Effect of Pressure on the Rate of Solvolysis. Formolysis and Methanolysis of Secondary Alkyl Tosylates[1]

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The effect of pressure on the formolysis and methanolysis rates of representative secondary alkyl tosylates was investigated, and the activation volumes, $\Delta V_0^{\neq}$, were estimated. The values of activation volume for formolysis were found to correlate excellently with σ^*. This conformity of $\Delta V_0^{\neq}$ to the Hammett-type correlation is interpreted as a consequence of the k_c-character of the reaction. The values of activation volume for methanolysis, however, converged to more negative values. The k_s-character of methanolysis is thought to be responsible for this behavior. The k_c-k_s-hybrid nature of the reaction is also discussed.

Solvolyses with tertiary substrates cannot be interpreted as direct displacement reactions, but many experimental results are consistent with the ionization hypothesis (**Lim**[2]), whereas primary substrates generally react by the direct displacement mechanism (**N**[2]). Since these two representations are intended to be extremes of a continuous sequence with no sharp dividing line, it is usual to refer to an intermediate set of borderline case for most of solvolyses of secondary substrates. Recently, the important participation of solvent molecule in solvolysis has come to be recognized even for secondary alkyl substrates. Schleyer[3] has interpreted the solvent assistance in the solvolysis of secondary alkyl substrates in terms of "a basic difference with respect to the magnitude of nucleophilic solvent participation: large in ordinary unhindered secondary (and primary) systems and small or absent in crowded substrates such as 2-adamantyl and tertiary derivatives."

Investigations of solvolytic displacement reactions under high pressure yield the activation volumes of the reactions, $\Delta V^{\neq}$, which will reflect the difference in degree of solvation between highly dipolar transition states and neutral initial states.[4] It may then be anticipated that the application of a high-pressure technique to the systematic study of solvolytic displacement reactions will permit us to analyse the reaction mechanism in terms of the activation volume. However, in previous reports on this subject, attention has been concentrated on the effect of the change in solvent composition on the activation volumes for solvolyses in aqueous binary solvent mixtures.[5] So far as we know, there have been only a few investigations in which the volume parameters were examined in terms of the substrate structure under otherwise identical conditions.[6] Moreover, no information is available about values of activation volume for solvolyses in polar solvents of low nucleophilicity.

The present paper will concern the investigation of the pressure effect on the solvolysis rates of representative secondary alkyl tosylates in two solvents—formic acid and methanol. Although a part of the desired rate data at atmospheric pressure can be gathered from the literature,[7] they were re-investigated in order to make an accurate estimate of $\Delta V_0^{\neq}$, the activation volume at atmospheric pressure.

Results and Discussion

The first-order rate constants for the formolysis and methanolysis of secondary alkyl tosylates under pressure are given in Table 1. All the measurements were carried out at 25.0 °C in order to avoid complicated corrections due to the temperature dependence of the reaction rate under pressure. The values of the activation volume at atmospheric pressure were determined by means of the following equation:

$$\Delta V^{\neq} = -RT(\partial \ln k/\partial P)_T \qquad (1)$$

where $\Delta V^{\neq}$ is the difference in the partial molal volumes between the transition state and the initial state. The evaluation of $\Delta V_0^{\neq}$ was made by the least-squares fit of the data to the following linear expression for $\ln k$ in the range from 1 to 700 kg/cm², because the plots of $\ln k$ against pressure were linear at least up to this pressure for most of the reactions examined:[8]

$$\ln k = a + bP \qquad (2)$$

The values of $\Delta V_0^{\neq}$ are listed in Table 2. The rate of each compound relative to the reference compound, isopropyl tosylate, is also shown.

Reaction Mechanism. As is shown in Table 1, the formolysis rate increased monotonously as the substituent became more electron-donating. The rate increase in formic acid was more significant than that in

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[1] Organic Reaction under High Pressure XI. Part X, see A. Sera, T. Miyazawa, T. Matsuda, Y. Togawa, and K. Maruyama, This Bulletin, **46**, 3490 (1973).

[2] S. Winstein, E. Grunwald, and H. W. Jones, *J. Amer. Chem. Soc.*, **73**, 2700 (1951).

[3] 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. von R. Schleyer, *ibid.*, **92**, 2538 (1970); b) J. L. Fry, J. M. Harris, R. C. Bingham, and P. von R. Schleyer, *ibid.*, **92**, 2540 (1970); c) P. von R. Schleyer, J. L. Fry, L. K. M. Lam, and C. J. Lancelot, *ibid.*, **92**, 2542 (1970); d) S. H. Liggero *et al.*, *ibid.*, **92**. 3789 (1970).

[4] W. J. le Nobel, "Progress in Physical Organic Chemistry", Vol. 5, ed. by A. Streitwieser, Jr. and R. W. Taft, Jr., Interscience Publisher, New York (1967) p 207.

[5] J. B. Hyne and coworkers, *Can. J. Chem.*, **48**, 2025, 2494 (1970); **49**, 2394 (1971); *J. Amer. Chem. Soc.*, **88**, 2104 (1966). B. T. Baliga and E. Whalley, *Can. J. Chem.*, **48**, 528 (1970), and references cited therein.

[6] a) W. J. le Noble, B. L. Yates, and A. W. Scaplehorn, *J. Amer. Chem. Soc.*, **89**, 3751 (1967); b) W. J. le Noble and A. Shurpik, *J. Org. Chem.*, **35**, 3588 (1970); c) B. T. Baliga and E. Whalley, *J. Phys. Chem.*, **73**, 654 (1969); d) K. J. Laidler and R. Martin, *Int. J. Chem. Kinet.*, **1**, 113 (1969); e) C. Yamagami and A. Sera, *Chem. Lett.*, **1972**, 741; f) A. Sera, T. Miyazawa, T. Matsuda, Y. Togawa, and K. Maruyama, This Bulletin, **46**, 3490 (1973).

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

TABLE 1. SOLVOLYSIS RATE CONSTANTS OF SECONDARY ALKYL TOSYLATES, R_1-CH(OTs)-R_2, UNDER PRESSURE AT 25.0 °C

	Substrate		Pressure (kg/cm^2)					
	R_1	R_2	1	100	300	500	700	1000
			Formolysis $10^5 k$ (s^{-1} a))					
(1)	Me	Me	2.47	—	2.97	3.34	3.71	4.27
(2)	Me	Et	6.04	—	7.07	7.69	8.69	—
(3)	Et	Et	13.1	—	15.2	16.1	18.1	—
(4)	Me	*iso*-Pr	32.5	34.0	37.3	41.4	45.1	—
(5)	Me	*t*-Bu	31.8	—	35.6	39.2	42.4	—
			Methanolysis $10^6 k$ (s^{-1} a))					
(1)	Me	Me	1.27	—	1.60	1.83	2.14	2.58
(2)	Me	Et	1.61	—	2.06	2.38	2.75	3.27
(3)	Et	Et	2.73	—	3.50	3.92	4.68	5.44
(4)	Me	*iso*-Pr	0.980	—	1.25	1.44	1.62	1.92
(6)	*iso*-Pr	*iso*-Pr	2.51	2.70	3.05	3.42	3.84	—
(7)	*iso*-Pr	*t*-Bu	0.850	0.966	1.09	1.23	1.37	—
(8)	*t*-Bu	*t*-Bu	7.52	8.45	9.52	10.8	12.2	13.7
(9)	*t*-Bu	C(Et)$_3$	109	117	132	147	163	—

a) Average of two or more experiments. Estimated error was less than 2% of its value.

methanol. An attempt to measure accurately the rate for the formolysis of (6) was unsuccessful because of its high reactivity under the conditions employed.[9] The correlation between log k at atmospheric pressure and σ^*_{add}[10] showed a good linearity with ρ^* of -3.7,[11] which is in good accord with the ρ^I value of -7.79 reported by Peterson *et al.* for the formolysis of unbranched alkyl tosylates.[7] In addition, the observed formolysis rates under pressure were also correlated to σ^*_{add} to give good straight lines.

Formic acid is considered to be a solvent in which a k_c-process proceeds quite readily because of its powerful ionizing ability as well as its poor nucleophilicity. Hence, the present reaction is thought to be k_c-like[12] in character. Moreover, the observed linear Hammett-Taft correlation indicates that the reaction is mainly controlled by the inductive effect of substituents, even in the case of 1-*t*-butylethyl tosylate (5), a sterically crowded substrate. On the other hand, the methanolysis rates varied irregularly along with the series of substrates. Although the high nucleophilic nature of this solvent facilitates a k_s-process,[13] this irregularity could not be interpreted as a manifestation of any single mechanism or as the predominance of one controlling factor over the whole range of substrates examined. This phenomenon must be a consequence of a change in the solvolysis mechanism from a k_s- to a k_c-process. In the absence of any appreciable steric hindrance in the transition state (for $(1)\sim(3)$), the reaction must be strongly assisted by a solvent molecule (k_s-character). The contribution of k_s-process to the over-all rate process should, however, become less important with an increase in the steric hindrance. This causes an apparent rate retardation. This is the case for (4)—(7), as is shown in Table 1.[14] Remarkable rate increases were observed for (8) and (9). This means that the presence of extremely bulky substituents causes the substrates to be solvolyzed no longer through a k_s-process, but through a k_c-process predominantly. Actually, di-*t*-butylmethyl tosylate (8) has been reported to have no tendency to undergo k_s-solvolysis.[3d] A comparison of the (8)/(1) rate ratio in the two solvents is worth noting; it is 320 in formic acid and 6 in methanol. These figures suggest the intervention of solvent assistance in the methanolysis of an unhindered substrate(1).[3d]

All the points discussed above demonstrate that the formolysis exhibits a more k_c-character than does the methanolysis, and that in the methanolysis the mechanistic shift from the k_s- to the k_c-process actually

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[8] In the case of compounds $(7)\sim(9)$, the plots of ln k against pressure exhibit good straight lines except points at atmospheric pressure, which deviated downwards by about 3%. This phenomenon, not regarded as a result of experimental uncertainty, may imply existence of any factors which would be depressed by application of external pressure. In these cases, we estimated $\Delta V_0^{\ddagger}$ regardless of the points at atmospheric pressure.

[9] A rough estimation showed that the formolysis rate constants amount to 9.6×10^{-4} s^{-1} for (6) and 1.2×10^{-2} s^{-1} for (8)[3d] at 25 °C.

[10] $\sigma^*_{\text{add}}=\sigma^*_{R2}+\sigma^*_{R1}$. R. W. Taft, Jr., "Steric Effects in Organic Chemistry", ed. by M. S. Newman, John Wiley & Sons, Inc., New York (1956), p. 556.

[11] Not including compound (4). Formolysis of this tosylate is 2.5 times as fast as that expected from the $\rho^*-\sigma^*$ relation. A compound with similar structural feature, 1-isopropylbutyl *p*-toluenesulfonate was reported to exhibit an analogous abnormal behavior in acetolysis, W. Pritzkow and K. H. Schöppler, *Chem. Ber.*, **95**, 834 (1962).

[12] The definition of these terms, k_c-, k_s-, and k_Δ-processes of solvolyses, was made by Winstein (S. Winstein, E. Allred, R. Heck, R. Glick, *Tetrahedron*, **3**, 1 (1957). In the present paper, however, the term "k_c-process" signifies non-k_s-process, and hence can include k_Δ-process in some cases. Distinction between k_c- and k_Δ-processes is out of the purpose of the present investigation.

[13] a) E. Grunwald and S. Winstein, *J. Amer. Chem. Soc.*, **70**, 846 (1948). For quantitative treatments of solvent nucleophilicity, see b) P. E. Peterson and F. J. Waller, *ibid.*, **94**, 991(1972); c) T. W. Bentley, F. L. Schadt, and P. von R. Schleyer, *ibid.*, **94**, 992 (1972), and references cited therein.

[14] The rate for (5) was too slow to be measured.

TABLE 2. ACTIVATION VOLUMES AND RELATIVE RATES FOR SOLVOLYSES OF SECONDARY ALKYL TOSYLATES, R_1-CH(OTs)-R_2

	Substrate		$\Delta V_0^{\ne\,a,b)}$ (cm³/mol)	Rel. rate$^{a)}$	$\Delta V_0^{\ne\,a,b)}$ (cm³/mol)	Rel. rate$^{a)}$
	R_1	R_2				
			Formolysis		Methanolysis	
(1)	Me	Me	−14.7	1	−18.9	1
(2)	Me	Et	−12.9	2.4	−19.4	1.3
(3)	Et	Et	−11.2	5.3	−18.4	2.1
(4)	Me	*iso*-Pr	−11.7	13	−18.3	0.78
(5)	Me	*t*-Bu	−10.5	13	—	—
(6)	*iso*-Pr	*iso*-Pr	—	39$^{c)}$	−15.2	2.0
(7)	*iso*-Pr	*t*-Bu	—	—	−15.4$^{e)}$	0.67
(8)	*t*-Bu	*t*-Bu	—	320$^{d)}$	−15.6$^{e)}$	5.9
(9)	*t*-Bu	C(Et)$_3$	—	—	−13.9$^{e)}$	86

a) At 25.0 °C at atmospheric pressure. b) Accurate to within 1 cm³/mol. c) See footnote 9. d) Ref. 3d. e) See footnote 8.

TABLE 3. SOLVENT PARTICIPATION PARAMETERS FOR SECONDARY ALKYL TOSYLATES (25 °C)

Substrate	$Q^{a)}$	$m^{b)}$	$m_{(\mathrm{AcOH-HCOOH})}{}^{c)}$	$(k_s/k_c)_{\mathrm{HCOOH}}{}^{d)}$
(1)	0.56	0.36	0.646	30
(2)	0.64	0.47	—	15
(3)	0.69	0.54	—	5
(5)	—	—	0.832	3

a) Defined by Schleyer (the lower the Q value the more sterically accessible the substrate is to nucleophilic attack). See Ref. 13c. b) Ref. 13c. c) Brosylates. S. Winstein, and H. Marshall, *J. Amer. Chem. Soc.*, **74**, 1120 (1952). d) Calculated according to the procedure proposed by Schleyer, see Ref. 3. The rate constant for trifluoroacetolysis of (5) was estimated to be $3\times10^{-3}\,s^{-1}$ with the aid of $\rho^I-\sigma^I$ plot given by Peterson, see Ref. 7. A revised trifluoroacetolysis rate constant for 2-adamantyl *p*-toluenesulfonate is taken from J. E. Nordlander, R. G. Gruetzmacher, and F. Miller, *Tetrahedron Lett.*, **1973**, 927.

operates. The contribution of the k_s-character, if any, in the formolysis of some secondary substrates will be discussed later.

Activation Volume. All the activation volumes presented in Table 2 are negative. Negative values of $\Delta V^{\ne}$ have long been observed for solvolytic reactions and other unimolecular ionization processes. This phenomenon has been interpreted in terms of the presence of a predominant electrostrictive volume contraction (the $\Delta_2V^{\ne}$ term in the definition of Evans and Polanyi$^{15)}$) in the transition state which is undoubtedly more polar than the initial state.$^{4)}$ In such circumstances, the change in $\Delta_1V^{\ne}$ (the contribution of a volume increase due to bond extension$^{15)}$) caused by variation in the substituents appears to play only a minor role. That is, the apparent values of $\Delta V^{\ne}$ must be governed by the change in $\Delta_2V^{\ne}$. Accordingly, the comparison of the values of $\Delta V^{\ne}$ for structurally-related substrates in a given solvent can be anticipated to provide useful information about the transition states.

The results shown in Table 2 clearly indicate the solvent dependence of the activation volumes. Since the $\Delta_1V^{\ne}$ term is insensitive to the solvent change,$^{16a)}$ the different behavior of $\Delta V_0^{\ne}$ in the two solvents may be thought to be a reflection of a difference in the electrostrictive effect. In general, the magnitude of this electrostrictive term for solvolytic reaction depends on the degree of charge dispersion in the transition state; when the developed charge is dispersed more extensively over the whole molecule, the electrostrictive volume contraction becomes less significant, and hence a less negative value of $\Delta V^{\ne}$ appears.$^{6a,d-f)}$ This concept should be verified in such a reaction as a limiting solvolysis. The application of this concept to the Hammett equation should reveal a correlation between $\Delta V^{\ne}$ and σ with a negative slope;$^{16b)}$ this was really demonstrated in our laboratory for the limiting hydrolysis of 1-aryl-1-methylethyl chlorides.$^{6f)}$ The formolysis of the present substrates conforms to this generalization. The activation volume for formolysis given in Table 2 actually shows a good linear correlation with respect to σ^*_{add},$^{17)}$ as is shown in Fig. 1.

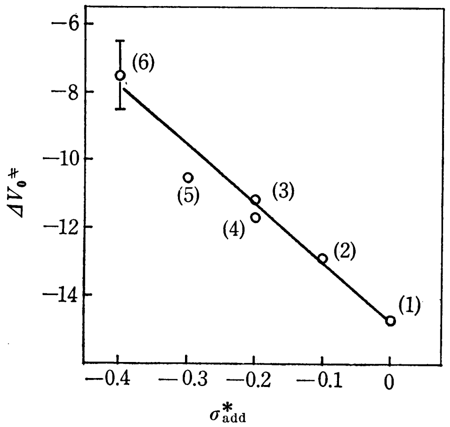

Fig. 1. Plot of $\Delta V_0^{\ne}$ against σ^*_{add} for the formolysis of secondary alkyl tosylates. Numeral denotes substrate number in Table 2; for (6) see footnote 17.

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15) M. G. Evans and M. Polanyi, *Trans. Faraday Soc.*, **31**, 875 (1935).

16) a) K. R. Brower, *J. Amer. Chem. Soc.*, **85**, 1401 (1963). b) For the linear correlation of $\Delta V^{\ne}$ with respect to σ, $-\delta\Delta V^{\ne}=2.303RT\sigma(\delta\rho/\delta P)_T$, see A. J. Ellis, W. S. Fyfe, R. I. Rutherford, A. Fischer, and J. Vaughan, *J. Chem. Phys.*, **31**, 176 (1959).

In contrast, the methanolysis of sterically-unhindered substrates afforded rather negative and leveled values of $\Delta V_0^{\neq}$, about -19 cm^3/mol. These results can best be understood if we assume that the transition state species are strongly solvated to nearly the same extent, regardless of their substituents. This is a result of the k_s-character of the reaction, in which the developed charge is mainly located on the reaction center. The mechanistic transformation from the k_s- to the k_c-process is seen to increase $\Delta V_0^{\neq}$ by $3\sim4$ cm^3/mol (see Table 2). An incipient carbonium ion, screened from nucleophilic solvation, must be stabilized electronically by substituents within the molecule. Consequently, two factors [(a) the decrease in electrostatic interaction due to charge dispersion, and (b) the diminution of the k_s-character, that is, the disappearence of tight nucleophilic solvation to the transition state species] make the $\Delta V_0^{\neq}$ for k_c-process less negative. It will be worthwhile to examine whether the $\Delta V_0^{\neq}$ of k_c-type substrates correlates with σ^*_{add} in methanolysis as well as in formolysis. Unfortunately, the correlation under consideration was obscure because of the presence of steric factors that would more or less affect the volume of the molecule.

The observation of more negative activation volumes for k_s-processes than those for k_c-processes appears to be general in the solvolyses of neutral substrates, although Hyne[18] expected that "the $\Delta V^{\neq}$ associated with the more ion-like transition state of an S_N1 mechanism would be more negative than in the case of an S_N2 mechanism." Baliga and Whalley[6c] have studied the hydrolyses of methyl and isopropyl bromides in water at 60 °C and reported the $\Delta V_0^{\neq}$ values as -17 cm^3/mol for the former and -10 cm^3/mol for the latter. There is no doubt that the former has a more k_s-character. Further evidence is given by our finding of -6.9 cm^3/mol as the value for the formolysis of a typical k_c-type secondary alkyl substrate, 2-adamantyl *p*-toluenesulfonate.[19]

Although it might be true that a solvolysis in formic acid is more k_c-like in character than in methanol, the contribution of solvent assistance can not be ignored in the case of a secondary system characterized by "borderline case" behavior.[20] For example, isopropyl tosylate has been reported to be solvolyzed with considerable nucleophilic assistance, even in formic acid.[3e] Helpful data to estimate provisionally the degree of k_s-contribution to over-all reaction are summarized in Table 3. Among the substrates presently examined, the k_s-character is greatest in (1); it then decreases successively from (1) to (5). According to this trend, the activation volume of a substrate possessing a more k_s-character will become somewhat more negative even in a k_c-like solvent. Hence, in the formolysis of substrates of the k_c-k_s hybrid character, the substituent effect on the activation volume must be considered to depend on two factors: a) the charge dispersion in the transition state, and b) the degree of its k_s-character. An analogous discussion was made by Laidler and Martin[6d] for the hydrolysis of benzyl chlorides.

On the other hand, in nearly pure k_c-processes the activation volumes should depend essentially on the degree of charge dispersion in the transition states, while in nearly pure k_s-processes some leveling effect on the activation volumes should be observed. In view of this, in the absence of steric factors, the transition states of secondary alkyl tosylates in methanolysis may be thought to be highly solvated, as in the case of primary substrates.

In order to get a more comprehensive understanding, measurements of partial molal volumes of the substrates will be required. Investigations in this direction are now in progress.

Experimental

Solvents. Formic acid (98—100%) was dried over anhydrous cupric sulfate and distilled *in vacuo.* The purified formic acid was stored frozen to avoid decomposition. Methanol was dried over activated magnesium and then distilled.

Materials. The desired alcohols were prepared as have been described in the literature. 1-*t*-Butylethyl tosylate (8) and 1-*t*-butyl-2,2-diethylbutyl tosylate(9) were prepared from the corresponding alcohols by the alkyl lithium method (*n*-BuLi was used).[21] All the other tosylates were prepared by the usual pyridine–*p*-toluenesulfonyl chloride method. The purity of each material was found by NMR analysis to be satisfactory.

Rate Measurement. The high-pressure apparatus and tecnique have already been described.[6f] The rate of production of *p*-toluenesulfonic acid was followed by a conductometric method. For fast reactions having half-lives of less than 1 hr, the medium in the high-pressure vessel was pre-chilled at 20 °C. In this case, the thermal equilibrium in the vessel was settled in about 15 min after pressurizing.

Formolysis. About a 0.019 mol/l solution was employed in each case. The first reading of conductance was taken after at least a 10% progress of the reaction because of a failure in the linear conductance-concentration relationship in this region. The rate constant was determined by the Guggenheim method[22] for (1) and by usual first-order rate expression for the others, using the least-squares method.

Methanolysis. A 0.003 mol/l solution of a tosylate (150—200 ml) was divided into 15-ml portions and stored in a refrigerator below 0 °C. Each aliquot was used for a single kinetic run. The rate constant was determined by the usual first-order rate expression, using the least-squares method. For an infinite conductance, the theoretical value of conductance was employed.

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[17] A rough estimation gave $\Delta V_0^{\neq} > -10$ cm^3/mol for (6) in accord with the present view.

[18] A. B. Lateef and J. B. Hyne, *Can. J. Chem.*, **47**, 1370 (1969).

[19] Unpublished result.

[20] It is of interest to compare the ρ^{I} values given by Peterson *et al.*[7] for folmolysis ($\rho^{\mathrm{I}}=-7.79$) and trifluoroacetolysis ($\rho^{\mathrm{I}}=-15.7$) of secondary alkyl tosylates. The smaller absolute value for the former seems to suggest the presence of some solvent assistance in formic acid.

[21] H. C. Brown, R. Bernheimer, C. J. Kim, and S. E. Scheppele, *J. Amer. Chem. Soc.*, **89**, 370 (1967).

[22] E. A. Guggenheim, *Phil. Mag.*, **2**, 538 (1926).