.⁻¹) are all similar to that of acetone (1721 ± 3 cm.⁻¹) and do not show either the reduction in frequency or the multiplicity that would be associated with carbonyl-phenyl interaction.

Alternatively, we should consider the possibility that the small rate increases observed in the case of β,β -diphenylethyl tosylate, and the large increase observed

in the case of β,β,β -triphenylethyl tosylate, is the result of steric assistance to ionization.^{10,12} Certainly, the very sudden increase observed in the last member of the series is of the kind we usually associate with steric, rather than with electronic effects.

Two possible objections to this analysis might be pointed out. It can be argued that the acetolysis of primary tosylates involves considerable participation by solvent, especially in the less hindered members. This might be avoided by utilizing neopentyl tosylate as the reference compound. However, in that case data are available to compare only three derivatives. Also we are comparing the reactivity of primary tosylates with the reactivity of ketones. Previously, we had compared the reactivity of secondary tosylates with the corresponding ketones. Accordingly, we turned our attention to these secondary derivatives. The data are summarized in Table III.

Table III. Relative Rates of Acetolysis of Phenyl-Substituted Secondary Brosylates and the Relative Rates of Reaction of the Corresponding Methyl Ketones with Borohydride

Brosylate	Relative rate of acetolysis at 50° ^a	Ketone	Relative rate of reaction with NaBH ₄ at 50°
CH ₃ CHCH ₃	1.00	CH ₃ CCH ₃	1.00
$\begin{array}{c} \text{OBs} \\ \\ \text{C}_6\text{H}_5\text{CH}_2\text{CHCH}_3 \end{array}$	0.32	$\begin{array}{c} \text{O} \\ \\ \text{C}_6\text{H}_5\text{CH}_2\text{CCH}_3 \end{array}$	1.6
$\begin{array}{c} \text{OBs} \\ \\ \text{C}_6\text{H}_5(\text{CH}_3)\text{CHCHCH}_3 \end{array}$	1.1 ^b 1.3 ^c	$\begin{array}{c} \text{O} \\ \\ \text{C}_6\text{H}_5(\text{CH}_3)\text{CHCCH}_3 \end{array}$	0.23
$\begin{array}{c} \text{OBs} \\ \\ (\text{C}_6\text{H}_5)_2\text{CHCHCH}_3 \end{array}$	1.8	$\begin{array}{c} \text{O} \\ \\ (\text{C}_6\text{H}_5)_2\text{CHCCH}_3 \end{array}$	0.19
$\begin{array}{c} \text{OBs} \\ \\ (\text{CH}_3)_2\text{CCHCH}_3 \end{array}$	3.5	$\begin{array}{c} \text{O} \\ \\ (\text{CH}_3)_2\text{CCCH}_3 \end{array}$	0.10 ^d
$\begin{array}{c} \text{OBs} \\ \\ \text{C}_6\text{H}_5(\text{CH}_3)_2\text{CCHCH}_3 \end{array}$	73	$\begin{array}{c} \text{O} \\ \\ \text{C}_6\text{H}_5(\text{CH}_3)_2\text{CCCH}_3 \end{array}$	0.034
$\begin{array}{c} \text{OBs} \\ \\ (\text{C}_6\text{H}_5)_3\text{CCHCH}_3 \end{array}$	417 ^e	$\begin{array}{c} \text{O} \\ \\ (\text{C}_6\text{H}_5)_3\text{CCCH}_3 \end{array}$	0.0051

^a Data from ref. 7 except where otherwise noted. ^b *threo*. ^c *erythro*. ^d Calculated from data in H. C. Brown and K. Ichikawa, *J. Am. Chem. Soc.*, **84**, 373 (1962). ^e Present study. Calculated from the rate constant for the tosylate, using a conversion factor: ROBS/ROTs = 3.

A major advantage for the present comparison involving the secondary brosylates is that we avoid the possibility that solvent participation may introduce any major complication in the interpretation of the data. It has been concluded that the acetolyses of secondary sulfonates are essentially limiting in character with little participation by the weakly nucleophilic solvent.³¹ Moreover, the entropies of activation for the acetolyses are all small and in the range anticipated for a limiting solvolysis. A further advantage is that we now have a total of seven derivatives to compare.

Here also we observe that the introduction of a single phenyl substituent into the parent molecules causes the rate of acetolysis to decrease and the rate of

(31) S. Winstein, E. Grunwald, and H. W. Jones, *J. Am. Chem. Soc.*, **73**, 2700 (1951).

the borohydride reaction to increase. Again, a second phenyl group reverses the initial effect in each series; there is now a rise in the acetolysis and a decrease in the borohydride rates. Three phenyl groups result in an increase by a factor of 400 in the acetolysis, and a decrease by a factor of 200 in the reduction. The introduction of a single methyl group into 1-phenyl-2-propyl brosylate results in a slight increase over the parent compound, and there is a moderate decrease in the corresponding ketone. Finally, the presence of two methyl groups causes a large increase, by a factor of 70, in the brosylate, and a corresponding decrease, by a factor of 30, in the ketone. The similarity of the structural effects in the two systems encouraged examination of a linear free energy plot of the data. Such a plot is shown in Figure 4. It is evident that the data do exhibit a reasonably good correlation.

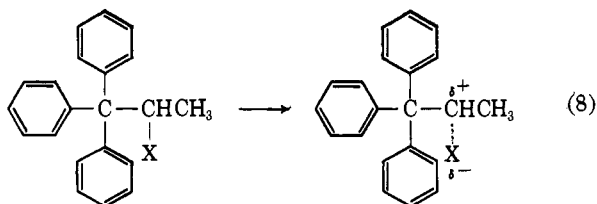
It is unfortunate that we do not yet have a really satisfactory treatment for the reactivities of aliphatic derivatives comparable to that which has worked so well for *meta* and *para* aromatic derivatives. In the absence of a sound theoretical basis for such correlations involving aliphatic compounds, great importance cannot be ascribed to the fact that a linear free energy relationship is indicated for the limited series of compounds under examination. Nevertheless, simple examination of the data reveals a good qualitative correlation of the reactivities in the two systems, and Figure 4 reveals that a reasonable quantitative relationship exists.

It is, of course, possible that the observed correlation is purely accidental, the result of the fortuitous cancellation of unrelated factors. Nevertheless, it appears reasonable to explore the possibility that the correlation is a reflection of the operation of similar factors in influencing the reactivities of the two families of compounds.

The variation in the acetolysis rates has been attributed primarily to phenyl bridging as the major factor. Yet this does not appear to be a significant factor in the reactivities exhibited by the ketones. The reactivities of the ketones can be interpreted simply in terms of the inductive effect of the phenyl and methyl substituents and their large steric requirements in the more highly substituted derivatives. We should consider the possibility that these factors play a major role in the observed reactivities in the acetolysis reaction.

Let us consider possible transition states for the acetolysis of β,β,β -triphenylethyl or 1,1,1-triphenyl-2-propyl sulfonate ester.

First, there is the possibility that ionization does not involve significant participation (eq. 8). In terms of



this possible transition state, the driving force for the fast rate of solvolysis would be relief of steric strain, with phenyl participation not a significant factor in the ionization.

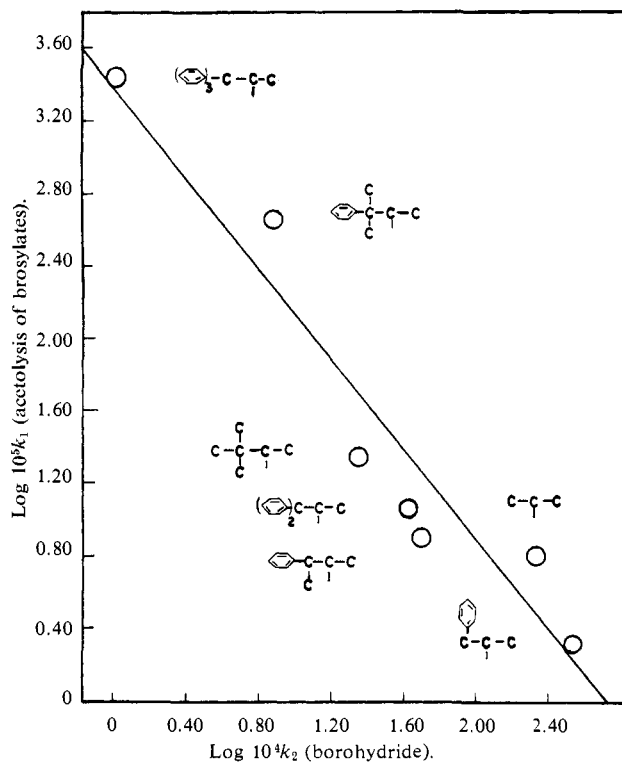
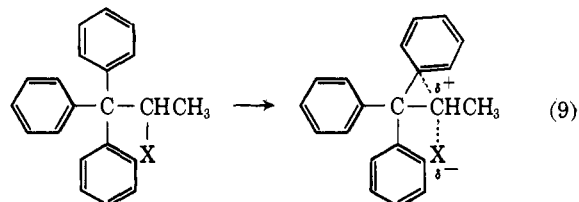
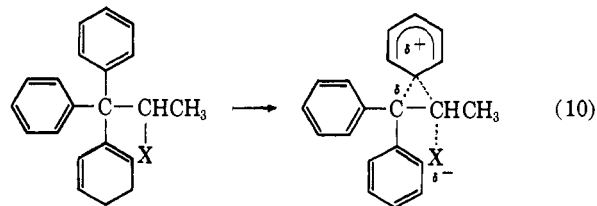


Figure 4. Logarithm of the rates of solvolysis of secondary brosylates with phenyl substituents in the α -position and the rates of reaction of the corresponding ketones with sodium borohydride, both at 50°.

Second, there is the possibility of moderate bridging by the phenyl group, with relief of steric strain still providing the dominant driving force (eq. 9).

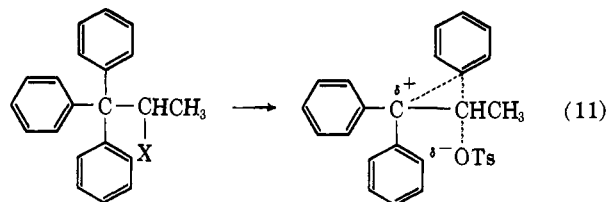


Third, there is the possibility that phenyl bridging provides all of the driving force, with the transition state being essentially a stabilized phenonium ion (eq. 10). This would appear to correspond to the views



of Ingold.⁶

Finally, the transition state may approach in structure the stabilized rearranged ion, which appears to be the actual intermediate formed in the solvolysis (eq. 11).



In this case the dominant driving force would be the stabilization provided by the formation of a low-energy tertiary carbonium ion.

A detailed consideration of all the available data on symmetrical β -phenylethyl systems leads to the conclusion that phenyl participation is not a significant factor in the rates of acetolysis of these derivatives.^{32,33} Consequently, there does not appear to be any reason to consider phenyl bridging as a stabilizing effect which provides driving force to facilitate ionization. Indeed, the phenyl group appears to be strictly marginal in its ability to participate, and such participation appears to be an important factor only in strained systems where it can provide a mechanism for relief of strain,³⁴ or in rearranging systems where rearrangement produces a more stable ion. On this basis, it appears safe to eliminate transition state 10 from further consideration.³⁵

In the case of substituted neophyl (2-phenyl-2-methylpropyl) derivatives, it has been demonstrated that the rates of acetolysis are moderately sensitive to the substituents and can be correlated by the σ^+ constants with a ρ -value of -2.96 .³⁶ This observation that derivatives containing deactivating substituents in the aromatic nucleus follow the correlation establishes the importance of phenyl participation in the neophyl derivatives and it argues for phenyl participation in the related β,β,β -triphenylethyl derivatives. On this basis, we can eliminate transition state 8 from further consideration.

We are now faced with the question of deciding whether transition state 9, moderate phenyl bridging with relief of steric strain as the major driving force, or transition state 11, major phenyl bridging with stabilization of the charge at an incipient tertiary carbonium center, provides the more satisfactory interpretation of the available data.

We have the following observations to assist us in making this choice. (1) There is no significant difference in rates of acetolysis of 3-phenyl-2-butyl and 1,1-diphenyl-2-propyl derivatives. (2) The rates of acetolysis of these derivatives exhibit only minor rate enhancements over the parent compound, with rate enhancements becoming large only in the two deriva-

(32) H. C. Brown, K. J. Morgan, and F. J. Chloupek, in preparation.

(33) It should be emphasized that this discussion refers only to the unsubstituted phenyl group, and it should not be extrapolated to anisyl and other derivatives containing highly activating substituents. The importance of participation by such activated aryl groups will be discussed in a later publication.

(34) For example, 1,2-benzo-4-cyclooctenyl tosylate undergoes formolysis at 35° at a rate that is 1000-fold greater than that of 1,2-benzo-5-cyclooctenyl tosylate: R. Huisgen, E. Rauenbusch, G. Seidle, and I. Winmer, *Ann.* 671, 41 (1964). The large effect in this system is presumably the result of participation by the aromatic ring, such participation being so large in this compound because of the favorable geometry and the strained condition of the cyclooctyl system. However, it is unexpected that the apparent large rate enhancement arises from a very slow rate for 1,2-benzo-5-cyclooctenyl tosylate and not from any unusually high rate for 1,2-benzo-4-cyclooctenyl tosylate. The rate for the latter compound is actually considerably slower than that observed for cyclooctyl tosylate itself.

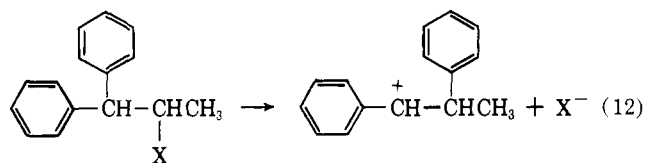
(35) Transition state 10 attempts to represent the possibility that bonding energy involving C_α , C_β , and the phenyl group provides the entire driving force in the observed fast rate. In this situation the transition state would resemble the phenonium ions which have been proposed as intermediates in the 3-phenyl-2-butyl and related systems.¹⁷ However, in the present system, the reacting species must cascade rapidly from the transition state to the highly stabilized rearranged carbonium ion. Consequently, there is no reason to postulate a minimum in the energy profile, corresponding to the formation of a phenonium intermediate, prior to the formation of the rearranged ion.

(36) R. Heck and S. Winstein, *J. Am. Chem. Soc.*, 79, 3432 (1957).

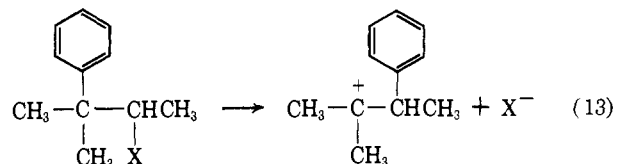
tives containing the phenyl group at a quaternary center. (3) There exists a close correlation between the rates of acetolysis of these derivatives and the rates of reaction of sodium borohydride with the corresponding ketones.

If the transition state were very close to the rearranged ion, we should expect the observed rates to reflect closely the relative stabilities of the tertiary ions which are produced. Yet the data differ markedly from such a relationship.

For example, the relative rates for 3-phenyl-2-butyl (1.3) and 1,1-diphenyl-2-propyl (1.8) are very similar in spite of the fact that the rearranged ion in the latter case would be benzylic (eq. 12).

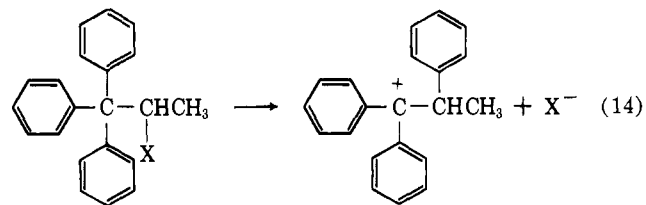


The rate of solvolysis of α -phenylethyl chloride is quite similar to that of *t*-butyl chloride, a relationship which is usually expressed in terms of the generalization that one phenyl group is comparable in its effect to two methyl groups in stabilizing a carbonium ion.³⁷ Consequently, we should not expect appreciable differences in the stabilities of the benzylic ion produced from 1,1-diphenyl-2-propyl (eq. 12) and the tertiary ion produced from 3-phenyl-3-methyl-2-butyl (eq. 13).



Yet the relative reactivities differ markedly (1.8 vs. 73).

Finally, a phenyl group is much more effective than a methyl group in stabilizing a carbonium ion. Consequently, we should expect an enormously larger rate enhancement for 1,1,1-triphenyl-2-propyl (eq. 14) than for 3-phenyl-3-methyl-2-butyl (eq. 13). Yet the



observed reactivities for these two derivatives are not very different, 73 vs. 417.

These discrepancies between the reactivities predicted on the basis that the transition state resembles the rearranged ion and the observed reactivities suggest that eq. 11 is not a satisfactory representation for the transition state.

The discussion leads, therefore, to a preference for eq. 9 as the recommended representation for the transition state.

It should be noted that a *p*-methoxy substituent in the neophyl structure results in a rate enhancement by only a factor of 88.³⁶ Moreover, the factor is even

(37) Ref. 17, p. 43.

less in 3-*p*-anisyl-3-methyl-2-butyl (33).³⁸ The same *p*-methoxy substituent causes a rate enhancement as high as 10⁸ for aromatic bromination. The low factors indicate reactions which are relatively insensitive to substituents and which can be generally said to involve transition states which resemble π -complexes, rather than σ -complexes.³⁹

Accordingly, the present discussion leads to the recommendation that the transition state resembles eq. 9, with relatively weak participation of the aromatic ring with the electron-deficient center. If bonding has not progressed sufficiently far to place any significant electron deficiency on the carbon atom holding the migrating phenyl ring, to what shall we attribute the fact that major rate enhancements in the phenyl series are observed only in those compounds containing the phenyl substituent at a quaternary center? We suggest that relief of steric strain accompanying ionization as well as relief of strain at the quaternary center accompanying bonding of the phenyl group to the developing electron-deficient center must provide a major fraction of the observed driving force. The proposed transition state involves both phenyl bridging and relief of steric strain. It is therefore in better agreement with the interpretation of the reaction advanced by Winstein⁷ than with that of Ingold. In view of the close similarity in the two reactions compared here, we are led to emphasize the steric contribution to the driving force. Moreover, the relatively small activating effect of *p*-methoxy argues that phenyl participation cannot be very far along the reaction path to the phenonium ion (eq. 10) or to the rearranged ion stage (eq. 11). Consequently, our arguments lead us to conclude that the enhanced rates in β,β,β -triphenylethyl and related derivatives are largely to be attributed to relief of steric strain with phenyl participation providing a portion of the mechanism for relief of that strain.^{7a,40}

In summary, the present study reveals a modest similarity in the effects of α -phenyl substituents on the rates of reaction of acetone with sodium borohydride and the effects of these substituents on the rates of acetolysis of the corresponding secondary brosylates. This similarity suggests that similar influences are operative in the two series. The observed reactivities of the acetone derivatives are most simply interpreted in terms of the combined inductive and steric effects of the substituents. It appears reasonable to interpret the similar behavior of the secondary brosylates in terms of the same influences. The failure of the observed rates to correlate with the relative stabilities of the rearranged carbonium ions suggests that the transition state does not resemble these ions closely. Moreover, markedly enhanced rates of solvolysis and markedly decreased rates of reduction are associated only

(38) R. Bernheimer, Ph.D. Thesis, Purdue University Libraries, 1961.

(39) L. M. Stock and H. C. Brown, "Advances in Physical Organic Chemistry," V. Gold, Ed., Academic Press, Inc. New York, N. Y., 1963.

(40) In this connection it should be pointed out that some confusion may arise as a consequence of the different usage of the term participation. In private conversation Professor Winstein has stated that he would attribute the driving force to phenyl participation even if 95% or more of the driving force were the result of relief of steric strain and only 5% or less were the result of stabilization of the transition state by phenyl bonding with the developing electron deficient center. There is no major objection to this practice provided the usage is clearly understood. It can, however, lead to misunderstanding if the reader is not aware that this usage of the term is meant to include *all* driving forces, whether steric or electronic in origin.

with those derivatives containing a quaternary center of large steric requirements. This suggests that relief of strain must be an important driving force in the solvolysis reaction. Consequently, it is proposed that the fast solvolyses of 3-phenyl-3-methyl-2-butyl and 1,1,1-triphenyl-2-propyl derivatives must involve both phenyl bridging and relief of steric strain, with the latter constituting a major component of the driving force.

Experimental

1-Phenyl-2-propanone. Commercial 1-phenyl-2-propanone (Eastman Kodak) was distilled through a Todd fractionating column packed with glass helices, b.p. 89.0–90.0° at 16 mm., n_{D}^{20} 1.5173 (lit.⁴¹ b.p. 60–62° at 0.8 mm., n_{D}^{25} 1.5180).

1,1-Diphenyl-2-propanone. The procedure described⁴² yielded the product, m.p. 58.6–59.5° (lit.⁴² m.p. 60–61°).

1,1,1-Triphenyl-2-propanone. The procedure of Greene and Zook⁴³ yielded 1,1,1-triphenyl-2-propanone, m.p. 137.5–139.0° (lit.⁴³ m.p. 137.5–139.0°), in an overall yield of 38%.

3-Phenyl-2-butanone. 1-Phenyl-2-butanone was alkylated with sodium isopropoxide and methyl iodide. The product, fractionated through the Todd column, exhibited b.p. 72–73° at 3.5 mm., n_{D}^{20} 1.5092 (lit.⁴⁴ b.p. 106–107° at 22 mm., n_{D}^{20} 1.5092).

3-Methyl-3-phenyl-2-butanone. 3-Phenyl-2-butanone was alkylated with potassium *t*-butoxide and methyl iodide, b.p. 78.5–79° at 3.5 mm., n_{D}^{20} 1.5096 (lit.⁴⁵ b.p. 72–74° at 2 mm., n_{D}^{25} 1.5074).

Rates of Reaction with Sodium Borohydride. The rates of reaction were examined in dry isopropyl alcohol utilizing the procedures described earlier,²⁶ with the following modifications. In the course of the procedure for the determination of residual borohydride, a white solid (presumably unreacted ketone) separated, absorbed iodine, and prevented accurate determinations of the iodine. This problem was circumvented by adding 50 ml. of 95% ethanol to 50 ml. of the 0.1 *M* solution of potassium iodate containing 2 g. of potassium iodide. This solution remained homogeneous during the addition of the aliquot of the reaction mixture and during the iodine generation and analysis. Control experiments utilizing this modified procedure yielded rate constants for acetophenone identical with those realized with the original analytical procedure.

1,1,1-Triphenyl-2-propanone proved to be only sparingly soluble in isopropyl alcohol. Consequently, it was necessary to utilize solutions that were 0.03 *M* in ketone and 0.006 *M* in sodium borohydride, in place of the usual concentrations, 0.1 *M* and 0.02 *M*, respectively. Ethanol was also utilized in the analytical procedure in this case. The more dilute solutions utilized for this compound resulted in a larger scatter in the rate constants, $\pm 8\%$ instead of the usual 3% reproducibility. This uncertainty, together with the short temperature range over which we could measure

(41) G. G. Smith, *J. Am. Chem. Soc.*, **75**, 1134 (1953).

(42) E. M. Schultz and S. Mickey, "Organic Syntheses," Coll. Vol. III, John Wiley and Sons, Inc., New York, N. Y., 1955, p. 343.

(43) J. L. Greene and H. Zook, *J. Am. Chem. Soc.*, **80**, 3629 (1958).

(44) C. M. Suter and A. W. Weston, *ibid.*, **64**, 533 (1942).

(45) W. K. Kumler, L. A. Strait, and E. L. Alpen, *ibid.*, **72**, 1463 (1950).

the rate, results in a relatively large uncertainty in the enthalpy and entropy of activation for this compound (Table I).

1,1,1-Triphenyl-2-propanol. 1,1,1-Triphenyl-2-propanone was reduced with lithium aluminum hydride in ether. There was obtained a 94% yield, m.p. 100.5–101.0°. Recrystallized from petroleum ether (b.p. 90–100°), the product exhibited m.p. 101.2–102.0°.

Anal. Calcd. for C₂₁H₂₀O: C, 87.45; H, 6.98. Found: C, 87.47; H, 6.87.

1,1,1-Triphenyl-2-propyl Tosylate. 1,1,1-Triphenyl-2-propanol proved to be exceptionally difficult to convert into its tosylate. The following procedure yielded the product in low yield and a number of successive preparations were required to obtain sufficient ester for the acetolysis study.

1,1,1-Triphenyl-2-propanol, 5.0 g., was dissolved in 10 g. of dry pyridine and treated with 6.5 g. of *p*-toluenesulfonyl chloride. The reaction mixture was maintained in a cold room at 20°F. for 5 days, then at 38°F. for 5 days, and finally at room temperature for 3 days. The reaction mixture was treated with ice water in the usual manner and the aqueous mixture was extracted four times with 50-ml. portions of chloroform. The chloroform extract was washed with water,

1 *M* sulfuric acid, cadmium chloride (10%) solution, sodium bicarbonate, water, and dried over anhydrous magnesium sulfate. Evaporation of the chloroform yielded 3.9 g. of a heavy brown oil, from which the tosylate was extracted with petroleum ether (b.p. 30–60°). The product was obtained from a 1:1 mixture of petroleum ether and ethyl ether by cooling to –78°. The white crystals exhibited m.p. 77–77.5°.

Anal. Calcd. for C₂₈H₂₆SO₃: C, 76.00; H, 5.92. Found: C, 75.72; H, 6.08.

Rate of Acetolysis. The small quantity of 1,1,1-triphenyl-2-propyl tosylate made it desirable to run the rates of acetolysis on a semimicro scale. The solvent was first tested by carrying out rate determinations at 70.0 utilizing the usual conditions: *k*₁ for isopropyl tosylate 2.10 ± 0.04 × 10⁻⁵ sec.⁻¹, and for isopropyl brosylate 6.92 ± 0.03 × 10⁻⁵ sec.⁻¹.⁴⁶ The semimicro procedure, utilizing 0.011 *M* solutions of the tosylate in the acid, yielded 2.09 ± 0.22 for isopropyl tosylate, and 7.6 ± 0.22 for isopropyl brosylate. These were considered to represent satisfactory checks and the procedure was then applied to 1,1,1-triphenyl-2-propyl tosylate.

(46) S. Winstein and E. Grunwald, *J. Am. Chem. Soc.*, 70, 846 (1948), report *k*₁ 6.90 and 6.98 × 10⁻⁶ sec.⁻¹.

Nucleophilic Reactivity of the Carbon–Carbon Double Bond. I. Solvolytic Ring Closure of 2-(Δ³-Cyclopentenyl)ethyl and 1-(Δ³-Cyclopentenyl)-2-propyl Arenesulfonates

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Contribution from the Converse Memorial Laboratory, Harvard University, Cambridge, Massachusetts. Received July 24, 1964

The double bond in 2-(Δ³-cyclopentenyl)ethyl tosylate and *p*-nitrobenzenesulfonate participates directly in the solvolysis of these esters, as shown not only by the direct formation of *exo*-norbornyl acetate as the product in acetic acid, but also by rate ratios from 5.8 in 50% aqueous ethanol to 640 in formic acid as the cyclopentylethyl ester is compared with its saturated cyclopentylethyl analog. No O¹⁸ scrambling occurs when the *p*-nitrobenzenesulfonate of 2-(Δ³-cyclopentenyl)ethanol-O¹⁸ is recovered after 1 half-life in acetic acid. *Endo*-norbornyl *p*-nitrobenzenesulfonate is formolyzed at a rate similar to that of 2-(Δ³-cyclopentenyl)ethyl *p*-nitrobenzenesulfonate, but is not formed to an appreciable extent in the formolysis of the latter.^{18,29} The acetolysis of 1-(Δ³-cyclopentenyl)-2-propyl *p*-nitrobenzenesulfonate has been studied. In the presence of enough sodium acetate to neutralize the strong acid produced, a mixture of unrearranged acetate and a cyclic product believed to be 6-methyl-*exo*-2-norbornyl acetate is obtained. In acetic acid without added sodium acetate, the initial product rearranges rapidly into 1-methyl-*exo*-norbornyl acetate. The factors governing the reduced “driving-force” ratio in the secondary case are discussed.

Introduction

It was observed long ago^{1,2} that when a nucleophilic displacement reaction is made to occur intramolecularly, the rate of the reaction passes through two maxima when the nucleophile is separated from the seat of the displacement by one and by three carbon atoms. At both locations the reactivity of the nucleophile, as judged by successful competition with outside reagents, appears greater than in bimolecular reactions between comparable molecular species. Examples involving sulfur^{3,4} and nitrogen^{1,2} atoms are familiar. There are also cases where considerable nucleophilic reactivity is displayed intramolecularly by a nucleophile too weak to give the corresponding reaction under bimolecular conditions. An example is the substantial driving force afforded by the iodine atom in *trans*-2-iodocyclohexyl *p*-toluenesulfonate,⁵ although alkyl iodides

(1) G. Salomon, *Trans. Faraday Soc.*, 32, 153 (1936).

(2) P. D. Bartlett, S. D. Ross, and C. G. Swain, *J. Am. Chem. Soc.*, 69, 2971 (1947).

(3) A. G. Ogston, *Trans. Faraday Soc.*, 44, 45 (1948).

(4) P. D. Bartlett and C. G. Swain, *J. Am. Chem. Soc.*, 71, 1406 (1949).

(5) S. Winstein, E. Grunwald, and L. L. Ingraham, *ibid.*, 70, 821 (1948).