to react with 2,4,5-triamino-6-hydroxypyrimidine sulfate according to procedure C. The product obtained after one crystallization from 80% formic acid (1.7 g, 23%, mp >360°) was a mixture of pteridines **2a** and **6a**: uv (0.1 *N* NaOH) $E_{255}/E_{365} = 3.3$; nmr (1:4 $FSO_3H-CF_3CO_2H$) δ 9.7 and 9.0 (C-7 and C-6 protons, relative peak areas *ca.* 8:1). The spectral data indicate the 7 isomer **6a** to be present to the extent of 10–15%.

B. *Via* **Keto Aldehyde 5.**—Treatment of 1,2-octanedione (**5**) with 2,4,5-triamino-6-hydroxypyrimidine sulfate according to procedure C gave a mixture of **2a** and **6a**: uv (0.1 *N* NaOH) $E_{255}/E_{365} = 3.1$; nmr (1:4 $FSO_3H-CF_3CO_2H$) δ 9.7 and 9.0 (C-7 and C-6 protons, relative peak areas *ca.* 3:2).

Oxidation Experiments.—Pteridines **2a**, **2c**, **2d**, and **6a** were oxidized with $KMnO_4$ according to the following typical procedure. A solution of the pteridine (0.1 g) in 0.1 *N* NaOH (20 ml) was heated to 70° on the steam bath and treated dropwise with 5% $KMnO_4$ (10 ml) over a 5-hr period. The mixture was kept at 70° overnight and excess oxidant was destroyed by adding a few drops of 50% $NaHSO_3$. Filtration through Celite and acidification of the yellow filtrate to pH 2 with 2 *N* HCl afforded a fine yellow solid which was collected by centrifugation, washed with H_2O, and dried: yield 0.04 g. On the basis of uv spectral comparison with authentic samples,[6] the product obtained from pteridines **2a**, **2c**, and **2d** was identified as 2-amino-4-hydroxypteridine-6-carboxylic acid, uv (0.1 *N* NaOH) 262, 364 nm. The product derived from pteridine **6a**, on the other hand, was identified as 2-amino-4-hydroxypteridine-7-carboxylic acid, uv (0.1 *N* NaOH) 266, 372 nm. Ir spectra (KCl) of the two acids were clearly distinguishable and were in accord with published curves.[25]

Registry No.—**1a**, 39276-30-6; **1b**, 39267-31-7; **1c**, 13133-44-3; **1d**, 39267-33-9; **1e**, 30780-46-2; **1f**, 39267-35-1; **2a**, 39267-36-2; **2b**, 39267-37-3; **2c**, 39267-38-4; **2d**, 39267-39-5; **2e**, 4215-03-6; **2f**, 31419-67-7; **3**, 6956-55-4; **4a**, 39267-67-9; **4b**, 39267-68-0; **4c**, 39267-69-1; **5**, 2363-86-2; **6a**, 39267-71-5; **6b**, 39267-72-6; **6c**, 39267-73-7; ethyl *n*-heptanoate, 106-30-9; ethyl *n*-octanoate, 106-32-1; methyl hydrocinnamate, 103-25-3; methyl 4-phenylbutyrate, 2046-17-5; 2,4,5-triamino-6-hydroxypyrimidine sulfate, 39267-74-8.

[25] C. J. Pouchert, "The Aldrich Library of Infrared Spectra," Aldrich Chemical Co., Inc., 1970, p 1034, spectra A and B.

Solvolyses of 6-Substituted *trans*-2α-Decalyl Tosylates. Remote Inductive Effects and Their Solvent Effects[1]

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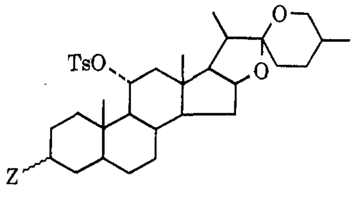
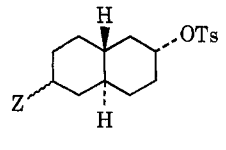
A series of 6-substituted *trans*-2α-decalyl tosylates was solvolyzed in trifluoroacetic acid, acetic acid, and ethanol. The relative rates of trifluoroacetolysis of the parent H, 6(eq)-CH_3O, 6(ax)-CH_3O, 6(eq)-C_6H_5, 6(ax)-C_6H_5, 6(eq)-Cl, 6(ax)-Cl, 6(eq)-CN, 6(ax)-CN, 6(eq)-CO_2CH_3, and 6-keto derivatives at 50° were 1.00, 1.25×10^{-1}, 9.85×10^{-2}, 4.58×10^{-1}, 6.23×10^{-1}, 1.33×10^{-1}, 2.22×10^{-1}, 5.49×10^{-2}, 4.04×10^{-2}, 1.50×10^{-1}, and 1.57×10^{-2}, respectively. Those of acetolysis were 1.00, 4.50×10^{-1}, 3.58×10^{-1}, 5.76×10^{-1}, 5.19×10^{-1}, 3.16×10^{-1}, 2.49×10^{-1}, 2.96×10^{-1}, 1.59×10^{-1}, 5.88×10^{-1}, and 1.49×10^{-1}, respectively. Those of ethanolysis were 1.00, 7.91×10^{-1}, 6.68×10^{-1}, 9.60×10^{-1}, 8.11×10^{-1}, 6.35×10^{-1}, 5.77×10^{-1}, 5.43×10^{-1}, 3.95×10^{-1}, 7.80×10^{-1}, and 6.28×10^{-1}, respectively. The acetolyses gave mainly a mixture of the Δ^1 and Δ^2 olefins and the inverted 2β-acetates with the minor retained 2α-acetate. Satisfactorily linear correlations were obtained by treatment of the rate data with the Hammett–Taft equation. The ρ^* values obtained for all the tosylates vary with solvent: −4.47 in trifluoroacetolysis, −2.05 in acetolysis, and −0.867 in ethanolysis. These results are explained in terms of remote inductive effects operating between the C_6 substituents and the C_2 reaction center. Plotting values for only the 6(eq) compounds and the 6(ax) compounds, respectively, yields significantly different ρ^* values: in acetolysis, −1.98 for eq and −2.63 for ax; in ethanolysis, −0.735 for eq and −1.30 for ax. The difference is explained in terms of a dipole–dipole interaction acting through the field between the C_6 substituents and the reaction site.

Investigation of remote substituent effects provides much useful information on the structural influence on chemical reactivity, and steroidal compounds have provided some suitable model systems for such investigation.[2–7] The significant factors governing the effects have been suggested by several groups and may be classified as (1) inductive effects, (2) electrostatic field effects, and (3) conformational transmission.[2,5,7] In a previous paper,[4] we demonstrated that the rate of acetolysis of A-ring substituted A/B-*trans*- and -*cis*-11α-*p*-toluenesulfonyloxy sapogenin derivatives decreases as the A-ring substituent becomes increasingly electronegative, and that the main cause of the rate variation is the transmission of inductive effects of the A-ring substituents through the carbon–carbon chains composing the sapogenin molecules. However, the concept of long-range inductive effects is a matter of considerable argument to the organic chemist, who traditionally expects to find significant inductive effects operating over short ranges only.[8] Our previous results have been accepted as important in connection with this argument.[2,5–7] We have therefore undertaken a study of the solvolysis of C_6-substituted





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[1] Presented in part at the 23rd Symposium on Organic Reaction Mechanisms, Kobe, Japan, Oct 3, 1972.

[2] D. N. Kirk and M. P. Hartshorn, "Steroid Reaction Mechanisms," Elsevier, Amsterdam, 1968, pp 16–20 and 234–235.

[3] D. H. R. Barton, "Theoretical Organic Chemistry, The Kekule Symposium," Butterworths, London, 1959, p 127.

[4] K. Takeda, H. Tanida, and K. Horiki, *J. Org. Chem.*, **31**, 734 (1966).

[5] R. T. Blickenstaff and K. Sophasan, *Tetrahedron*, **28**, 1945 (1972), and references cited therein.

[6] (a) R. Baker and J. Hudec, *Chem. Commun.*, 479 (1967); (b) R. Baker and K. L. Rabone, *J. Chem. Soc. B*, 1598 (1970).

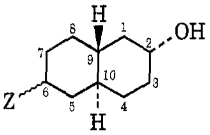
[7] D. N. Jones and R. Grayshan, *J. Chem. Soc. C*, 2421 (1970).

[8] For example, E. S. Gould, "Mechanism and Structure in Organic Chemistry," Holt, Rinehart and Winston, New York, N. Y., 1959, pp 200–209.

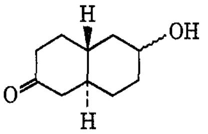
trans-2α-decalyl (*trans,cis*-2-decalyl) tosylates[9] in trifluoroacetic acid, acetic acid, and ethanol. The decalin molecule is much simpler in structure than the sapogenin system and offers little possibility for the bending of aliphatic chains and the rotation about carbon–carbon bonds. It is therefore unlikely that the steric relationship between a polar substituent and the reaction center will change during a reaction. In addition, a structural similarity exists between both the systems; the same number of carbon atoms connect the reaction center and the substituent by the shortest carbon path in both systems. Trifluoroacetic acid has been shown to be a favorable solvent for the demonstration of inductive effect.[10]

Results

Preparations.—The preparation of series of parent and 6-substituted *trans*-decalin-2α-ols (**1–10**) from 2α(e)- and 2β(a)-hydroxy-*trans*-6-decalones (**11e**-OH and **11a**-OH)[11] was described in a previous paper,[12]



1, Z = H
2, Z = eq-CH_3O
3, Z = ax-CH_3O
4, Z = eq-C_6H_5
5, Z = ax-C_6H_5
6, Z = eq-Cl
7, Z = ax-Cl
8, Z = eq-CN
9, Z = ax-CN
10, Z = eq-CO_2CH_3



11e-OH, eq-OH
11a-OH, ax-OH

which also reported the nmr spectral parameters, infrared hydroxy stretching frequencies, vpc behaviors of the alcohols, and other physical properties. Each of the compounds (**1–10**) used in the present study was shown by vpc to be over 99.0% pure. Treatment with *p*-toluenesulfonyl chloride in pyridine converted **1–10** into the tosylates (**1**-OTs–**10**-OTs), whose nmr spectral parameters and other physical constants are given in the Experimental Section.

Rates.—Acetolysis and trifluoroacetolysis were done in buffered media (in the presence of 1.1 equiv of sodium acetate or sodium trifluoroacetate), but ethanolysis was carried out without addition of base. The rates of acetolysis and ethanolysis were determined by standard procedure[13] using a potentiometer. Infinity titers corresponded to theoretical values. In each experiment the reaction was followed to 80% completion. Good first-order kinetics were observed in all runs. The rates of trifluoroacetolysis were measured by a modification of the spectrophotometric method advanced by Peterson and coworkers.[14] The samples were quenched in methanol and the decrease in the ultraviolet absorption maximum at 273.2 mμ was followed until 50% completion of the reaction. The measurement at infinity, however, did not exhibit absorbance corresponding to the theoretical values. Therefore, tosylate remaining at any time was calculated according to 1–3, and the rate constant was

$$A = c_{\mathrm{OTs}} \cdot \epsilon_{\mathrm{OTs}} + c_{\mathrm{PS}} \cdot \epsilon_{\mathrm{PS}} \tag{1}$$

$$c^{\circ}_{\mathrm{OTs}} = c_{\mathrm{OTs}} + c_{\mathrm{PS}} \tag{2}$$

$$c_{\mathrm{OTs}} = \frac{A - c^{\circ}_{\mathrm{OTs}} \cdot \epsilon_{\mathrm{PS}}}{\epsilon_{\mathrm{OTs}} - \epsilon_{\mathrm{PS}}} \tag{3}$$

obtained by determination of the slope of a straight line obtained by plotting ln c_{OTs} against time.

Here A is the absorbance at 273.2 mμ of an actual sample, c°_{OTs} is the initial concentration (moles/liter) of tosylate, c_{OTs} and c_{PS} are the concentrations of tosylate and *p*-toluenesulfonic acid, respectively, and ϵ_{OTs} and ϵ_{PS} are the molar extinction coefficients at 273.2 mμ of tosylate and *p*-toluenesulfonic acid, respectively.

The first-order rate constants were calculated by the least-squares method with a FACOM 270-20 computer, the correlation coefficients of all the plots being 0.999 ± 0.001. The rate constants and activation parameters thus obtained in trifluoroacetolysis, acetolysis, and ethanolysis are listed in Table I. For comparison of reactivities, the relative rate at 50.0° were calculated taking the rate for the parent compound as unity. The acetolysis rate of **1e**-OTs has been determined by several workers. Moritani, *et al.*,[15] reported by a titration method rate constants of 52.2 $\times 10^{-5}$ sec^{-1} at 104.50°, 11.7 $\times 10^{-5}$ at 90.09°, and 1.95 $\times 10^{-5}$ at 75.07° with $\Delta H^{\ddagger}$ of 28.5 kcal mol^{-1} and $\Delta S^{\ddagger}$ of 1.6 eu, in which the concentration of the tosylate was 17.8 mM. Baker and Rabone[6b] reported by an uv spectrometric method rate constants of 2.18 $\times 10^{-5}$ sec^{-1} at 75.0° and 31.1 $\times 10^{-5}$ at 100.0° with $\Delta H^{\ddagger}$ of 26.8 kcal mol^{-1} and $\Delta S^{\ddagger}$ of -3.4 eu, in which the concentration of the tosylate was 2.5 mM. When the acetolysis was carried out in a 20 mM solution, we obtained rate constants of 3.94 $\times 10^{-5}$ sec^{-1} at 80.2°, 11.5 $\times 10^{-5}$ at 90.0°, and 35.3 $\times 10^{-5}$ at 100.0°, which are compatible with Moritani's values. Extrapolation of the observed rates in Table I and those of Moritani and Baker to 50° gives acetolysis rate constants of 13.5 $\times 10^{-7}$ sec^{-1} at the concentration of 1.0 mM, 10.2 $\times 10^{-7}$ at 2.5 mM, 7.58 $\times 10^{-7}$ at 17.8 mM, and 8.30 $\times 10^{-7}$ at 20.0 mM. These data indicate an importance of concentration dependence of the rate constants.[16] Therefore, discussion arising from comparison of the rates in Table I is based on the assumption that the major factor for the concentration dependence in a solvent (for example, molecule–molecule association) is constant among the present tosylates, *i.e.*, independent of the C_6 substituents.

Acetolysis Products.—The acetolysis products from **1e**-OTs have already been reported, together with those from its epimer *trans*-2β-decalyl tosylate.[17] Thus, **1e**-OTs produces Δ^1-octalin in 23.7%, Δ^2-octalin in 40.2%, 2α-decalyl acetate in 2.2%, 2β-decalyl acetate in 33.3%, and other minor olefins in 0.59% yield. In

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[9] All the compounds used in the present study are *dl* mixtures. For convenience, only one enantiomorph is shown in figures and, according to steroid conventions, the hydrogen at C-9 is assigned as the β orientation.

[10] (a) P. E. Peterson and G. Allen, *J. Amer. Chem. Soc.*, **85**, 3608 (1963); (b) J. E. Nordlander and W. G. Deadman, *ibid.*, **90**, 1590 (1968); (c) W. G. Dauben and J. L. Chitwood, *ibid.*, **90**, 6876 (1968).

[11] R. L. Clarke and C. M. Martin, *J. Amer. Chem. Soc.*, **81**, 5716 (1959).

[12] (a) K. Takeda and S. Yamamoto, *Chem. Pharm. Bull.*, **20**, 314 (1972); (b) *ibid.*, **20**, 1125 (1972).

[13] S. Winstein, C. Hanson, and E. Grunwald, *J. Amer. Chem. Soc.*, **70**, 812 (1948); S. Winstein, E. Grunwald, and L. L. Ingraham, *ibid.*, **70**, 821 (1948).

[14] P. E. Peterson, R. E. Kelly, Jr., R. Belloli, and K. A. Sipp, *J. Amer. Chem. Soc.*, **87**, 5169 (1965).

[15] I. Moritani, S. Nishida, and M. Murakami, *J. Amer. Chem. Soc.*, **81**, 3420 (1959).

[16] A referee suggested the importance of molecule–molecule association for this dependence.

[17] N. C. G. Campbell, D. M. Muir, R. R. Hill, J. H. Parish, R. M. Southam, and M. C. Whiting, *J. Chem. Soc. B*, 355 (1968).

the present study, the 6-methoxyl epimers (**2e**- and **3e**-OTs), the 6-chloro epimers (**6e**- and **7e**-OTs), and the keto tosylate (**11e**-OTs) were solvolyzed in glacial acetic acid containing 10% excess sodium acetate at 100.0°. Total yields of the products, determined by vpc, were roughly quantitative. In all cases, formation of the Δ^1- and Δ^2-olefinic mixture was observed in more than 50% yield, and the substitution products were mainly composed of the acetates of inverted configuration (the β acetates). For example, **2e**-OTs gave a mixture of the Δ^1-octalin and the Δ^2-octalin in 58.0% yield, the 2α-decalyl acetate in 2.1% yield, and the 2β-acetate in 32.8% yield. The products from the other tosylates are described in the Experimental Section. It is seen that substituent effects on product composition are not significant.

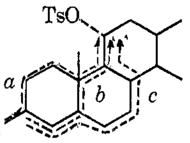
Discussion

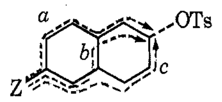
The present compounds are conformationally fixed equatorial cyclohexyl derivatives. Cyclohexyl tosylate acetolyzes at 50° with a rate constant of 0.19×10^{-5} sec^{-1}, a $\Delta H^{\ddagger}$ of 28.1 kcal mol^{-1}, and a $\Delta S^{\ddagger}$ of 1.8 eu. *trans*-4-*tert*-Butylcyclohexyl tosylate with a fixed equatorial conformation acetolyzes at 50° with a rate constant of 0.17×10^{-5} sec^{-1}, a $\Delta H^{\ddagger}$ of 28.1 kcal mol^{-1}, and a $\Delta S^{\ddagger}$ of 1.8 eu.[18,19] Acetolysis of the present **1e**-OTs proceeds at 50° with a rate constant of 0.135×10^{-5} sec^{-1}, a $\Delta H^{\ddagger}$ of 26.7 kcal mol^{-1}, and a $\Delta S^{\ddagger}$ of -2.8 eu.[20] It has been suggested that cleavage of the secondary C–OTs in solvolysis can occur with either solvent (k_s) or hydride (k_Δ) assistance and that the two pathways by k_s and k_Δ are discrete and in competition with one another.[21] As the degree of assistance decreases to zero with the right substrate structure and solvent, k_Δ or k_s approaches k_c (anchimerically and nucleophilically unassisted process).[22] Then the ratio k_s/k_c is a measure of the degree of nucleophilic solvent participation in the absence of anchimeric assistance; when no such solvent participation is present $k_s/k_c = 1$.[21c] We have treated the rate constants of **1e**-OTs in acetic and trifluoroacetic acids with reference to those for 2-adamantyl tosylate as proposed by Schleyer, *et al.*,[21] to get a minimal measure of nucleophilic solvent assistance to ionization. Assistance factors in acetic acid $(k_s/k_c)_{\mathrm{HOAc}}$ thus derived are 48 for **1e**-OTs[23] and 35 for cyclohexyl.[24] Therefore, the values of rates, activation parameters, and solvent assistance of the above compounds are comparable to one another.

It is seen in Table I that the introduction of an electronegative substituent into the C_6 position decreases the solvolysis rates and, further, the magnitude of the decrease increases going from ethanol to acetic acid to trifluoroacetic acid. For example, the introduction of an α-cyano group drops the relative rate to 4.04×10^{-2} in trifluoroacetic acid, 1.59×10^{-1} in acetic acid, and 3.95×10^{-1} in ethanol. The effects of carbonyl substitution are larger; the relative rates of **11e**-OTs are 1.57×10^{-2} in trifluoroacetic acid, 1.49×10^{-1} in acetic acid, and 6.28×10^{-1} in ethanol. In the previous paper[4] we observed an analogous decrease in the acetolysis rates of 11α-*p*-toluenesulfonyloxy steroidal sapogenins with introduction of the C_3 substituents, although solvent effects upon the rate variation were not investigated there. The method used to correlate the substituent effects with the acetolysis rates was based on the Hammett–Taft approach.[25,26] The rate-retarding effects of substituents were calculated from Taft substituent constants (σ^*) on the assumption that the inductive effects would be transmitted to the reaction center through all possible bond paths in the molecule. The observed effect would correspond to a summation for all possible paths (the multiple-path treatment). It was further assumed, in common with the normal Taft treatment, that the effect of any substituent would be attenuated by each bond of the intervening carbon chain. The net effect of a polar substituent was then calculated from the expression

$$\Sigma\sigma_t^* = \sigma^* \, [a^l + b^m + c^n + \cdots\cdots\cdots]$$

where a, b, $c \cdots$ are the attenuation factors appropriate to each bond path and l, m, $n \cdots$ are the numbers of unit groups comprising the bond path; 0.500 for one





methylene and 0.508 for one ethylene were used as the attenuation factors. The ρ^* value of -3.3 obtained from the sapogenin acetolysis is close to the value of -3.49 reported for the acetolysis of substituted cyclohexyl tosylates.[28] The close ρ^* value of the sapogenin, obtained in spite of the increased separation between the substituent and the reaction center, is a result of the higher efficiency of the transmission of polar effects through the multiple pathways (there is a mutual cancelling out of the effects of increased separation and higher efficiency).

For the Hammett–Taft treatments of the present rates, $\Sigma\sigma_t^*$ was calculated as -0.0375 for the parent compound (**1**), $+0.0975$ for the CH_3O compounds (**2** and **3**), $+0.0403$ for the phenyl compounds (**4** and **5**), $+0.197$ for the Cl compounds (**6** and **7**), $+0.244$ for the CN compounds (**8** and **9**), $+0.188$ for the $COOCH_3$ compound (**10**), and $+0.309$ for the C=O compound (**11**). Plotting the logarithms of the relative solvolysis

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(18) The rate constants were taken from J. L. Mateos, C. Perez, and H. Kwart, *Chem. Commun.*, 125 (1967). The $\Delta H^{\ddagger}$ and $\Delta S^{\ddagger}$ were calculated by us with a computer.

(19) The rates were also studied by S. Winstein and N. J. Holness, *J. Amer. Chem. Soc.*, **77**, 5562 (1955).

(20) When a 20 m*M* solution of the tosylate was acetolyzed, k_1, $\Delta H^{\ddagger}$, and $\Delta S^{\ddagger}$ were 0.083×10^{-5} sec^{-1}, 28.2 kcal mol^{-1}, and 0.8 eu, respectively. Refer to "Rates" in Results.

(21) (a) J. L. Fry, C. J. Lancelot, L. K. M. Lam, J. M. Harris, R. C. Bingham, D. J. Raber, R. E. Hall, and P. v. R. Schleyer, *J. Amer. Chem. Soc.*, **92**, 2538 (1970); (b) J. L. Fry, J. M. Harris, R. C. Bingham, and P. v. R. Schleyer, *ibid.*, **92**, 2540 (1970); (c) P. v. R. Schleyer, J. L. Fry, L. K. M. Lam, and C. J. Lancelot, *ibid.*, **92**, 2542 (1970).

(22) (a) S. Winstein, E. Allred, R. Heck, and R. Glick, *Tetrahedron*, **3**, 1 (1958); (b) footnote 2, 3, in ref 21c.

(23) The value was 34 for *trans*-2β-decalyl tosylate. The solvolyses of this compound and some related compounds will be described in a detail in a subsequent paper.

(24) Cited from J. E. Nordlander and T. J. McCrary, Jr., *J. Amer. Chem. Soc.*, **94**, 5133 (1972). The value of 30 was also reported for 4,4-dimethylcyclohexyl tosylate.

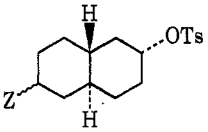
(25) In some cases a logical estimation of inductive effects of substituents was achieved by application of the Hammett–Taft relationship, $\log k/k_0 = \rho^*\sigma^*$.[10a,27,28]

(26) Application of this method to other steroid systems to test its generality was suggested by Kirk and Hartshorn. Refer to ref 2.

(27) P. E. Peterson, *Tetrahedron Lett.*, 181 (1963).

(28) A. Streitwieser, Jr., *J. Amer. Chem. Soc.*, **78**, 4935 (1956).

TABLE I
SOLVOLYSIS RATES AND ACTIVATION PARAMETERS[a-c]



Compd (Subst., Z)	Trifluoroacetolysis		Acetolysis		Ethanolysis	
	Temp., °C	k_1, sec^{-1}	Temp, °C	k_1, sec^{-1}	Temp, °C	k_1, sec^{-1}
	15.0	$(3.32 \pm 0.03) \times 10^{-5}$	80.2	$(5.19 \pm 0.12) \times 10^{-5}$	85.3	$(3.80 \pm 0.08) \times 10^{-5}$
	30.0	$(2.21 \pm 0.04) \times 10^{-4}$	95.0	$(2.52 \pm 0.25) \times 10^{-4}$	100.0	$(1.64 \pm 0.06) \times 10^{-4}$
1e-OTs	40.0	$(6.84 \pm 0.10) \times 10^{-4}$	110.3	$(1.12 \pm 0.05) \times 10^{-3}$	115.0	$(6.16 \pm 0.33) \times 10^{-4}$
(H)	50.0^d	2.04×10^{-3}	50.0^d	1.35×10^{-6}	50.0^d	7.26×10^{-7}
	Rel rate	1.00	Rel rate	1.00	Rel rate	1.00
	$\Delta H^{\ddagger}$	21.2 ± 0.2	$\Delta H^{\ddagger}$	26.7 ± 0.1	$\Delta H^{\ddagger}$	25.2 ± 0.3
	$\Delta S^{\ddagger}$	-5.5 ± 0.6	$\Delta S^{\ddagger}$	-2.8 ± 0.2	$\Delta S^{\ddagger}$	8.8 ± 0.8
	30.0	$(2.52 \pm 0.02) \times 10^{-5}$	80.1	$(2.89 \pm 0.18) \times 10^{-5}$	85.2	$(3.02 \pm 0.04) \times 10^{-5}$
	40.0	$(8.05 \pm 0.09) \times 10^{-5}$	94.5	$(1.45 \pm 0.06) \times 10^{-4}$	100.0	$(1.33 \pm 0.03) \times 10^{-4}$
2e-OTs	55.0	$(4.45 \pm 0.04) \times 10^{-4}$	110.1	$(7.44 \pm 0.51) \times 10^{-4}$	115.0	$(5.00 \pm 0.29) \times 10^{-4}$
(eq-CH_3O)	50.0^d	2.56×10^{-4}	50.0^d	6.08×10^{-7}	50.0^d	5.74×10^{-7}
	Rel rate	1.25×10^{-1}	Rel rate	4.50×10^{-1}	Rel rate	7.91×10^{-1}
	$\Delta H^{\ddagger}$	22.1 ± 0.4	$\Delta H^{\ddagger}$	28.4 ± 0.1	$\Delta H^{\ddagger}$	25.3 ± 0.4
	$\Delta S^{\ddagger}$	-6.7 ± 1.2	$\Delta S^{\ddagger}$	0.7 ± 0.3	$\Delta S^{\ddagger}$	-9.0 ± 1.0
	30.0	$(1.98 \pm 0.05) \times 10^{-5}$	84.8	$(3.63 \pm 0.09) \times 10^{-5}$	85.2	$(2.34 \pm 0.06) \times 10^{-5}$
	40.0	$(6.58 \pm 0.15) \times 10^{-5}$	100.4	$(1.95 \pm 0.06) \times 10^{-4}$	100.1	$(9.98 \pm 0.05) \times 10^{-5}$
3e-OTs	55.0	$(3.42 \pm 0.05) \times 10^{-4}$	115.0	$(8.29 \pm 0.49) \times 10^{-4}$	115.0	$(3.64 \pm 0.02) \times 10^{-4}$
(ax-CH_3O)	50.0^d	2.01×10^{-4}	50.0^d	4.83×10^{-7}	50.0^d	4.85×10^{-7}
	Rel rate	9.85×10^{-2}	Rel rate	3.58×10^{-1}	Rel rate	6.68×10^{-1}
	$\Delta H^{\ddagger}$	21.9 ± 0.1	$\Delta H^{\ddagger}$	27.9 ± 0.03	$\Delta H^{\ddagger}$	24.7 ± 0.3
	$\Delta S^{\ddagger}$	-7.9 ± 0.2	$\Delta S^{\ddagger}$	-1.4 ± 0.1	$\Delta S^{\ddagger}$	-11 ± 1
	20.0	$(2.74 \pm 0.06) \times 10^{-5}$	80.2	$(3.33 \pm 0.07) \times 10^{-5}$	85.2	$(3.51 \pm 0.09) \times 10^{-5}$
	35.0	$(1.73 \pm 0.06) \times 10^{-4}$	95.0	$(1.72 \pm 0.05) \times 10^{-4}$	100.0	$(1.51 \pm 0.03) \times 10^{-4}$
4e-OTs	50.1	$(9.48 \pm 0.36) \times 10^{-4}$	110.2	$(7.83 \pm 0.36) \times 10^{-4}$	115.0	$(5.63 \pm 0.16) \times 10^{-4}$
(eq-C_6H_5)	50.0^d	9.35×10^{-4}	50.0^d	7.78×10^{-7}	50.0^d	6.97×10^{-7}
	Rel rate	4.58×10^{-1}	Rel rate	5.76×10^{-1}	Rel rate	9.60×10^{-1}
	$\Delta H^{\ddagger}$	21.6 ± 0.1	$\Delta H^{\ddagger}$	27.6 ± 0.2	$\Delta H^{\ddagger}$	25.0 ± 0.3
	$\Delta S^{\ddagger}$	-5.8 ± 0.2	$\Delta S^{\ddagger}$	-1.2 ± 0.6	$\Delta S^{\ddagger}$	-9.5 ± 0.8
	15.0	$(2.07 \pm 0.08) \times 10^{-5}$	85.0	$(5.13 \pm 0.17) \times 10^{-5}$	85.3	$(2.88 \pm 0.11) \times 10^{-5}$
	30.0	$(1.34 \pm 0.03) \times 10^{-4}$	100.0	$(2.59 \pm 0.06) \times 10^{-4}$	100.0	$(1.24 \pm 0.03) \times 10^{-4}$
5e-OTs	45.0	$(7.47 \pm 0.05) \times 10^{-4}$	115.0	$(1.11 \pm 0.09) \times 10^{-3}$	115.0	$(4.47 \pm 0.06) \times 10^{-4}$
(ax-C_6H_5)	50.0^d	1.27×10^{-3}	50.0^d	7.01×10^{-7}	50.0^d	5.89×10^{-7}
	Rel rate	6.23×10^{-1}	Rel rate	5.19×10^{-1}	Rel rate	8.11×10^{-1}
	$\Delta H^{\ddagger}$	21.2 ± 0.1	$\Delta H^{\ddagger}$	27.6 ± 0.2	$\Delta H^{\ddagger}$	24.8 ± 0.5
	$\Delta S^{\ddagger}$	-6.4 ± 0.3	$\Delta S^{\ddagger}$	-1.5 ± 0.6	$\Delta S^{\ddagger}$	-10.5 ± 1.4
	30.0	$(2.70 \pm 0.05) \times 10^{-5}$	85.0	$(3.23 \pm 0.12) \times 10^{-5}$	85.2	$(2.37 \pm 0.07) \times 10^{-5}$
	45.0	$(1.56 \pm 0.02) \times 10^{-4}$	100.0	$(1.67 \pm 0.07) \times 10^{-4}$	100.0	$(1.03 \pm 0.03) \times 10^{-4}$
6e-OTs	60.0	$(7.79 \pm 0.16) \times 10^{-4}$	115.1	$(7.24 \pm 0.37) \times 10^{-4}$	115.0	$(3.86 \pm 0.28) \times 10^{-4}$
(eq-Cl)	50.0^d	2.71×10^{-4}	50.0^d	4.27×10^{-7}	50.0^d	4.61×10^{-7}
	Rel rate	1.33×10^{-1}	Rel rate	3.16×10^{-1}	Rel rate	6.35×10^{-1}
	$\Delta H^{\ddagger}$	21.9 ± 0.04	$\Delta H^{\ddagger}$	27.8 ± 0.3	$\Delta H^{\ddagger}$	25.1 ± 0.3
	$\Delta S^{\ddagger}$	-7.4 ± 0.1	$\Delta S^{\ddagger}$	-1.8 ± 0.9	$\Delta S^{\ddagger}$	-9.9 ± 0.8
	30.0	$(4.53 \pm 0.15) \times 10^{-5}$	85.0	$(2.77 \pm 0.23) \times 10^{-5}$	90.0	$(3.05 \pm 0.07) \times 10^{-5}$
	45.0	$(2.66 \pm 0.32) \times 10^{-4}$	100.0	$(1.39 \pm 0.10) \times 10^{-4}$	105.0	$(1.26 \pm 0.02) \times 10^{-4}$
7e-OTs	60.0	$(1.28 \pm 0.52) \times 10^{-3}$	115.2	$(6.59 \pm 0.48) \times 10^{-4}$	120.0	$(4.35 \pm 0.13) \times 10^{-4}$
(ax-Cl)	50.0^d	4.53×10^{-4}	50.0^d	3.36×10^{-7}	50.0^d	4.19×10^{-7}
	Rel rate	2.22×10^{-1}	Rel rate	2.49×10^{-1}	Rel rate	5.77×10^{-1}
	$\Delta H^{\ddagger}$	21.7 ± 0.2	$\Delta H^{\ddagger}$	28.3 ± 0.3	$\Delta H^{\ddagger}$	24.4 ± 0.4
	$\Delta S^{\ddagger}$	-6.8 ± 0.5	$\Delta S^{\ddagger}$	-0.9 ± 0.7	$\Delta S^{\ddagger}$	-12.4 ± 1.1
	40.0	$(3.46 \pm 0.33) \times 10^{-5}$	89.7	$(5.05 \pm 0.09) \times 10^{-5}$	85.2	$(2.15 \pm 0.04) \times 10^{-5}$
	55.0	$(1.96 \pm 0.04) \times 10^{-4}$	105.0	$(2.49 \pm 0.10) \times 10^{-4}$	100.0	$(9.57 \pm 0.19) \times 10^{-5}$
8e-OTs	70.0	$(9.42 \pm 0.50) \times 10^{-4}$	119.9	$(1.05 \pm 0.14) \times 10^{-3}$	115.0	$(3.65 \pm 0.23) \times 10^{-4}$
(eq-CN)	50.0^d	1.12×10^{-4}	50.0^d	3.99×10^{-7}	50.0^d	3.94×10^{-7}
	Rel rate	5.49×10^{-2}	Rel rate	2.96×10^{-1}	Rel rate	5.43×10^{-1}
	$\Delta H^{\ddagger}$	22.9 ± 0.1	$\Delta H^{\ddagger}$	27.7 ± 0.02	$\Delta H^{\ddagger}$	25.5 ± 0.3
	$\Delta S^{\ddagger}$	-6.0 ± 0.2	$\Delta S^{\ddagger}$	-2.2 ± 0.1	$\Delta S^{\ddagger}$	-9.0 ± 0.9
	40.0	$(2.62 \pm 0.05) \times 10^{-5}$	89.7	$(2.75 \pm 0.05) \times 10^{-5}$	90.0	$(2.00 \pm 0.06) \times 10^{-5}$
	55.0	$(1.43 \pm 0.07) \times 10^{-4}$	105.0	$(1.37 \pm 0.06) \times 10^{-4}$	105.0	$(7.86 \pm 0.15) \times 10^{-5}$
9e-OTs	70.0	$(6.68 \pm 0.20) \times 10^{-4}$	119.9	$(5.76 \pm 0.42) \times 10^{-4}$	120.0	$(2.76 \pm 0.02) \times 10^{-4}$
(ax-CN)	50.0^d	8.25×10^{-5}	50.0^d	2.15×10^{-7}	50.0^d	2.87×10^{-7}

TABLE I (*Continued*)

	Trifluoroacetolysis		Acetolysis		Ethanolsis	
(Subst., Z)	Temp, °C	k_1, sec^{-1}	Temp, °C	k_1, sec^{-1}	Temp, °C	k_1, sec^{-1}
	Rel rate	4.04×10^{-2}	Rel rate	1.59×10^{-1}	Rel rate	3.95×10^{-1}
	$\Delta H^{\ddagger}$	22.4 ± 0.04	$\Delta H^{\ddagger}$	27.8 ± 0.1	$\Delta H^{\ddagger}$	24.1 ± 0.1
	$\Delta S^{\ddagger}$	-8.1 ± 0.1	$\Delta S^{\ddagger}$	-3.2 ± 0.1	$\Delta S^{\ddagger}$	-14.4 ± 0.1
	30.0	$(2.92 \pm 0.17) \times 10^{-5}$	80.2	$(3.29 \pm 0.07) \times 10^{-5}$	85.2	$(2.92 \pm 0.01) \times 10^{-5}$
	44.5	$(1.67 \pm 0.03) \times 10^{-4}$	95.0	$(1.71 \pm 0.18) \times 10^{-4}$	100.0	$(1.29 \pm 0.05) \times 10^{-4}$
10e–OTs	60.1	$(8.96 \pm 0.15) \times 10^{-4}$	110.0	$(7.42 \pm 0.31) \times 10^{-4}$	115.0	$(4.78 \pm 0.25) \times 10^{-4}$
(eq-CO_2CH_3)	50.0[d]	3.06×10^{-4}	50.0[d]	7.94×10^{-7}	50.0[d]	5.66×10^{-7}
	Rel rate	1.50×10^{-1}	Rel rate	5.88×10^{-1}	Rel rate	7.80×10^{-1}
	$\Delta H^{\ddagger}$	22.2 ± 0.1	$\Delta H^{\ddagger}$	27.4 ± 0.4	$\Delta H^{\ddagger}$	25.2 ± 0.5
	$\Delta S^{\ddagger}$	-6.1 ± 0.4	$\Delta S^{\ddagger}$	-1.8 ± 1.1	$\Delta S^{\ddagger}$	-9.3 ± 1.2
	50.0	$(3.21 \pm 0.04) \times 10^{-5}$	90.7	$(3.01 \pm 0.32) \times 10^{-5}$	90.0	$(3.18 \pm 0.05) \times 10^{-5}$
	65.0	$(1.60 \pm 0.02) \times 10^{-4}$	105.8	$(1.52 \pm 0.24) \times 10^{-4}$	105.0	$(1.25 \pm 0.01) \times 10^{-4}$
11e-OTs	80.0	$(7.10 \pm 0.08) \times 10^{-4}$	120.0	$(5.89 \pm 0.46) \times 10^{-4}$	120.0	$(4.39 \pm 0.18) \times 10^{-4}$
(=CO)	50.0[d]	3.20×10^{-5}	50.0[d]	2.01×10^{-1}	50.0[d]	4.56×10^{-7}
	Rel rate	1.57×10^{-2}	Rel rate	1.49×10^{-1}	Rel rate	6.28×10^{-1}
	$\Delta H^{\ddagger}$	22.7 ± 0.1	$\Delta H^{\ddagger}$	28.1 ± 0.3	$\Delta H^{\ddagger}$	24.1 ± 0.06
	$\Delta S^{\ddagger}$	-8.9 ± 0.2	$\Delta S^{\ddagger}$	-2.3 ± 0.9	$\Delta S^{\ddagger}$	-13.2 ± 0.1

[a] The concentrations of tosylates were 50 m*M* for trifluoroacetolyses and 1.0 m*M* for acetolyses and ethanolyses. Temperature deviation was ±0.03°. [b] Error limits for rate constants are 95% confidence limits [degree of freedom, $\phi = n - 2$ $(n = 10)$]. [c] $\Delta H^{\ddagger}$ and $\Delta S^{\ddagger}$ were calculated by the Eyring equation and their errors are standard deviations. [d] Rates at 50° were calculated from observed rates at other temperatures and used for comparison of reactivities.

rates at 50° in trifluoroacetic acid, acetic acid, and ethanol against the $\Sigma\sigma_t^*$ constants, respectively, yielded reasonably linear correlations as shown in Figures 1–5. The ρ^* values thus obtained are listed in Table II with correlation coefficients. In Table II, A, B, and C designate the ρ^* values determined from the rates of the C_6-equatorial compounds, the C_6-axial compounds, and both the C_6-axial and C_6-equatorial compounds, respectively. The differences among the ρ^*(A), ρ^*(B), and ρ^*(C) values in trifluoroacetic acid cannot be thought to be mathematically significant if the relationship between correlation coefficients and number of compounds is considered. However, the differences between the ρ^*(A) and ρ^*(B) values in acetic acid and ethanol are significant; the ρ^*(B) values from the axial compounds are seen to be larger than those for the equatorial compound (Figures 4 and 5).

TABLE II

ρ^* VALUES

Solvent	ρ^* value		No. of compound	Correlation coefficient
CF_3COOH	(A)	−4.59	7	0.948
	(B)	−4.25	5	0.853
	(C)	−4.47	11	0.894
CH_3COOH	(A)	−1.98	7	0.900
	(B)	−2.63	5	0.988
	(C)	−2.05	11	0.871
C_2H_5OH	(A)	−0.735	7	0.901
	(B)	−1.30	5	0.970
	(C)	−0.867	11	0.792

The *magnitude of* ρ^* *increases* with solvent change from ethanol to acetic acid to trifluoroacetic acid. That the highest ρ^* is in trifluoroacetic acid is a reasonable result of the enhanced inductive effects in this solvent of low nucleophilicity. Enhancement of an electronic effect of this kind in trifluoroacetic acid has been well studied.[10a,14,29]

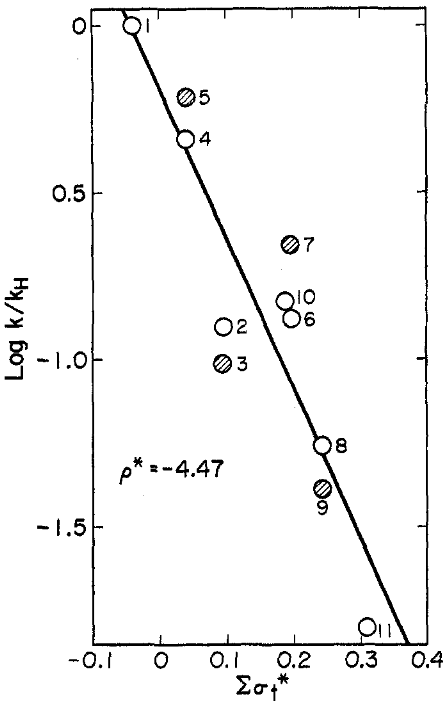


Figure 1.—$\rho^*\sigma^*$ correlation obtained from trifluoroacetolysis rates of both the C_6-axial and C_6-equatorial compounds at 50°. Points denoted by open circles refer to C_6-equatorial; those denoted by shaded circles refer to C_6-axial compounds. Numbers with circles refer to compound numbers of the tosylates in Table I.

In connection with a model for electrostatic field effects, it was of interest to us to examine the influence of the orientation of C_6 substituents on the solvolysis rates of the C_2-equatorial tosylates. The rate ratios of the tosylates bearing the C_6-axial substituent to those bearing the C_6-equatorial substituent, k_{ax}/k_{eq}, were calculated and are presented in Table III. It was observed by Noyce and Johnston[30] that 3α(a)-chloro-5α-cholestan-6α-yl tosylate solvolyzes in acetic acid

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[29] P. E. Peterson, C. Casey, E. V. P. Tao, A. Agtarap, and G. Thompson, *J. Amer. Chem. Soc.*, **87**, 5163 (1965).

[30] (a) D. S. Noyce and G. A. Selter, *J. Org. Chem.*, **36**, 3458 (1971); (b) D. S. Noyce, B. N. Bastian, R. T. S. Lau, R. S. Monson, and B. Wienstein, *ibid.*, **34**, 1247 (1969); (c) D. S. Noyce and B. E. Johnston, *ibid.*, **34**, 1252 (1969).

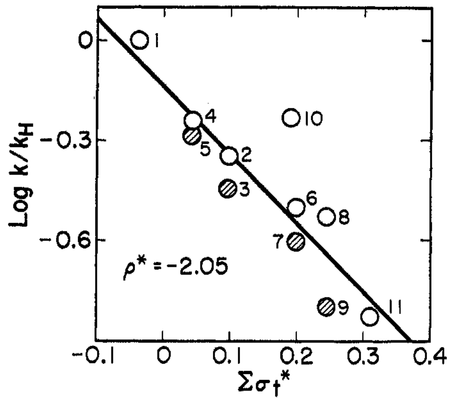


Figure 2.—$\rho^*\sigma^*$ correlation obtained from acetolysis rates of both the C_6-axial and C_6-equatorial compounds at 50° (use of points and numbers as in Figure 1).

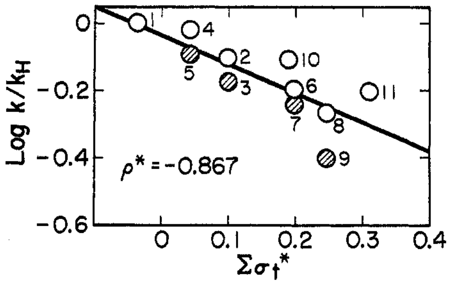


Figure 3.—$\rho^*\sigma^*$ correlation obtained from ethanolysis rates of both the C_6-axial and C_6-equatorial compounds (use of points and numbers as in Figure 1).

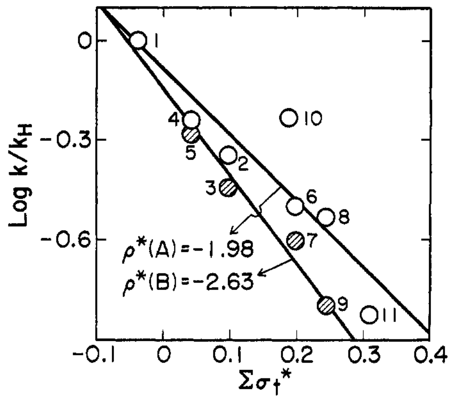


Figure 4.—Individual $\rho^*(A)\sigma^*$ and $\rho^*(B)\sigma^*$ correlations obtained from acetolysis rates of the C_6-axial and C_6-equatorial compounds (use of points and numbers as in Figure 1).

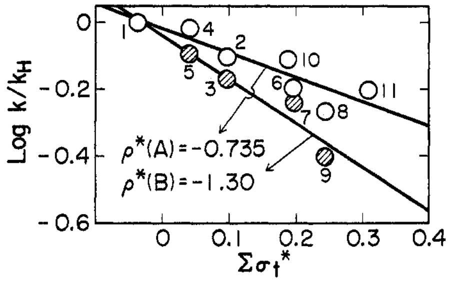


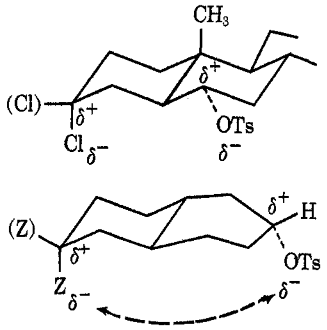
Figure 5.—Individual $\rho^*(A)\sigma^*$ and $\rho^*(B)\sigma^*$ correlations obtained from ethanolysis rates of the C_6-axial and C_6-equatorial compounds (use of points and numbers as in Figure 1).

TABLE III

RATE RATIOS BETWEEN C_6(ax)- AND C_6(eq)-SUBSTITUTED TOSYLATES AT 50.0°

Substituent	k_{ax}/k_{eq}		
	CF_3COOH	AcOH	EtOH
CH_3O	0.785	0.794	0.845
C_6H_5	1.36	0.901	0.845
Cl	1.67	0.787	0.909
CN	0.737	0.539	0.728

faster than its 3β (equatorial) epimer; $k_{ax}/k_{eq} = 1.8$ at 75°. As the major factor for this,[30] they pointed out that the negative end of the chloro dipole substituent in the more reactive 3α tosylate lies closer to the reaction center than the corresponding end in the less reactive 3β tosylate. In the present study, the C_6-(equatorial) substituted compounds are a little more reactive than the C_6-(axial) substituted compounds and the k_{ax}/k_{eq} ratios are roughly constant, being in the range of 0.7–0.9 in all three solvents, although trifluoroacetolyses of chloro- and phenyl-substituted compounds are exceptions. The inductive effect operating through C–C bonds cannot provide an explanation of this reactivity difference resulting from the orientation of the C_6 substituents. Inspection of molecular models indicates that the negative ends of the axial dipolar substituents lie closer to the negative end of the leaving tosyloxy group, assuming the usual half-chair conformation for the reacting ring.



We consider the reason why reactivities of the C_6 (axial) tosylates are lower than those of their equatorial counterparts is that unfavorable dipole–dipole interaction between the substituent and the leaving tosyloxy group (between the two δ^- in the picture) is greater in the axial compounds. As mentioned above, the ρ^*(B) values in acetic acid and ethanol are larger than the corresponding ρ^*(A) values; the rate-retarding effects of the axial substituent are greater than those of the equatorial substituents. This fact is thought to be an important indication for a field effect such as dipole–dipole interaction. The ρ^*(B) value in trifluoroacetic acid is not larger than the ρ^*(A) value. In this highly acidic solvent, solvation (protonation) of the negative ends of the dipoles would be very strong, rendering them incapable of interaction.

Experimental Section

Melting points were taken on a Yanagimoto melting point apparatus and are uncorrected. Nmr spectra were determined on a Varian A-60 spectrometer using tetramethylsilane as internal standard. Infrared spectra were measured on a Nippon Bunko DS201B spectrometer. Uv spectra were measured on a Hitachi EPS-032 and/or a Hitachi EPU-2A spectrometer. Vpc analyses were performed on a Hitachi gas chromatograph Model K53 equipped with a hydrogen flame ionization detecter using the following columns: (A) 1 m × 3 mm stainless steel column packed with Carbowax 20M 5%, (B) 2 m × 3 mm Carbowax

20M 10%, and (C) 2 m × 3 mm DEGS 10%. Nitrogen was used as a carrier gas.

2α- and 2β-hydroxy-*trans*-6-decalones (11e-OH and 11a-OH) were prepared from 6-methoxy-2-tetralol[31] by methods described in the literature.[11]

6-Substituted 2α-*trans*-decalols (1e-OH–10e-OH) were synthesized from 11e-OH or 11a-OH in accordance with methods described in the literature.[12]

General Procedure of Tosylation.—To a solution of the alcohol, whose purity (more than 99.0%) was checked by vpc analyses, in pyridine was added about 1.3–1.5 molar equiv of *p*-toluenesulfonyl chloride under ice cooling and the mixture was allowed to stand at 6–10°. Cracked ice and water were added to the reaction mixture and the resulting precipitate or mixture was extracted with ether. The ether solution was washed with chilled water, dried over sodium sulfate, evaporated, and purified by silica gel chromatography followed by recrystallization. Properties and elementary analyses of *p*-toluenesulfonates prepared in this study are summarized in Table IV. Nmr data of the C_2 and C_6 protons were used to establish the configuration of substituents and the molar extinction coefficient (ϵ) at 273.2 mμ of the tosylates was used for the trifluoroacetolysis rates.

TABLE IV

PROPERTIES, ANALYSES, AND SPECTRAL PARAMETERS OF *p*-TOLUENESULFONATES[a]

Compd	Mp, °C	Formula	Nmr in $CDCl_3$, δ[b] C_2 H	C_6 H	ϵ_{max}[c]
1e-OTs	62–63	$C_{17}H_{24}O_3S_1$	4.44 (21)		448
2e-OTs	90–91	$C_{18}H_{26}O_4S_1$	4.43 (21)	3.13 (21)	455
3e-OTs	66–67	$C_{18}H_{26}O_4S_1$	4.47 (21)	3.50 (7)	452
4e-OTs	112–113	$C_{23}H_{28}O_3S_1$	4.43 (21)	2.56 (21)	461
5e-OTs	92–94	$C_{23}H_{28}O_3S_1$	4.44 (21)	3.12 (10)	466
6e-OTs	146–147	$C_{17}H_{23}O_3S_1Cl_1$	4.43 (21)	3.80 (21)	463
7e-OTs	83–84	$C_{17}H_{23}O_3S_1Cl_1$	4.43 (21)	4.4–4.6	457
8e-OTs	157–158	$C_{18}H_{23}O_3S_1N_1$	4.42 (21)	2.4–2.5	460
9e-OTs	131–133	$C_{18}H_{23}O_3S_1N_1$	4.44 (21)	2.98 (7)	457
10e-OTs	98–99	$C_{19}H_{26}O_5S_1$	4.43 (21)	2.3–2.4	460
11e-OTs	80–82	$C_{17}H_{22}O_4S_1$	4.53 (23)		460

[a] Satisfactory analyses (±0.3% in C, H, and S) were reported for all compounds in the table: Ed. [b] Downfield from $(CH_3)_4Si$. Values in parentheses are half-height band widths in hertz. [c] Molecular extinction coefficient of λ_{max} 273.2 mμ in CH_3OH solutions, taken with a Hitachi EPU-2A spectrometer using a 10-mm cell with cap.

Kinetic Measurements in Acetic Acid and Ethanol.—Measurements of the rates of acetolyses and ethanolyses were carried out by the standard procedure.[13] Reagent grade acetic acid was heated under reflux with about 5% potassium permanganate for 10 hr, distilled, dried over phosphorus pentoxide, and then redistilled. The distilled acid was further purified by collecting the fraction boiling at 117–118° after refluxing with addition of 5% of acetic anhydride; 1% acetic anhydride was then added. Sodium acetate standard solution was made by dissolving anhydrous sodium carbonate in acetic acid and by refluxing for 5 hr with sufficient acetic anhydride to remove the water of neutralization, and its concentration was adjusted to 0.022 *M* at room temperature. Sodium acetate solution (1.1 m*M*) was diluted with the above acetic acid before use. Ethanol (99.5%) was heated under reflux with about 3% sodium metal for 2 hr and then distilled through a vacuum-jacketed column packed with glass rings. The middle fraction was collected and stored under argon.

For acetolysis, a solution of 1.0 m*M* of the tosylate in acetic acid containing 1.1 m*M* sodium acetate was prepared at room temperature. Aliquots (4.0 ml) were distributed into tubes which were sealed under nitrogen after freezing in Dry Ice-acetone. The tubes were placed in a constant-temperature bath and were successively withdrawn after appropriate intervals of time. "Infinity" tubes were removed after at least 10 half-lives and usually three were taken for each run. The contents were cooled and diluted with 10 ml of acetic acid and remaining sodium acetate was titrated with standard 0.004 *N* perchloric acid in acetic acid using a Metrohm potentiograph E336 A. Plots of log $(A_t - A_\infty)$ *vs.* time, where A_∞ and A_t are titers at infinity and at the given times, respectively, were uniformly linear. The slopes multiplied by −2.303 gave the pseudo-first-order rate constants.

Ethanolysis was carried out without addition of base. Rates were measured by the above-described technique, the concentration of tosylates being 1.0 m*M*. The tubes (4.0 ml), which were withdrawn after appropriate intervals of time, were cooled and diluted with 10 ml of 99.5% ethanol. Rates of acid formation were followed by potentiometric titration using 0.004 *N* aqueous sodium hydroxide. The rate constants were determined by the infinity titer method as in the acetolysis.

Kinetic Measurements in Trifluoroacetic Acid.—The rates of trifluoroacetolysis were measured by a modification of the spectrophotometric method advanced by Peterson and coworkers.[14] Trifluoroacetic acid (2 l.) and trifluoroacetic acid anhydride (50 ml) were refluxed for 5 hr. The solution was then distilled through a vacuum-jacketed column packed with glass rings. The middle fraction was collected and stored under argon. After distillation, 1% trifluoroacetic anhydride was added to the acid. Buffered medium was made in a volumetric flask by dissolving anhydrous sodium carbonate in the above trifluoroacetic acid, allowing it to stand for 1 day at room temperature with sufficient trifluoroacetic anhydride to remove the water of neutralization, then adjusting its concentration to 0.06 *M*. A solution of 0.05 *M* of the tosylates in trifluoroacetic acid containing 0.06 *M* sodium trifluoroacetate was prepared at 0° and aliquots (1.0 ml) were distributed into tubes which were sealed under nitrogen after freezing in Dry Ice–acetone. The tubes were placed in a constant-temperature bath and were successively withdrawn after appropriate intervals of time. The contents were cooled in a salt–ice bath. Each tube was opened, poured into a 50-ml volumetric flask, and diluted with methanol up to the mark. The absorbance of the remaining tosylate was measured at 273.2 mμ using a Hitachi EPU-2A spectrometer. In all the measurements, the spectrometer was zeroed at 285.0 mμ with the actual sample. The rate constants were determined by the plots against time of log c_{OTs}, calculated from the equations given in Results.

The validity of this method was confirmed by direct comparison with rate constants calculated by the infinity titer method for the compounds **8e**-OTs, **9e**-OTs, and **11e**-OTs. The differences between rate constants obtained by the two methods were within 3%.

Acetolysis Products.—A solution of 0.6 mmol of the tosylate in 30 ml of acetic acid containing 0.022 *M* sodium acetate was sealed in a glass bomb under nitrogen after being frozen in Dry Ice–acetone. The bomb was then heated at 100.0° for a specified time (10–11 half-lives), calculated from the previously determined rate constant. The bomb was cooled and opened; the reaction mixture was poured into water and extracted with ether. The combined ethereal extract was washed with water, aqueous potassium carbonate, and water, dried over sodium sulfate, and evaporated. The product was analyzed by vpc and the ratio of acetate to olefin was determined by peak area measurement. The olefin and acetate fractions were then separated on a small column of silica gel (4–5 g); elution with 2 or 3 column volumes of *n*-hexane gave the olefin fraction and further elution with ether-*n*-hexane (1:4) gave the acetate fraction. The olefin fractions were collected, dried under reduced pressure, and weighed. The acetate fractions were collected and identified with authentic samples.[12] The yields of the acetates were determined to be quantitative by vpc with internal standards. No data indicating rearranged acetates were obtained in the product analyses. The olefin fractions were shown to consist of the Δ^1 olefin and the Δ^2 olefin by nmr and mass spectra and vpc analyses. Separation of the olefins by vpc was not satisfactory on our columns. The olefin fraction from **2e**-OTs showed nmr ($CDCl_3$) δ 3.18 (1 H, broad s, $W_{1/2}$ = 21 Hz, C_6-ax H), 3.35 (3 H, s, OCH_3), 5.4–5.7 (2 H, m, olefinic protons); mass spectrum *m/e* 166 (M^+). That from **3e**-OTs showed nmr ($CDCl_3$) δ 3.30 (3 H, s, OCH_3), 3.52 (1 H, broad s, $W_{1/2}$ = 7 Hz, C_6-eq H), 5.4–5.7 (2 H, m, olefinic protons); mass spectrum *m/e* 166 (M^+). That from **6e**-OTs showed nmr ($CDCl_3$) δ 3.90 (1 H, broad s, $W_{1/2}$ = 21 Hz, C_6-ax H), 5.4–5.7 (2 H, m, olefinic protons); mass spectrum *m/e* 170 (M^+). That from **7e**-OTs showed nmr ($CDCl_3$) δ 4.53 (1 H, broad s, $W_{1/2}$ = 7 Hz, C_6-eq H), 5.4–5.7 (2 H, m, olefinic protons); mass spectrum *m/e* 170 (M^+). That from **11e**-OTs showed nmr ($CDCl_3$) δ 5.5–5.7 (2 H, m, olefinic protons); mass spectrum *m/e* 150 (M^+).

Products and yields from **1e**-OTs and **2e**-OTs were described in Results. Products from **3e**-OTs were an olefin mixture of 57.9%,

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[31] W. Nagata and T. Terasawa, *Chem. Pharm. Bull.*, **9**, 267 (1961).

the 2α-acetate of 2.7%, and the 2β-acetate of 34.0%. Those from **6e**-OTs were the olefin mixture of 57.1%, the 2α-acetate of 1.7%, and the 2β-acetate of 35.4%. Those from **7e**-OTs were the olefin mixture of 58.1%, the 2α-acetate of 1.6%, and the 2β-acetate of 34.0%. Those from **11e**-OTs were the olefin mixture of 55.2%, the 2α-acetate of 1.1%, and the 2β-acetate of 31.9%.

Registry No.—**1e**, 2529-06-8; **1e**-OTs, 19124-24-4; **2e**, 36284-21-6; **2e**-OTs, 39003-14-0; **3e**, 36126-50-8; **3e**-OTs, 39003-16-2; **4e**, 36407-90-6; **4e**-OTs, 36126-60-0; **5e**, 36126-54-2; **5e**-OTs, 39062-17-4; **6e**, 36126-58-6; **6e**-OTs, 39010-18-9; **7e**, 36284-22-7; **7e**-OTs, 39010-20-3; **8e**, 36126-73-5; **8e**-OTs, 39010-22-5; **9e**, 36126-63-3; **9e**-OTs, 39010-24-7; **10c**, 36126-75-7; **10e**-OTs, 39010-26-9; **11e**, 34824-00-5; **11e**-OTs, 36126-61-1; *p*-toluenesulfonyl chloride, 98-59-9.

The Cycloaddition of Ethylene to Acrylonitrile

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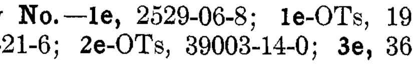
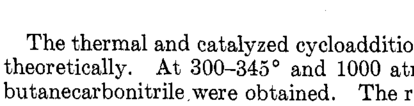
The thermal and catalyzed cycloadditions of ethylene to an acrylonitrile were investigated experimentally and theoretically. At 300–345° and 1000 atm ethylene pressure, up to 30% conversion of acrylonitrile to cyclobutanecarbonitrile were obtained. The reaction reached equilibrium under these conditions. This was shown by obtaining the thermodynamic properties of cyclobutanecarbonitrile by spectroscopic means, and calculating the free-energy change for the reaction: $\Delta F° = -21{,}500 + 45.52T$. Below 300° kinetic control occurred. A catalyst search revealed weak acceleration by nickel(0) compounds. This is the second example of cycloaddition of ethylene catalyzed by a transition metal.

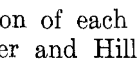
In connection with work on the synthesis and polymerization of 1-bicyclobutanecarbonitrile,[2] the need arose for a ready synthesis of cyclobutanecarbonitrile as a possible intermediate. The cycloaddition of ethylene to acrylonitrile suggested itself as such a route.



Although this reaction has not been reported previously, cyclodimerization of each of these olefins to itself is known. Coyner and Hillman[3] showed that acrylonitrile underwent cyclodimerization at 200° in 20% yield, and this reaction has subsequently received much attention in the patent literature.[4-7] The biradical mechanism was ascribed to this reaction.[3]



Recently Back and coworkers[8] carried out the thermal cyclodimerization of ethylene to cyclobutane. At



450° with a reaction time of 5–20 min, a 0.02% conversion to cyclobutane was achieved.

The results of our studies on the cycloaddition of ethylene to acrylonitrile form the basis of the present report.

Results

Thermal Cycloadditions.—The reactions were carried out in stainless steel pressure vessels at elevated temperatures. It was found necessary to work at 300–345° to obtain significant conversions to cyclobutanecarbonitrile. Ethylene, at 1000 atm pressure, was used in large excess over acrylonitrile (17:1–30:1) to form the desired cycloaddition and to minimize the competing cyclodimerization of acrylonitrile. This pressure was about optimum; use of 3000 atm led to lower decomposition temperatures and tar formation.[9] Polymer and tar formation were minimized by adding inhibitors. Best results below 300° were achieved with *p*-methoxyphenol or 2,6-di-*tert*-butylresorcinol; above 300° these inhibitors were used in conjunction with cupric salts. Addition of a little water[6] to the reaction mixtures was also beneficial in minimizing tar formation. The results are summarized in Table I. There is considerable scatter owing to experimental difficulties. However, under best conditions, up to 30% of the acrylonitrile charged can be converted to cyclobutanecarbonitrile.

Calculation of Equilibrium Constants.—It was considered important to establish whether the observed yields were limited by equilibrium or by kinetic factors. To this end we calculated the free-energy change of the cycloaddition reaction as a function of temperature, using spectroscopic methods to determine the individual free energies.

The thermodynamic properties of ethylene[10] and of acrylonitrile[11,12] as functions of temperature were already available. The heat of formation of cyclobutanecarbonitrile was also known.[13] For the variation of

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[3] E. C. Coyner and W. S. Hillman, *J. Amer. Chem. Soc.*, **71**, 324 (1949).

[4] K. Sennewald, A. Goetz, and G. Kalbrath, German Patent 1,081,008 (1960) to Knapsack-Griesheim AG; *Chem. Abstr.*, **55**, 13338 (1961).

[5] French Patent 1,397,085 (1965) to Knapsack-Griesheim AG; *Chem. Abstr.*, **63**, 6885 (1965).

[6] J. D. Idol, J. L. Greene, and N. R. Gray, U. S. Patent 3,275,675 (1966) to Standard Oil Co. of Ohio; *Chem. Abstr.*, **65**, 18507 (1966).

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[9] A referee has suggested that cycloadditions of acrylonitrile work best in the gas phase, and that the deleterious effect of increased pressure consists of increasing the amount of liquid phase.

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[11] F. Halverson, R. F. Stamm, and P. J. Whalen, *J. Chem. Phys.*, **16**, 808 (1948).

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