

Trifluoroacetylolysis of *exo*- and *endo*-2-Norbornyl and Related Tosylates¹

J. Eric Nordlander,* Robert R. Gruetzmacher, Walter J. Kelly, and Satya P. Jindal

Contribution from the Department of Chemistry, Case Western Reserve University, Cleveland, Ohio 44106. Received January 26, 1973

Abstract: Rates of trifluoroacetylolysis have been measured for *exo*- and *endo*-2-norbornyl tosylates (both of which produce *exo*-norbornyl trifluoroacetate) and for model reactants cyclopentyl and *trans*-2-methylcyclopentyl tosylates. A new photometric method was used for the relatively fast *exo*-norbornyl reactions. The *exo*:*endo* rate ratio at 25° is 1120. The rates relative to that of 2-adamantyl tosylate in trifluoroacetic acid are compared with those for acetic acid to derive nucleophilic solvent assistance factors for acetylolysis according to the recent analysis of Schleyer, *et al.* The results for *endo*-norbornyl tosylate indicate unexceptional rate-determining behavior and support partitioning of a first-formed nucleophilically solvated tight ion pair between C₁-C₆ σ -bond participation and covalent solvent attachment. The dependence of rate on solvent for *exo*-norbornyl relative to 2-adamantyl tosylate is reasonably explained by greater charge dispersal in an incipient σ -bridged norbornyl cation than for a localized 2-adamantyl cation.

Since the pioneering studies of Winstein and Tifan² of the solvolysis of *exo*- and *endo*-2-norbornyl brosylates (**1a** and **2a**, respectively), extraordinary effort has been directed toward the establishment of mechanistic detail for this system.^{3,4} According to Winstein's interpretation,^{2,5} with which a variety of

(1) Solvolytic Displacement Reactions in Trifluoroacetic Acid. IV. Part III: J. E. Nordlander, R. R. Gruetzmacher, and F. Miller, *Tetrahedron Lett.*, 927 (1973).

(2) (a) S. Winstein and D. Trifan, *J. Amer. Chem. Soc.*, **71**, 2953 (1949); (b) S. Winstein, B. K. Morse, E. Grunwald, H. W. Jones, J. Corse, D. Trifan, and H. Marshall, *ibid.*, **74**, 1127 (1952); (c) S. Winstein and D. Trifan, *ibid.*, **74**, 1147, 1154 (1952).

(3) For reviews see (a) H. C. Brown, *Chem. Soc., Spec. Publ.*, No. 16, 140 (1962); (b) J. A. Berson in "Molecular Rearrangements," Part 1, P. de Mayo, Ed., Interscience, New York, N. Y., 1963, Chapter 3; (c) P. D. Bartlett, "Nonclassical Ions," W. A. Benjamin, New York, N. Y., 1965; (d) G. E. Gream, *Rev. Pure Appl. Chem.*, **16**, 25 (1966); (e) H. C. Brown, *Chem. Brit.*, **2**, 199 (1966); (f) G. D. Sargent, *Quart. Rev., Chem. Soc.*, **20**, 301 (1966); (g) H. C. Brown, *Chem. Eng. News*, **45**, 87 (1967); (h) D. E. Sunko and S. Borčić in "Isotope Effects in Chemical Reactions," C. J. Collins and N. S. Bowman, Ed., Van Nostrand-Reinhold, New York, N. Y., 1970, Chapter 3; (i) G. D. Sargent in "Carbonium Ions," Vol. 3, G. A. Olah and P. v. R. Schleyer, Ed., Interscience, New York, N. Y., 1972, Chapter 24; (j) H. C. Brown, *Accounts Chem. Res.*, **6**, 377 (1973).

(4) Leading references are (a) R. Baker and T. J. Mason, *J. Chem. Soc., Perkin Trans. 2*, 18 (1972); (b) B. Adler, C. Duschek, M. Herrmann, W. Pritzkow, H. Schmidt, R. Thomas, and M. Wahren, *J. Prakt. Chem.*, **314**, 24 (1972); (c) C. C. Lee and F. L. Kung, *J. Label. Compounds*, **8**, 77 (1972); (d) L. Radom, J. A. Pople, V. Buss, and P. v. R. Schleyer, *J. Amer. Chem. Soc.*, **94**, 311 (1972); (e) R. M. Cooper, M. C. Gossel, and M. J. Perkins, *J. Chem. Soc., Perkin Trans. 2*, 594 (1972); (f) N. H. Werstiuk, R. R. MacDonald, R. W. Ouwehand, W. L. Chan, F. P. Cappelli, J. G. Ballard, R. E. Young, R. E. Massey, G. Timmins, and I. Goodwin, *Can. J. Chem.*, **50**, 618 (1972); (g) C. J. Collins, I. T. Glover, M. D. Eckhart, V. F. Raaen, B. M. Benjamin, and B. S. Benjaminov, *J. Amer. Chem. Soc.*, **94**, 899 (1972); (h) H. L. Goering and J. V. Cleavinger, *ibid.*, **94**, 1010 (1972); (i) R. K. Howe, P. Carter, and S. Winstein, *J. Org. Chem.*, **37**, 1473 (1972); (j) E. Huang, K. Ranganayakulu, and T. S. Sorensen, *J. Amer. Chem. Soc.*, **94**, 1779, 1780 (1972); (k) P. Carter and S. Winstein, *ibid.*, **94**, 2171 (1972); (l) J. P. Hardy, A. F. Diaz, and S. Winstein, *ibid.*, **94**, 2363 (1972); (m) T. S. Sorensen and K. Ranganayakulu, *Tetrahedron Lett.*, 2447 (1972); (n) L. A. Spurlock and R. G. Fayter, *J. Amer. Chem. Soc.*, **94**, 2707 (1972); (o) W. Kirmse and S. Rainer, *Chem. Ber.*, **105**, 2754 (1972); (p) P. G. Gassman and J. M. Hornback, *J. Amer. Chem. Soc.*, **94**, 7010 (1972); (q) J. K. Stille, W. A. Feld, and M. E. Freeburger, *ibid.*, **94**, 8485 (1972); (r) D. Faulkner and M. A. McKervey, *Tetrahedron Lett.*, 705 (1973); (s) P. K. Freeman and B. K. Stevenson, *J. Amer. Chem. Soc.*, **95**, 2890 (1973).

(5) (a) S. Winstein, E. Clippinger, R. Howe, and E. Vogelfanger, *J. Amer. Chem. Soc.*, **87**, 376 (1965); (b) S. Winstein, Abstracts, 21st National Organic Chemistry Symposium, Salt Lake City, Utah, June 1969, pp 150-153.

other solvolytic results have been adduced to conform,^{3,4} *exo*-2-norbornyl sulfonate (**1**) ionizes with C₁-C₆ σ -bond participation, k_{Δ} ,⁶ to form the delocalized cation, **3**, and subsequently racemic *exo* product. The *endo* substrate, **2**, on the other hand, is considered to ionize in the common protic solvents with nucleophilic solvent assistance, k_s ,⁶ to the classical ion **4**, most but not all of which gravitates to **3**, the remainder giving active *exo* product by simple inversion. The recent spectroscopic evidence of Olah and coworkers⁷ for a σ -bridged ("carbonium-ion") structure for the stable 2-norbornyl cation has provided impressive support for the postulate of electronically assisted *exo* ionization.

An alternative viewpoint, also based on extensive experimentation, has been advanced by Brown,^{3a,8,9} by which both the *exo* and *endo* substrates are considered to undergo anchimerically unassisted ionization. The singular rate and product characteristics^{2,3,9} of the norbornyl system are instead attributed to steric effects, particularly hindrance to ionization¹⁰ of the *endo* isomer, and to rapid equilibration of enantiomeric localized norbornyl cations, **5**.

Recent solvolysis investigations have shown trifluoroacetic acid, among media producing covalent products, to possess an exceptional combination of

(6) (a) S. Winstein, E. Allred, R. Heck, and R. Glick, *Tetrahedron*, **3**, 1 (1958); (b) P. v. R. Schleyer, J. L. Fry, L. K. M. Lam, and C. J. Lancelot, *J. Amer. Chem. Soc.*, **92**, 2542 (1970).

(7) (a) G. A. Olah, A. M. White, J. R. DeMember, A. Commeyras, and C. Y. Lui, *J. Amer. Chem. Soc.*, **92**, 4627 (1970); (b) G. A. Olah, P. R. Clifford, and C. L. Jewell, *ibid.*, **92**, 5531 (1970); (c) G. A. Olah, J. R. DeMember, C. Y. Lui, and R. D. Porter, *ibid.*, **93**, 1442 (1971); (d) G. A. Olah, *ibid.*, **94**, 808 (1972); (e) G. A. Olah, G. D. Mateescu, and J. L. Riemenschneider, *ibid.*, **94**, 2529 (1972); (f) G. A. Olah, G. Liang, G. D. Mateescu, and J. L. Riemenschneider, *ibid.*, **95**, 8698 (1973); (g) G. A. Olah, *Angew. Chem., Int. Ed. Engl.*, **12**, 173 (1973).

(8) (a) H. C. Brown and M.-H. Rei, *J. Amer. Chem. Soc.*, **90**, 6216 (1968), and references therein; (b) H. C. Brown and S. Ikegami, *ibid.*, **90**, 7122 (1968); (c) S. Ikegami, D. L. VanderJagt, and H. C. Brown, *ibid.*, **90**, 7124 (1968).

(9) (a) Colter, E. C. Friedrich, N. J. Holness, and S. Winstein, *J. Amer. Chem. Soc.*, **87**, 378 (1965); (b) R. Howe, E. C. Friedrich, and S. Winstein, *ibid.*, **87**, 379 (1965); (c) S. Winstein, *ibid.*, **87**, 381 (1965).

(10) E. N. Peters and H. C. Brown, *J. Amer. Chem. Soc.*, **94**, 5889, 7920 (1972).

Table I. Rate Data for Acetolysis and Trifluoroacetolysis

Compound	Acetic acid ^a				Trifluoroacetic acid ^b			
	Temp, °C	10 ⁵ k, sec ⁻¹	ΔH [‡] , kcal/mol	ΔS [‡] , cal/(deg mol)	Temp, °C	10 ⁵ k, sec ⁻¹	ΔH [‡] , kcal/mol	ΔS [‡] , cal/(deg mol)
Isopropyl-OTs	100.0	42.2 ^c	24.7	-8.3	50.0	50.9	19.9	-13.2
	75.0	3.60 ^c			40.0	10.3		
	25.0	0.00774 ^d			25.0	2.14 ^d		
					24.9	2.11		
Cyclopentyl-OTs	70.0	33.2 ^e	24.1	-4.2	25.0	273 ^d	16.0	-16.5
	50.0	3.82 ^e			24.9	270		
	30.0	0.323 ^e			15.0	104 ^e		
	25.0	0.168 ^d			4.6	34.9		
<i>trans</i> -2-Methylcyclopentyl-OTs	65.0	19.5	25.2	-0.9	25.0	640 ^d	16.1	-14.5
	55.0	6.36			15.0	244		
	45.0	2.07			5.0	83.8		
	25.0	0.133 ^d			-5.9	25.4		
<i>endo</i> -2-Norbornyl-OTs (2b)	99.7	63.3 ^f	25.8	-4.4	34.6	111	19.0	-14.8
	74.8	5.09 ^f			25.0	41.7		
	49.8	0.252 ^f			15.0	12.5		
	25.0	0.00828 ^d			4.7	3.89		
<i>exo</i> -2-Norbornyl-OTs (1b)	74.8	519 ^f	21.6	-7.2	25.0	46,800	17.7	-0.8
	49.7	46.7 ^f			22.6	35,300		
	25.2	2.40 ^f			20.2	29,000		
	25.0	2.33 ^d			12.9	13,000		
				5.6	5,410			

^a In the present work, substrate initially 0.075 M in acetic acid containing 1.0 wt % acetic anhydride; reactions followed titrimetrically. ^b Substrate initially 0.050 M in trifluoroacetic acid containing 1.0 wt % trifluoroacetic anhydride and 0.60 M sodium trifluoroacetate; reactions followed photometrically. ^c Reference 6b. ^d Calculated from data at other temperatures. ^e H. C. Brown and G. Ham, *J. Amer. Chem. Soc.*, **78**, 2735 (1956). ^f P. v. R. Schleyer, M. M. Donaldson, and W. E. Watts, *ibid.*, **87**, 375 (1965). ^g D. D. Roberts and W. Hendrickson [*J. Org. Chem.*, **34**, 2415 (1969)] have reported 10⁵k = 92 at 15° under higher concentration conditions.

high ionizing power and low nucleophilicity.¹¹ We report here rate data for the trifluoroacetolysis of the 2-norbornyl tosylates and model substrates, which provide new insight by extending markedly the range of solvents over which rate behavior of the norbornyl system has been studied.

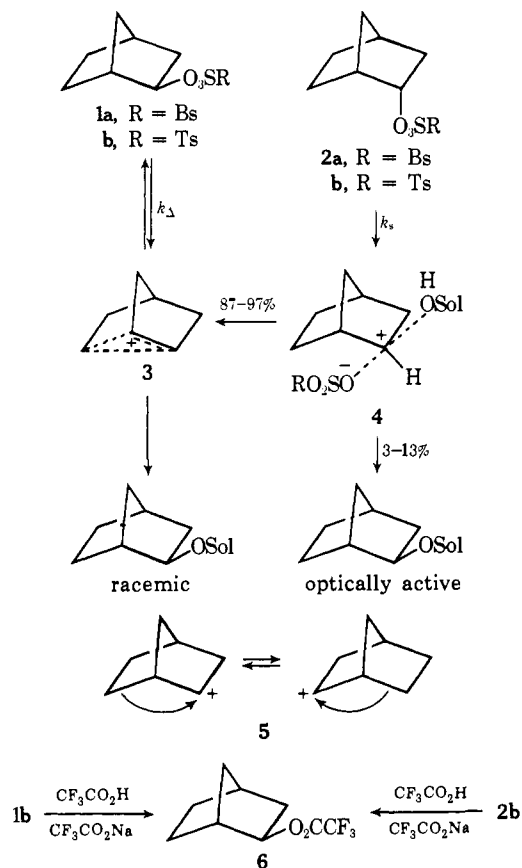
Results and Discussion

The trifluoroacetolyses (buffered with sodium trifluoroacetate) of *exo*- and *endo*-norbornyl tosylates (1b and 2b, respectively) were found to be notably clean reactions, both epimers producing *exo*-norbornyl trifluoroacetate (6) at 25° in near-quantitative yield.

Table I lists first-order rate data for acetolysis and trifluoroacetolysis of the norbornyl tosylates and isopropyl, cyclopentyl, and *trans*-2-methylcyclopentyl tosylates. Standard aliquot methods were used to follow the reactions, except for the relatively fast *exo*-norbornyl trifluoroacetolysis (half-life 1.96 sec at 22.6°), for which a new technique was developed based on rapid mixing and continuous photometric observation.¹² Relative rate constants are presented in Table II.

(11) Leading references are: (a) P. E. Peterson and F. J. Slama, *J. Amer. Chem. Soc.*, **90**, 6516 (1968); (b) J. E. Nordlander and W. J. Kelly, *ibid.*, **91**, 996 (1969); (c) A. Streitwieser, Jr., and G. A. Dafforn, *Tetrahedron Lett.*, 1263 (1969); (d) A. F. Diaz and S. Winstein, *J. Amer. Chem. Soc.*, **91**, 4300 (1969); (e) P. E. Peterson and R. J. Kamat, *ibid.*, **91**, 4521 (1969); (f) R. J. Jablonski and E. I. Snyder, *ibid.*, **91**, 4445 (1969); (g) I. L. Reich, A. Diaz, and S. Winstein, *ibid.*, **91**, 5635 (1969); (h) V. J. Shiner, Jr., and W. Dowd, *ibid.*, **91**, 6528 (1969); (i) V. J. Shiner, Jr., R. D. Fisher, and W. Dowd, *ibid.*, **91**, 7748 (1969); (j) M. Hanack, S. Bocher, I. Heterich, K. Hummel, and V. Vott, *Justus Liebig's Ann. Chem.*, **733**, 5 (1970); (k) C. C. Lee and W. K.-Y. Chwang, *Can. J. Chem.*, **48**, 1025 (1970); (l) G. A. Dafforn and A. Streitwieser, Jr., *Tetrahedron Lett.*, 3159 (1970); (m) J. M. Harris, R. E. Hall, and P. v. R. Schleyer, *J. Amer. Chem. Soc.*, **93**, 2551 (1971); (n) P. E. Peterson and J. F. Coffey, *ibid.*, **93**, 5208 (1971); (o) P. E. Peterson and F. J. Waller, *ibid.*, **94**, 991 (1972); (p) T. W. Bentley, F. L. Schadt, and P. v. R. Schleyer, *ibid.*, **94**, 992 (1972); (q) I. L. Reich, A. F. Diaz, and S. Winstein, *ibid.*, **94**, 2256 (1972).

(12) J. E. Nordlander, R. R. Gruetzmacher, and J. E. Stuehr, *Rev. Sci. Instrum.*, **43**, 1835 (1972).



Of immediate interest is the *exo*/*endo* rate ratio in trifluoroacetic acid, 1120 at 25°, the largest value yet recorded. By itself, the quotient of $>10^3$ reveals substantial mechanistic dissimilarity between the epimeric reactants ($\Delta\Delta F^\ddagger = 4.2$ kcal/mol). On the other hand, this ratio is enhanced by only fourfold from that in acetic acid, 281. Under a k_A mechanism for the *exo*

Table II. Relative Solvolysis Rates and Acetic Acid Nucleophilic Assistance Factors for Tosylates at 25.0°

Tosylate	CF ₃ CO ₂ H		CH ₃ CO ₂ H		(k _s /k _e) _{CH₃CO₂H}
	1	1	1	1	
2-Adamantyl	1		1		
<i>endo</i> -2-Norbornyl (2b)	0.475		13.9		30.0
<i>exo</i> -2-Norbornyl (1b)	522	1120	3920	281	7.53
Isopropyl	0.0238		13.0		547
Cyclopentyl	3.04		283		93.0
<i>trans</i> -2-Methylcyclopentyl	7.13		224		31.4

reactant, one might have anticipated a sizable increase in *exo/endo* rate ratio in changing to trifluoroacetic acid. This could be the consequence of loss of nucleophilic solvent assistance to ionization, or dissociation,¹³ of the *endo* epimer, *i.e.*, a transition in *endo* mechanism from *k_s* toward *k_e* (describing ionization with neither intramolecular intermolecular nucleophilic assistance).⁶

A complication in the comparison between solvents is the relative extent of ion-pair return. For *exo*-norbornyl brosylate, but not *endo*-,² ionization rates are indicated polarimetrically to exceed those of solvolysis, by a factor of 4.6 in acetic acid.¹⁴ The polarimetric trifluoroacetolysis rate for *exo*-norbornyl tosylate is not at present accessible. Data on comparative return phenomena for several other systems, however, have shown the apparent partitioning of carbonium-sulfonate ion pairs not to differ greatly from acetic to trifluoroacetic acid.¹⁵ If this condition is assumed to obtain as well for the norbornyl system, then an *exo/endo* rate ratio of approximately 1120 × 4.6 = 5150 would be indicated.

An instructive framework for further interpretation of the present results is the analysis presented recently by Schleyer and coworkers^{6b,16} for the estimation of nucleophilic solvent contributions to rates of secondary alkyl sulfonates, *k_s/k_e*. In this scheme 2-adamantyl tosylate is taken as a substrate approximating *k_e* behavior in all common solvents, and trifluoroacetic acid as a medium in which secondary tosylates react generically by a pathway approaching *k_e*. The departure of *k_{ROT_s}/k_{2-AdOT_s}* in a given solvent from that in trifluoroacetic acid (TFA) thus constitutes a measure of *k_s/k_e* for ROTs under the former conditions, eq 1. The

results of this treatment of the acetolysis of the norbornyl and model tosylates are presented in Table II.¹⁷

$$\left(\frac{k_s}{k_e}\right)_{\text{ROT}_s, \text{solvent}} = \frac{(k_{\text{ROT}_s}/k_{2\text{-AdOT}_s})_{\text{solvent}}}{(k_{\text{ROT}_s}/k_{2\text{-AdOT}_s})_{\text{TFA}}} \quad (1)$$

On this basis *endo*-norbornyl tosylate is revealed to derive nucleophilic solvent assistance in acetolysis by a factor of 30. This value, appropriately, is substantially smaller than that for the minimally hindered isopropyl tosylate, 547. It also falls moderately below that for cyclopentyl tosylate, 93, and is essentially the same as that for the β-branched model,^{18,19} *trans*-2-methylcyclopentyl tosylate, 31. This pattern provides a significant indication, we believe, of normal solvolytic behavior for *endo*-norbornyl tosylate. If the mechanism for this reactant were distinguished by steric hindrance to ionization or dissociation, one would reasonably expect an unusually large solvent nucleophilic contribution to its rate-determining step. This effect should arise both as compensation for frontside retardation and from formation of a higher energy and hence structurally later transition state.²⁰

The present results emphasize a principal question in *endo*-norbornyl solvolysis, the relationship between nucleophilic solvent involvement with the first-formed (gegenion-paired) carbonium ion and the predominantly racemic nature of the subsequent *exo* product. For isopropyl tosylate the (*k_s/k_e*)_{HOAc} value of 547 correlates with complete inversion of configuration, as demonstrated by Streitwieser, *et al.*,²¹ for 2-octyl tosylate. For *endo*-norbornyl tosylate, in contrast, the lesser assistance factor of 30 is associated with only 7% simple inversion.²⁰

Winstein and Trifan²⁰ described this solvent interaction as metastable discrete "solvation," depicted by structure 4, at greater than covalent bonding distance; replacement of the anion in 4 with a second solvent molecule could in principle lead to a symmetrically solvated carbonium ion,²² although such a species in the present case could be discounted on the basis of the absence of *endo* product. A generalization of this solvation hypothesis was presented in the same period by Streitwieser.²²

(17) Insufficient data are available for application of eq 1 over this reactant series in other solvents.

(18) *cis*-2-Methylcyclopentyl might seem a better model than the *trans* isomer for *endo*-norbornyl, but affords an unwanted potential driving force due to backside hydride migration from the methine carbon. Like *endo*-norbornyl, *trans*-2-methylcyclopentyl presents a β-alkyl branch in a five-membered ring.

(19) See ref 3c for a discussion of ring-size effects in models for norbornyl derivatives.

(20) G. S. Hammond, *J. Amer. Chem. Soc.*, 77, 334 (1955).

(21) (a) A. Streitwieser, Jr., T. D. Walsh, and J. R. Wolfe, Jr., *J. Amer. Chem. Soc.*, 87, 3682 (1965); (b) A. Streitwieser, Jr., and T. D. Walsh, *ibid.*, 87, 3686 (1965).

(22) A. Streitwieser, Jr., "Solvolytic Displacement Reactions," McGraw-Hill, New York, N. Y., 1962, pp 66-69 ff.

(13) See (a) R. A. Sneen and J. W. Larsen, *J. Amer. Chem. Soc.*, 91, 362 (1969); (b) R. A. Sneen and H. M. Robbins, *ibid.*, 91, 3100 (1969); (c) R. A. Sneen and J. W. Larsen, *ibid.*, 91, 6031 (1969); (d) V. J. Shiner, Jr., in "Isotope Effects in Chemical Reactions," C. J. Collins and N. S. Bowman, Ed., Van Nostrand-Reinhold, New York, N. Y., 1970, Chapter 2; (e) D. J. Raber, J. M. Harris, R. E. Hall, and P. v. R. Schleyer, *J. Amer. Chem. Soc.*, 93, 4821 (1971); (f) R. A. Sneen and W. A. Bradley, *ibid.*, 94, 6975 (1972); (g) R. A. Sneen and P. S. Kay, *ibid.*, 94, 6983 (1972); (h) R. A. Sneen and J. V. Carter, *ibid.*, 94, 6990 (1972); (i) R. A. Sneen and H. M. Robbins, *ibid.*, 94, 7868 (1972); (j) R. A. Sneen, G. R. Felt, and W. C. Dickason, *ibid.*, 93, 638 (1973).

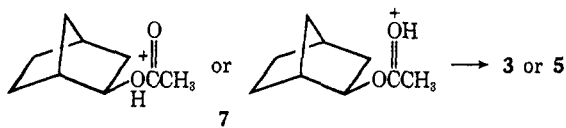
(14) Winstein and Trifan, ref 2c, first reported *k_a/k_t* = 3.46 for acetolysis of *exo*-norbornyl brosylate at 25°. Winstein, *et al.*, ref 5a, later recommended 4.6 as a more appropriate value.

(15) The following values have been reported for the fraction, *F*, of bridged ion pairs proceeding to product. For 2-phenylethyl tosylate in acetic acid at 90°, 0.32 (J. L. Coke, F. E. McFarlane, M. C. Mourning, and M. G. Jones, *J. Amer. Chem. Soc.*, 91, 1154 (1969)); in trifluoroacetic acid at 75°, 0.42 (ref 11q). For 1-phenyl-2-propyl tosylate at 50° in acetic acid, 0.18; in trifluoroacetic acid, 0.094 (ref 11d). Oxygen isotopic scrambling data have disclosed the following upper-limit *F* values. For 2-octyl brosylate in acetic acid at 75°, 0.906-0.948; in trifluoroacetic acid at 25°, 0.801. For *trans*-4-*tert*-butylcyclohexyl tosylate in acetic acid at 75°, 0.955-0.968; in trifluoroacetic acid at 25°, 0.924 (A. F. Diaz, I. Lazdins, and S. Winstein, *ibid.*, 90, 1904 (1968)). See ref 1 for an evident departure, however. The approximate constancy of ion pair partitioning in these two media appears more valid for *k_Δ* than for *k_e* or *k_s* reactions.

(16) See also footnotes 12 and 15 in ref 11p.

More recent studies have cast new light on the k_s role of solvent toward secondary alkyl systems. Kinetic analyses of solvolyses in acetic and formic acids of series of 1-aryl-2-propyl tosylates²³ and *threo*-3-aryl-2-butyl brosylates²⁴ have permitted separations of the k_s and k_A pathways which correlate excellently with strict inversion and retention stereochemistries, respectively. These findings demonstrate a close tie between k_s solvent participation and product σ -bond formation; support is absent here for intermediate half-bonded solvation with potential for racemization.

For acetolysis of *endo*-norbornyl brosylate, the observation of 93% leakage to racemic carbonium ion and the modest but significant nucleophilic solvent assistance factor (30) are most reasonably in accord, we believe, with Winstein's originally suggested²⁰ partitioning of an initial tight ion pair, discretely but noncovalently solvated at the carbon backside, between bond formation with this solvent molecule (optically active *exo* product) and C₁-C₆ σ -bond participation at the frontside (racemic *exo* product from **3**, or **5**). This unusual competition results from the fixed juxtaposition of the nucleophilic strained σ -bond and the carbonium ion frontside peculiar to the *endo*-norbornyl structure. The alternative of leakage from directly formed optically active oxonium ion **7** would appear energetically much less favorable.



While the application of Schleyer's analysis to *endo*-norbornyl tosylate discloses a potential increase in *exo/endo* rate ratio of 30 in going from acetic to trifluoroacetic acid, the observed enhancement is limited to 4 by reason of a " k_s/k_c " value of 7.5 for acetolysis of the *exo* tosylate. It is unlikely, however, that this factor in the *exo* case is a reflection of nucleophilic solvent participation, since only 0.01% of *endo* acetate has been detected²⁵ (at 30°), and studies of addition reactions have shown *endo* approach to the norbornane structure to be severely restricted.^{3,4}

A more satisfactory explanation for the *exo* " k_s/k_c " factor is available in bridged-ion terms. The greater positive charge dispersal in a σ -assisted *exo*-norbornyl transition state relative to that for a localized 2-adamantyl cation should cause the former's rate to be less responsive to solvent ionizing power than that of the latter. Consistently, Grunwald-Winstein m values (aqueous ethanol, 25°) are 0.91 for 2-adamantyl tosylate²⁶ and 0.75 for *exo*-2-norbornyl tosylate.²⁷ It is readily shown that the calculation of $(k_s/k_c)_{\text{HOAc}} > 1$

(23) P. v. R. Schleyer and C. J. Lancelot, *J. Amer. Chem. Soc.*, **91**, 4297 (1969), and preceding communications.

(24) (a) H. C. Brown, C. J. Kim, C. J. Lancelot, and P. v. R. Schleyer, *J. Amer. Chem. Soc.*, **92**, 5244 (1970); (b) H. C. Brown and C. J. Kim, *ibid.*, **93**, 5765 (1971).

(25) H. L. Goering and C. B. Schewene, *J. Amer. Chem. Soc.*, **87**, 3516 (1965). See also H. C. Brown, J. H. Kawakami, and K.-T. Liu, *ibid.*, **92**, 5536 (1970).

(26) 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).

(27) Unpublished data kindly provided by J. M. Harris, D. J. Raber, and P. v. R. Schleyer. The m value also measured for *endo*-norbornyl tosylate, 0.54, supports the present conclusion of nucleophilic solvent assistance which is appreciable while less than that for 2-propyl tosylate, $m = 0.42$,²⁶ on steric grounds.

for *exo*-norbornyl tosylate by eq 1 is equivalent to a smaller m value for *exo*-norbornyl than for 2-adamantyl. If the Grunwald-Winstein equation²⁸ $\log(k/k_0) = mY$ is recast in terms of 2-adamantyl tosylate and acetic acid as reference reactant and solvent, respectively, the condition that " m " for *exo*-norbornyl be less than unity corresponds to

$$\log(k_{\text{TFA}}/k_{\text{HOAc}})_{\text{exo-OTs}} < \log(k_{\text{TFA}}/k_{\text{HOAc}})_{2\text{-AdOTs}} \quad (2)$$

i.e.

$$\frac{(k_{\text{TFA}}/k_{\text{HOAc}})_{2\text{-AdOTs}}}{(k_{\text{TFA}}/k_{\text{HOAc}})_{\text{exo-OTs}}} = \frac{(k_{\text{exo-OTs}}/k_{2\text{-AdOTs}})_{\text{HOAc}}}{(k_{\text{exo-OTs}}/k_{2\text{-AdOTs}})_{\text{TFA}}} > 1 \quad (3)$$

Experimental Section

Melting points are corrected.

trans-2-Methylcyclopentanol was prepared in 75% yield (0.20-mol scale) by standard hydroboration-oxidation²⁹ of 1-methylcyclopentene (Chemical Samples Co.), bp 151–153° [lit.²⁹ bp 152–153°].

Model Tosylates. Isopropyl,³⁰ cyclopentyl (mp 27.5–28.5° [lit. mp 28.0–28.2°, 31 28.5–29.0°³²]), and *trans*-2-methylcyclopentyl (mp 33.5–34.5° [lit.³³ mp 33.8–34.5°]) tosylates were prepared from the alcohols and *p*-toluenesulfonyl chloride in the usual manner.^{32,34}

***exo*- and *endo*-2-Norbornyl Tosylates.** Following the procedure of Winstein and Trifan,²⁰ norcamphor was reduced with lithium aluminum hydride to the epimeric alcohols, and the corresponding tosylate mixture was solvolyzed in 80% aqueous dioxane at 65° for 10 hr. Chromatography of the product over silica gel in hexane afforded the unreacted *endo* tosylate in 42% yield after low-temperature crystallization from hexane, mp 27.0–28.0° [lit. mp 28.1–29.2°, 2a 27.2–28.0°³⁵], and the *exo* alcohol in 47% yield after similar recrystallization, mp 127.5–128.4° [lit.²⁰ mp 127.8–128.5°]. The latter was converted to *exo*-norbornyl tosylate in the usual manner.^{32,34} mp 53.5–54.5° [lit. mp 53–54°, 2c 53.7–54.6°³⁶].

Products of Trifluoroacetolysis of Norbornyl Tosylates. *exo*- and *endo*-Norbornyl tosylates (0.384 g, 1.44 mmol) were solvolyzed separately in 30 ml of trifluoroacetic acid (1.0 wt % trifluoroacetic anhydride) containing 1.80 mmol of sodium trifluoroacetate at room temperature for 3 and 12 hr, respectively. The reaction mixture was poured into 200 ml of water, and the product was extracted into three 200-ml portions of ether. The ether solution was washed with 10% sodium bicarbonate solution and with water, dried over anhydrous magnesium sulfate, and concentrated to 10 ml by solvent distillation through a Vigreux column. In both cases gas chromatography of the product through two columns (silicone gum rubber SE-30 and diethylene glycol polyadipate, both 10% on 60–80 mesh Diatoport S (F&M Scientific)) showed a single peak (other than solvent). Saponification of the products with 0.1 *N* sodium hydroxide solution at room temperature for 10 hr, followed by ether extraction, water washing, drying, and distillation, yielded only *exo*-2-norbornanol in the case of each epimeric tosylate, as evidenced by gas chromatography and ir and nmr spectra.

Kinetic Measurements. Acetolysis rates of *trans*-2-methylcyclopentyl tosylate were determined by the standard³⁶ titration of aliquots from ampoules with sodium acetate in acetic acid, using Bromophenol Blue as indicator. Initial substrate concentrations were ca. 0.075 *M* in acetic acid containing 1.0 wt % acetic anhydride.

(28) (a) E. Grunwald and S. Winstein, *J. Amer. Chem. Soc.*, **70**, 846 (1948); (b) S. Winstein, E. Grunwald, and H. W. Jones, *ibid.*, **73**, 2700 (1951); (c) A. H. Fainberg and S. Winstein, *ibid.*, **78**, 2770 (1956), and later papers.

(29) H. C. Brown and G. Zweifel, *J. Amer. Chem. Soc.*, **81**, 247 (1959).

(30) W. Hüchel and K. Tomopoulos, *Justus Liebigs Ann. Chem.*, **610**, 78 (1957).

(31) J. D. Roberts and V. C. Chambers, *J. Amer. Chem. Soc.*, **73**, 5034 (1951).

(32) Table I, footnote *e*.

(33) W. Hüchel and E. Mogle, *Justus Liebigs Ann. Chem.*, **649**, 13 (1961).

(34) R. S. Tipson, *J. Org. Chem.*, **9**, 235 (1944).

(35) Table I, footnote *f*.

(36) (a) S. Winstein, E. Grunwald, and L. L. Ingraham, *J. Amer. Chem. Soc.*, **70**, 821 (1948); (b) R. S. Bixler and C. Niemann, *J. Org. Chem.*, **23**, 742 (1958).

For the trifluoroacetylation of all tosylates except *exo*-norbornyl, Peterson's method³⁷ for spectrophotometric assay of quenched aliquots was used. Initial substrate concentrations were *ca.* 0.050 *M* in carefully distilled trifluoroacetic acid containing 0.060 *M* sodium trifluoroacetate and 1.0 wt % trifluoroacetic anhydride. *exo*-Norbornyl tosylate reacted too swiftly to allow sampling procedures. A new technique was thus developed¹² for continuous photometric observation of the reaction following rapid reactant introduction in a closed thermostated cell; it was applied to this reaction at 22.6, 20.2, and 12.9°. A fourth rate constant was measured at 5.6° as follows. Fifteen samples of *ca.* 13 mg (0.05 mmol) of pulverized tosylate were accurately weighed in 25-ml volumetric flasks. In a cold room, each flask was suspended in turn in a large ambient water bath (5.6°), and after several minutes for temperature equilibration 1.0 ml of trifluoroacetylation medium (see above, this paragraph), prethermostated in the same bath, was added quickly by syringe. The flask was shaken briskly for 3 sec

(37) (a) P. E. Peterson, R. E. Kelley, Jr., R. Belloli, and K. A. Sipp, *J. Amer. Chem. Soc.*, **87**, 5169 (1965); see also (b) J. E. Nordlander and W. G. Deadman, *ibid.*, **90**, 1590 (1968).

to dissolve the reactant uniformly, and after a programmed interval the reaction was quenched by rapid, turbulent addition of 20 ml of -70° 95% ethanol from a syringe. Points were thus distributed over 2 half-lives (after preliminary runs established the approximate rate). From Dry Ice storage, each flask in turn was warmed to 25° with gentle agitation in a thermostated water bath, filled to the mark with 95% ethanol, and mixed well. Without delay, a sample was transferred to an optical cell and its absorbance in the region of 273 nm measured with a Cary 15 spectrophotometer. After normalization of initial concentrations, the data were treated as in the aliquot procedure³⁷ to obtain the rate constant.

Acknowledgment. Support of this work by National Science Foundation Grants GP-8421 and GP-27032 and the provision of a research fellowship to R. R. G. by Texaco, Inc., are gratefully acknowledged. We appreciate helpful information and comments from Professors D. J. Raber, H. C. Brown, J. M. Harris, G. A. Olah, and P. v. R. Schleyer, and the provision of a preprint of ref 3i by Professor G. D. Sargent.

Ion-Molecule Reactions of Acids and Esters with Alcohols. Gas Phase Analogs of Acidic Esterification Processes

Peter W. Tiedemann and José M. Riveros*

Contribution from the Instituto de Química, University of Sao Paulo, Caixa Postal 20780, São Paulo, Brazil. Received April 20, 1973

Abstract: The main ion-molecule reactions that formic acid, acetic acid, propionic acid, and their esters undergo with the lower alcohols have been investigated by ion cyclotron resonance at low electron energies and pressures up to 5×10^{-5} Torr. Formation of protonated ester has been observed to occur readily at 10^{-5} Torr by the reaction of protonated acetic acid, or propionic acid, and the neutral alcohol. Formic acid yields a protonated ester only with the protonated propanols and butanols suggesting a different mechanism. Esters are shown to react only with protonated propanols and butanols to yield ions of the type $(\text{RCO}_2\text{R}'\text{R}'')^+$, when the proton affinity of the alcohol is higher than that of the ester. The mechanism of this reaction is compared with chemical ionization studies which show such ions to be intermediates in the gas phase transesterification induced by carbonium ions.

The elucidation of reaction pathways for the esterification of organic acids and hydrolysis of esters constitutes a classical chapter of mechanistic organic chemistry which dates back to the beginning of the century.¹ A multiplicity of mechanisms has been recognized for these reactions according to their class (basic or acidic), the site of cleavage, and the molecularity of the rate-determining step.²

The fact that esterification and hydrolysis involve the participation of ionic species suggests that these reactions may be in principle sensitive to solvent participation, or solvation effects. Such effects can be eliminated, and the intrinsic reactive features of these processes unraveled by techniques like ion cyclotron resonance, when applied to the gas phase analogs of these reactions.^{3,4} Preliminary observations using icr techniques on the analog of the base-promoted transesterification have already been reported, and similarities drawn between gas phase and solution mechanisms.^{5,6}

The present paper describes the gaseous ion-molecule reactions originating when formic acid, acetic acid, and their esters are allowed to react with the lower aliphatic alcohols in the cell of an ion cyclotron resonance spectrometer. Such reactions can be viewed as gas phase analogs of the acid-promoted esterification. Two distinct pathways are encountered for these reactions which depend on the relative gas phase basicities of the reactant species, and the type of alcohol used in the reactions. The results are also used to compare the gas phase behavior with the mechanisms usually found in solution.

Experimental Section

Spectra were taken in a Varian V-5900 ICR-9 spectrometer provided with a dual inlet system and a cell of $1.27 \times 2.54 \times 12.7$ cm³. Ionization was achieved with 15 eV electrons, using low emission currents (in general less than 0.2 μA). Double resonance experiments were carried out with low irradiating fields (about 10 mV/cm), and usually in the pulsed mode. Pressures were read directly from the ion pump control. The systems reported in the

(1) B. Holmberg, *Ber.*, **45**, 2997 (1912).

(2) C. K. Ingold, "Structure and Mechanism in Organic Chemistry," Cornell University Press, Ithaca, N. Y., 1953, pp 752-782.

(3) J. D. Baldeschwieler and S. S. Woodgate, *Accounts Chem. Res.*, **4**, 114 (1971).

(4) J. L. Beauchamp, *Annu. Rev. Phys. Chem.*, **22**, 527 (1971).

(5) P. W. Tiedemann, Abstracts, 23rd Meeting of the SBPC, Curitiba, Brazil, July 1971, Paper C-67.

(6) L. K. Blair, P. C. Isolani, and J. M. Riveros, *J. Amer. Chem. Soc.*, **95**, 1057 (1973).