its anhydride. This solution (0.25 *M* in tosylate) was stirred at room temperature for 35 min. Crude kinetics of the solvolysis reaction were obtained by monitoring the growth of product peaks (the methyl group in the tosylate anion) in the nmr spectrum.

Deuteriotrifluoroacetic acid was prepared by treating freshly distilled (39°) trifluoroacetic anhydride with an excess of D_2O. The acid was then distilled (71°) and the solvolysis solutions were prepared as with the undeuterated acid.

Isolation and Characterization of Solvolysis Products. Upon completion of the solvolysis reaction, the solution was cooled and the contents of the flask rinsed with ether and water into a stirred solution of 10% excess (based on the solvolysis solvent) NaOH in 150 ml of ice and H_2O. The aqueous solution was extracted twice with 50-ml portions of ether, and the combined organic portions were dried over K_2CO_3 and $MgSO_4$. Analytical vapor phase chromatography was performed on the filtered ether solutions. Equation 1, in which F_1 and F_2 are the correction factors for the sensitivity of the compounds to thermal detection and the concentrations are relative, was used to calculate the product ratios. The correction factors were determined on each analysis from a standard solution. Isolation of products was accomplished by concentrating the solution by distillation of the ether through a 20-cm vacuum-jacketed column packed with glass helices, with the oil bath temperature less than 43°. The residue was purified by preparative vapor phase chromatography.

$$\frac{\text{cyclohexene area}}{[\text{cyclohexene}]} = F_1\frac{\text{ester area}}{[\text{ester}]} = F_2\frac{\text{alcohol area}}{[\text{alcohol}]} \quad (1)$$

Product Stability. To the normal acetic or trifluoroacetic acid solvent systems (containing the buffer) was added 0.93 g (0.005 mol) of *p*-toluenesulfonic acid monohydrate and an extra milliliter of anhydride. For formic acid studies, the *p*-toluenesulfonic acid monohydrate was dissolved in benzene, the water was removed by azeotropic distillation (78°), and the benzene was evaporated. The dried acid (0.86 g, 0.005 mol) was then added to the buffered formic acid solvent. The product to be tested (0.3 g, 0.004 mol of cyclohexene or 0.0015 mol of ester) was added, and the solution was subjected to normal solvolysis and work-up conditions.

Solvolytic Behavior of 7,7-Dimethoxybicyclo[2.2.1]hept-2-yl Tosylates[1]

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Contribution from the Department of Chemistry, The Ohio State University, Columbus, Ohio 43210. *Received January 17, 1973*

Abstract: The solvolysis of *exo*- and *endo*-7,7-dimethoxybicyclo[2.2.1]hept-2-yl tosylates has been studied in acetic acid buffered with sodium acetate and in absolute ethanol buffered with *syn*-dimethylurea (DMU). Whereas the exo isomer appeared to solvolyze in a straightforward manner, the endo isomer underwent ionization with MeO-4 neighboring group participation. As a result, the *exo*- and *endo*-7,7-dimethoxybicyclo[2.2.1]hept-2-yl tosylates gave different products on acetolysis and on ethanolysis. The implications of these results on bicyclic cation theory are discussed.

The 2-norbornyl cation remains as one of the more discussed subjects in organic chemistry. Even after extensive amounts of investigation, the nature of this cation is not agreed upon.[3] Numerous approaches have been taken to resolve the question of whether the 2-norbornyl cation is a classical ion with its charge localized on a particular carbon or a nonclassical ion with a highly delocalized electronic structure. Rate studies, product studies, spectroscopic measurements, and theoretical calculations have all been utilized in attempts to obtain the definitive answer. The most effort has been devoted to kinetic and product studies. The emphasis on these approaches is probably a consequence of the historical reasons for the initial suggestion of the existence of the nonclassical norbornyl cation.[4,5] In most of the early studies, attention was focused on the effects of carbonium ion stabilizing groups such as alkyl and aryl moieties.[3] As part of our general interest in this area, we carried out several studies of the effect of electron-withdrawing substituents on both the rates of solvolysis and product compositions obtained from *exo*- and *endo*-bicyclo[2.2.1]heptyl tosylates.[1,6-8] We now wish to present the details of our study of the solvolytic behavior of *exo*- and *endo*-7,7-dimethoxybicyclo[2.2.1]hept-2-yl tosylate.

Synthesis. *exo*-7,7-Dimethoxybicyclo[2.2.1]heptan-

(1) For preliminary reports of portions of this work, see P. G. Gassman and J. L. Marshall, *Tetrahedron Lett.*, 2429, 2433 (1968); P. G. Gassman, J. L. Marshall, J. G. Macmillan, and J. M. Hornback, *J. Amer. Chem. Soc.*, **91**, 4282 (1969).

(2) National Science Foundation Cooperative Predoctoral Fellow, 1964–1966.

(3) For discussions of some diverse opinions, see: (a) G. D. Sargent, *Quart. Rev., Chem. Soc.*, 20, 301 (1966); (b) G. E. Gream, *Rev. Pure Appl. Chem.*, 16, 25 (1966); (c) H. C. Brown, *Chem. Brit.*, 199 (1966); (d) H. C. Brown, *Chem. Eng. News*, **45**, No. 7, 87 (1967); (e) H. C. Brown, I. Rothberg, P. Schleyer, M. M. Donaldson, and J. J. Harper, *Proc. Nat. Acad. Sci. U. S.*, **56**, 1653 (1966); (f) G. A. Olah and A. M. White, *J. Amer. Chem. Soc.*, **91**, 5801 (1969); (g) G. A. Olah, A. M. White, J. R. DeMember, A. Commeyras, and C. Y. Lui, *ibid.*, **92**, 4627 (1970); (h) G. A. Olah, G. D. Mateescu, and J. L. Riemenschneider, *ibid.*, **94**, 2529 (1972); (i) 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., 1971, p 160; (j) B. L. Murr and J. A. Conkling, *J. Amer. Chem. Soc.*, **92**, 3462, 3464 (1970); (k) N. H. Werstiuk, R. R. MacDonald, E. W. Ouwehand, W. L. Chan, F. P. Cappelli, J. G. Ballard, R. E. Young, R. E. Massey, G. Timmins, I. Goodwin, A. Walling, and Y. Teruta, *Can. J. Chem.*, 50, 618 (1972); (l) P. D. Bartlett, "Nonclassical Ions," W. A. Benjamin, New York, N. Y., 1965; (m) M. J. S. Dewar and A. P. Marchand, *Annu. Rev. Phys. Chem.*, 16, 321 (1965); (n) B. Capon in "Organic Reaction Mechanisms, 1967," B. Capon, M. J. Perkins, and C. W. Rees, Ed., Wiley-Interscience, New York, N. Y., 1968; (o) G. D. Sargent in "Carbonium Ions," Vol. 3, G. Olah and P. v. R. Schleyer, Ed., Wiley-Interscience, New York, N. Y., 1972, p 1099; (p) S. Winstein, E. Clippinger, R. Howe, and E. Vogelfanger, *J. Amer. Chem. Soc.*, 87, 376 (1965); (q) S. Winstein, *ibid.*, 87, 381 (1965); (r) P. v. R. Schleyer, *ibid.*, **89**, 699, 701 (1967).

(4) T. P. Nevell, E. de Salas, and C. L. Wilson, *J. Chem. Soc.*, 1188 (1939).

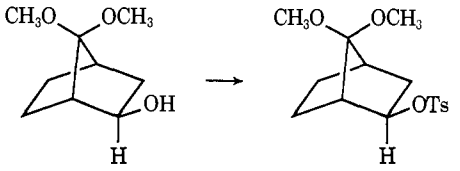
(5) S. Winstein and D. Trifan, *J. Amer. Chem. Soc.*, 71, 2953 (1949).

(6) P. G. Gassman and J. L. Marshall, *ibid.*, 88, 2822 (1966).

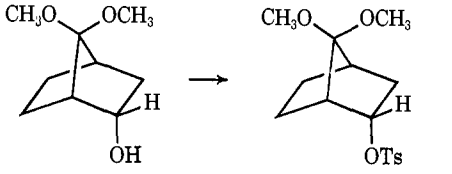
(7) P. G. Gassman and J. G. Macmillan, *ibid.*, **91**, 5527 (1969).

(8) P. G. Gassman and J. M. Hornback, *ibid.*, **94**, 7010 (1972).

2-ol (**1**) and *endo*-7,7-dimethoxybicyclo[2.2.1]heptan-2-ol (**2**) were prepared and characterized as previously described.[6] Treatment of **1** and **2** with *p*-toluenesulfonyl chloride in pyridine gave the tosylates **3** and **4**, respectively.



1 **3**



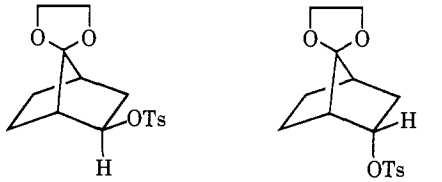
2 **4**

Acetolysis. The rate constants obtained for the solvolysis of **3** and **4** in anhydrous acetic acid buffered with sodium acetate are listed in Table I. As can be seen from Table I, the rates of **3** and **4** differ by only a factor of 38 at 25°. This difference is larger than the corresponding exo/endo rate ratios of 10 for the exo and endo epimers **5** and **6**,[7] and of 0.17 for the isomeric tosylates **7** and **8**.[6] However, the solvolytic behavior of these two epimeric pairs has been interpreted as being anomalous, since the exo and endo isomers give different product ratios. Thus, it was of prime importance to establish the nature of the products from the acetolysis of **3** and **4** in order to ascertain whether they were solvolyzing to give a common intermediate.

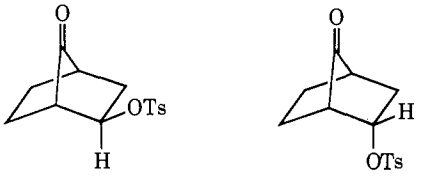
Table I. Rates of Solvolysis of *exo*- and *endo*-7,7-Dimethoxybicyclo[2.2.1]hept-2-yl Tosylates in Anhydrous Acetic Acid Buffered with Sodium Acetate

Compd	Temp, °C	Rate, sec^{-1}	$\Delta H^{\pm}$, kcal/mol	$\Delta S^{\pm}$, eu
3	100.00 ± 0.02	(1.07 ± 0.04) × 10^{-3}		
	90.00 ± 0.02	(3.58 ± 0.13) × 10^{-4}	26.8	−0.7
	75.85 ± 0.02	(8.12 ± 0.03) × 10^{-5}		
	25.0[a]	9.53 × 10^{-8}		
4	100.00 ± 0.02	(6.35 ± 0.01) × 10^{-5}		
	90.00 ± 0.02	(2.05 ± 0.13) × 10^{-5}	27.5	−5.8
	75.77 ± 0.02	4.39 × 10^{-6}		
	25.0[a]	2.51 × 10^{-9}		

[a] Extrapolated from higher temperature.

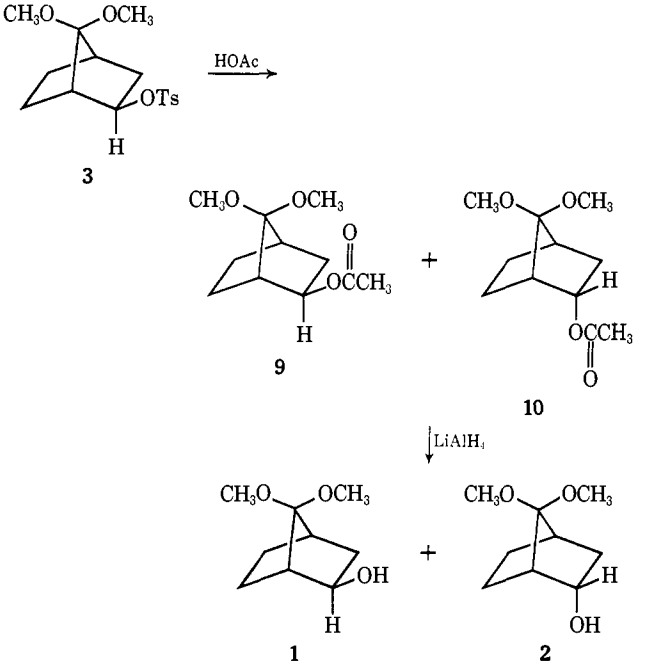


5 **6**



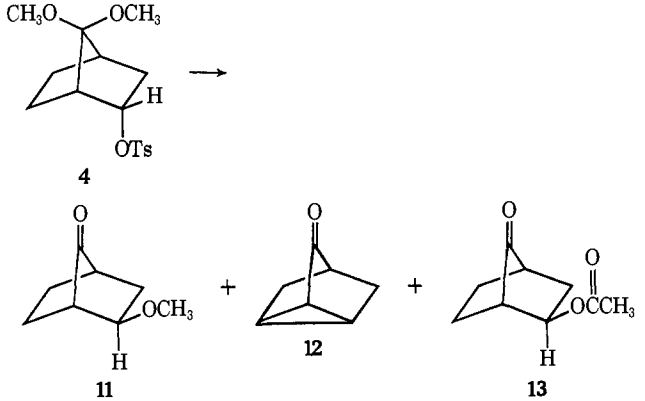
7 **8**

The acetolysis of **3** gave a 71% yield of a mixture which consisted of 95.5% of **9** and 4.5% of **10**.[9] The structures of **9** and **10** were established by lithium aluminum hydride reduction of the mixture of acetates to a corresponding mixture of alcohols, which was separated by preparative vpc to give samples of **1** and **2** which were identical in all respects with authentic samples. Suitable control reactions established that **9** and **10** were not interconverting under the reaction conditions.



3 **9** **10** **1** **2**

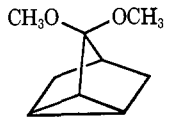
When **4** was solvolyzed in acetic acid buffered with sodium acetate, a very different product mixture was obtained. In contrast to the mixture of ketals obtained from **3**, **4** gave a mixture consisting of the three ketonic products **11** (16%), **12** (29%), and **13** (55%). It could be demonstrated that **11**, **12**, and **13** were stable for 10 half-



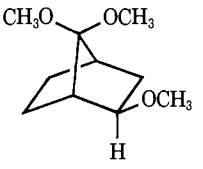
4 **11** **12** **13**

(9) In addition to a 71% yield of the mixture of **9** and **10**, we also found approximately 12% of a third product which was neither *exo*- nor *endo*-2-acetoxybicyclo[2.2.1]heptan-7-one (no carbonyl absorption in the infrared region of the spectrum attributable to the carbonyl moiety in the 7 position). Lithium aluminum hydride reduction of this uncharacterized intermediate gave a mixture of *syn*- and *anti*-7-hydroxy-*exo*-2-hydroxybicyclo[2.2.1]heptane. These diols were characterized through comparison with authentic samples [J. K. Crandall, *J. Org. Chem.*, **29**, 2830 (1964); H. Kwart and W. G. Vosburgh, *J. Amer. Chem. Soc.*, **76**, 5400 (1954)]. On the basis of these data, this rather unstable third product was tentatively assigned the structure 2,7-diacetoxy-7-methoxybicyclo[2.2.1]heptane.

lives under the solvolysis conditions. Similarly, it was shown that both **9** and **10** were stable under the reaction conditions used for the solvolysis of **4**. In checking for possible intermediates in the formation of **11**, **12**, and **13**, we subjected **14** and **15** to the reaction conditions. It was established that neither **14** nor **15** was an inter-

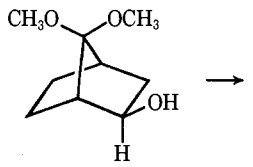


14

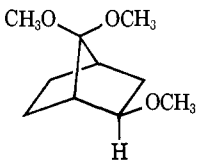


15

mediate in the formation of any of the observed products. The structures of **12** and **13** were established through comparison of their vpc retention times and spectral properties with authentic samples of nortricyclanone (**12**) and *exo*-2-acetoxybicyclo[2.2.1]heptan-7-one (**13**).[6] An authentic sample of **11** was prepared by treating **1** with sodium hydride in tetrahydrofuran followed by methyl iodide to give **15** in 91% yield.



1



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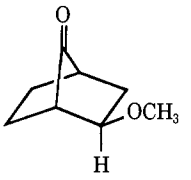
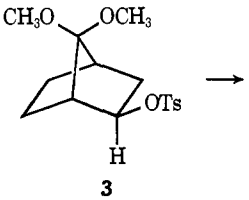


11

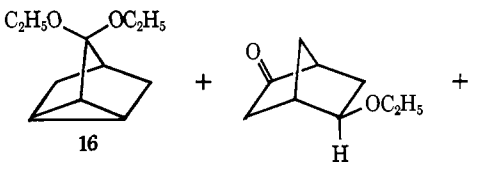
Hydrolysis of **15** with 5% aqueous sulfuric acid gave **11** in 91% yield. The spectral properties of **11** were identical with those of the corresponding solvolysis product.

Ethanolysis. The diverse behavior noted for the acetolysis of **3** and **4** suggested that totally different mechanisms might be involved in the solvolysis of these two isomeric tosylates. In order to evaluate whether this change in mechanism (*vide post*) was solvent dependent, we examined the ethanolysis of **3** and **4**. In order to minimize the effect of acid catalysis by the *p*-toluenesulfonic acid being generated during ethanolysis, the solvent was buffered with *syn*-dimethylurea (DMU). Under these conditions good pseudo-first-order kinetics could be obtained for greater than 50% reaction. The ethanolysis rates are listed in Table II. As can be seen from an examination of the data, the kinetic behavior in ethanol parallels that observed in acetic acid. The exo/endo rate ratio in ethanol was 19 at 25°. The parallel kinetic observations suggest that a parallel might also exist in product formation. This suspicion was confirmed by an examination of the solvolysis products.

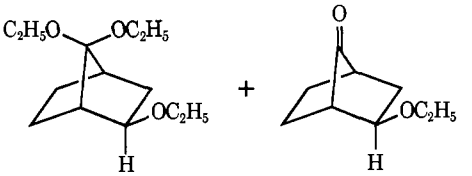
In ethanol, **3** solvolyzed to produce a 91% yield of a mixture consisting of **16** (11%), **17** (22%), **18** (65%), and **19** (2%). All structural assignments were made through comparison with authentic samples. An authentic sample of **16** was prepared *via* treatment of nortricyclanone[10] (**12**) with triethyl orthoacetate in the



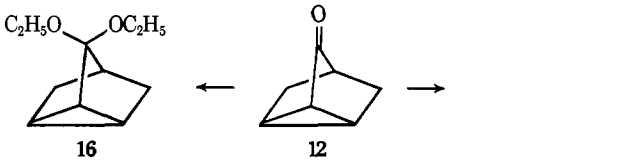
3



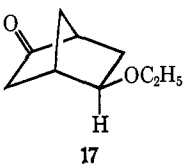
16 **17**



18 **19**



16 **12**

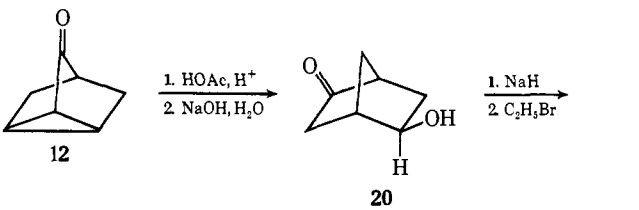


17

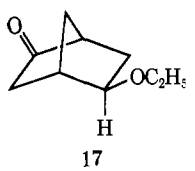
presence of IR-120 ion exchange resin in absolute ethanol. Under these conditions, pure **16** could be obtained in 81% yield. *exo*-5-Ethoxybicyclo[2.2.1]heptan-2-one (**17**) was prepared by refluxing an ethanolic solution of **12** in the presence of *p*-toluenesulfonic acid. Aqueous work-up gave **17** in 76% yield.[11] 2,7,7-Triethoxybicyclo[2.2.1]heptane (**18**) was prepared in two steps from **1**. Conversion of **1** into **21** with sodium hydride in dimethylformamide followed by ethyl bromide was readily accomplished. Under acidic conditions in etha-

(10) J. Meinwald, J. Crandall, and W. E. Hymans, *Org. Syn.*, **45**, 77 (1965).

(11) An alternate, more lengthy, but less ambiguous synthesis of **17** was accomplished *via* the acid-catalyzed addition of acetic acid to **12**, followed by hydrolysis to give *exo*-5-hydroxybicyclo[2.2.1]heptan-2-one



12 **20**



17

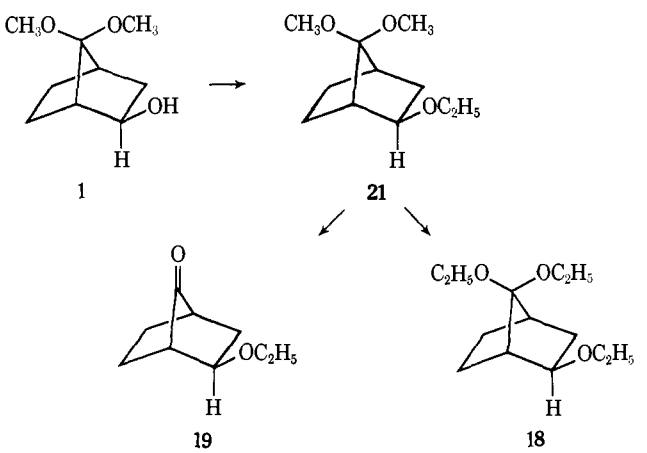
(**20**).[12] Treatment of **20** with sodium hydride in dimethylformamide followed by ethyl bromide also gave **17**.

(12) J. Meinwald, J. K. Crandall, and P. G. Gassman, *Tetrahedron*, **18**, 815 (1962).

Table II. Rates of Solvolysis of 3 and 4 in Anhydrous Ethanol Buffered with *syn*-Dimethylurea (DMU).

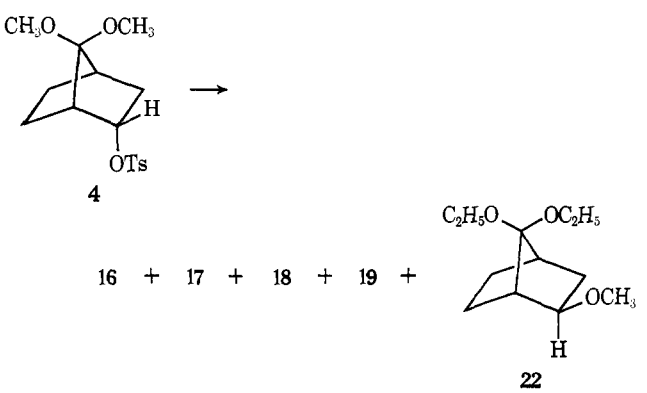
Compd	Temp, °C	Rate, sec^{-1}	$\Delta H^{\ddagger}$, kcal/mol	$\Delta S^{\ddagger}$, eu
3	100.00 ± 0.02	(2.99 ± 0.04) × 10^{-4}		
	90.00 ± 0.02	(1.08 ± 0.01) × 10^{-4}	26.2	−4.9
	80.00 ± 0.02	(3.74 ± 0.01) × 10^{-5}		
	25.0[a]	3.19 × 10^{-8}		
4	130.00 ± 0.02	(1.75 ± 0.02) × 10^{-4}		
	120.00 ± 0.02	(8.03 ± 0.02) × 10^{-5}	25.5	−13.0
	110.00 ± 0.02	(3.16 ± 0.15) × 10^{-5}		
	25.0[a]	1.69 × 10^{-9}		

[a] Extrapolated from higher temperatures.



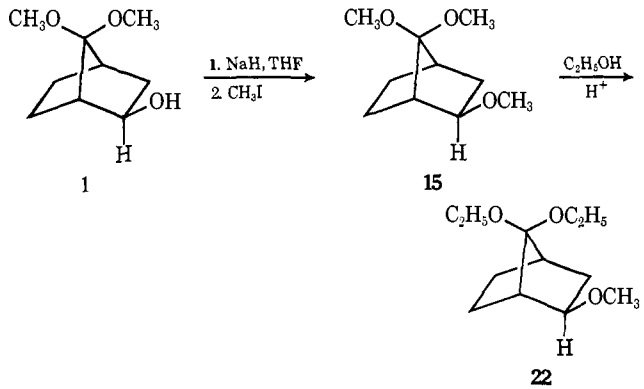
nol, **21** underwent rapid ketal exchange to give **18**. Similarly, acid-catalyzed hydrolysis of **21** gave **19**.

The ethanolysis of **4** differed from that of **3** in that **4** gave lesser amounts of the same four products which had been obtained from **3**, plus major amounts of 7,7-diethoxy-*exo*-2-methoxybicyclo[2.2.1]heptane (**22**). The



total product mixture (77% yield) consisted of **16** (8%), **17** (12%), **18** (57%), **19** (5%), and **22** (18%). The structure of **22** was established through comparison with an authentic sample which was prepared *via* the sequence **1** → **15** → **22**. In order to establish the stability of certain plausible intermediates to the reaction conditions, **14** and **21** were subjected to refluxing ethanol containing *p*-toluenesulfonic acid and *syn*-dimethylurea. Under these conditions, **14** was converted to a mixture of **16** and **17**, while **21** gave **18**. It was further established that **18** was partially converted to **19** under the work-up conditions.[13] These results indicate to us

(13) This conversion occurred during vpc analysis. Surprisingly, the diethyl ketal, **16**, and all the dimethyl ketals were stable to the same vpc process.

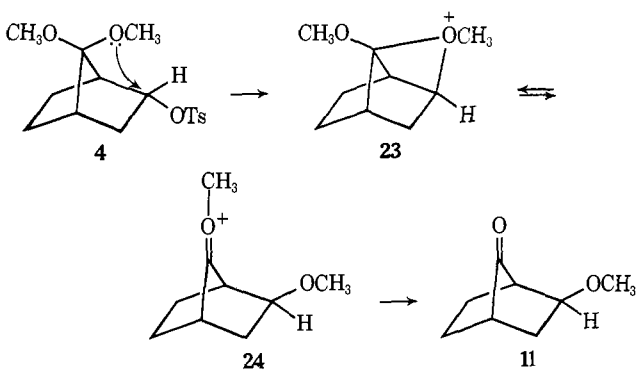


that **16** and **18** were reasonable mechanistic precursors of **17** and **19**, respectively, in the ethanolysis of **3** and **4**.

Discussion

The rate differences and the product differences noted for the acetolysis and ethanolysis of **3** and **4** require that **3** and **4** solvolyze *via* different mechanistic paths. The formation of the *exo*-2-methoxybicyclo-[2.2.1]heptane derivatives from **4** in both the acetolysis and methanolysis provided convincing evidence for interaction of the *syn*-methoxyl group with the incipient cation which develops in the ionization of **4**. Although examples of MeO-3, MeO-5, and MeO-6 neighboring group participation have been well established in the chemical literature,[14,15] interaction of a methoxyl function with an incipient cationic center *via* MeO-4 neighboring group participation appeared to be unrecognized prior to this example.[1]

The most striking difference in the products from the solvolysis of **3** and **4** occurred under the acetolysis conditions. Whereas **3** gave only products which were sp^3 hybridized at C-7, **4** gave only products which



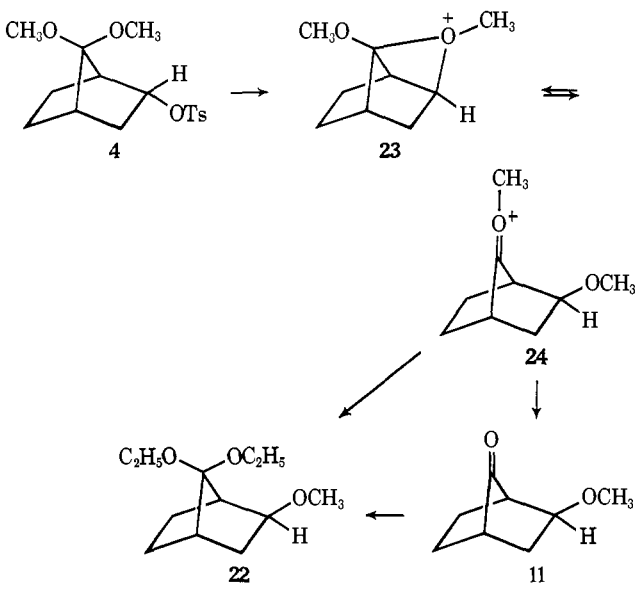
were sp^2 hybridized at C-7. We feel that these observations are readily interpreted in terms of the formation of **23** in the rate-determining step for the acetolysis of **4**. Opening of **23** to give **24** followed by loss of a methyl group would then produce **11**. Various reaction paths can be conceived for the conversion of **4** into **12** and **13**. However, the failure of **9**, **10**, **14**, and **15** to yield either **12** or **13** under the reaction conditions rules out numerous plausible routes. The ketonic nature of **12** and **13** and the failure of **3** to yield such ketonic products implies that these prod-

(14) B. Capon, *Quart. Rev., Chem. Soc.*, **18**, 45 (1964), and references contained therein.

(15) S. Winstein and E. L. Allred, *J. Amer. Chem. Soc.*, **89**, 3991, 3998, 4012 (1967).

ucts must arise *via* a path which is not open to **3**.[16] Thus, we are forced to conclude that both **12** and **13** are derived from either **23** or **24** by some undefined (and presumably complex) process.

The ethanolysis of **4** also provided unequivocal evidence for MeO-4 neighboring group participation. However, the overall picture in the case of ethanolysis was less well defined due to ketal exchange and ketal formation. In addition to different mixtures of **16**, **17**, **18**, and **19** obtained from both **3** and **4**, **4** gave a

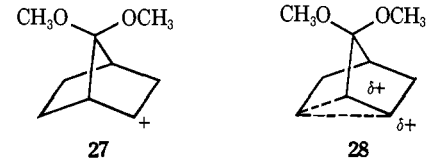


14% yield of **22**. The formation of **22** was most readily rationalized in terms of the intermediacy of **23** and **24**. Direct ketalization of **24** followed by an ethoxy–methoxyl group interchange would produce **22**. An alternate process would involve the formation of **11** as a discrete intermediate followed by acid-catalyzed ketal formation. The complete absence of **22** from the product mixture formed in the ethanolysis of **3** indicated that **22** was not arising from **16**, **17**, **18**, **19**, or any other product or intermediate common to the solvolysis of both **3** and **4**. Thus, the ethanolysis of these two tosylates must follow distinct mechanistic paths (at least in part).

On the basis of the premise that **4** undergoes both acetolysis and methanolysis *via* MeO-4 neighboring group participation, several interesting questions arise. Among the more significant questions to be answered are: (a) since **3** undergoes acetolysis 38 times faster than **4**, what rate effect can be attributed to MeO-4 neighboring group participation in the case of **4**; (b) why does not the ion formed from **3** interact with the *syn*-methoxyl group to eventually yield the same ion as is formed initially in the solvolysis of **4**; and (c) where does the solvolysis of **3** fit into the total picture of solvolytic behavior of the bicyclo[2.2.1]hept-2-yl cations?

The rate effect of the MeO-4 neighboring group participation in the acetolysis of **4** is difficult to ascertain with much accuracy. If we compare the rate of acetolysis of **3** with that of bicyclo[2.2.1]hept-*exo*-2-yl tosylate (**25**), we see that the two methoxyl groups provide a rate-retarding effect of 4.1×10^{-3}. If we assume that in the absence of MeO-4 neighboring group participation both **3** and **4** would yield the same ion initially[2c-e] (*vide post*) and that the steric effect of the *syn*-7-methoxyl group will be negligible in determining the rate ratios, then **4** should solvolyze at a rate 4.1×10^{-3} slower than bicyclo[2.2.1]hept-*endo*-2-yl tosylate (**26**). Under these conditions, the predicted rate would be 3.4×10^{-10} sec^{-1} *vs.* an observed rate of 2.51×10^{-9} sec^{-1}. Hence, in the absence of nonclassical ion formation and steric acceleration by the *syn*-7-methoxyl group the *maximum* rate factor attributable to MeO-4 neighboring group participation would be *ca.* 7. This factor would be reduced by nonclassical ion formation, but increased in size if the *syn*-7-methoxyl group were providing any steric acceleration.[17]

A second point of interest, as indicated above, was concerned with the nature of the cation generated from **3**. In principle, this ion could be envisaged as having either the classical cationic structure, **27**, or the delocalized nonclassical structure, **28**. We feel that the



ion generated from **3** is on the borderline between **27** and **28**.[19] In support of this suggestion are several facts. First, no trace of **11** could be found in the acetolysis of **3**. If **3** were producing a purely classical cation such as **27**, we would expect subsequent interaction with the *syn*-methoxyl group to produce ion **23** and eventually **11**. The absence of such an interaction with the *syn*-methoxyl group indicates to us that some other type of stabilization is preempting stabilization by the nonbonding electrons on oxygen. Such stabilization could be derived from participation of the C_1–C_6 bonding electrons to form a delocalized ion such as **28**. Ample precedent exists for the formation of independent, noninterconverting ions from epimeric tosylates, due to neighboring group participation in the ionization of the epimeric tosylates by independent functions.[20] Although such participation would appear to be sufficiently strong that leakage to ion **23** does not occur, we feel that very little charge must reside at C-1. This contention is supported by the absence of Wagner–Meerwein rearrangement products and by the formation of both exo and endo acetates in the solvolysis of **3**. Thus, the ion formed from **3** must lie at the

(16) The ketoacetate, **13**, would not be expected to arise from **12**, since the acid-catalyzed addition of acetic acid to **12** gives 2,5-disubstituted norbornanes as discussed above.

(17) Such steric acceleration can be tentatively ruled out by an evaluation of the additivity of both 7-*syn*- and *anti*-methoxyl groups. As Schleyer and coworkers have shown,[18] an *anti*-7-methoxyl group has a rate retarding effect of 8.36×10^{-2} relative to hydrogen on the rate of acetolysis of the *exo*-2-tosylate. If this effect were completely additive, the predicted rate change due to two methoxyl groups at C-7 would be 7.0×10^{-3}. The observed effect was 4.1×10^{-3}. Thus, the steric effect of the *syn*-7-methoxyl group should not be accountable for an effect greater than a rate factor of 2.

(18) P. v. R. Schleyer, P. J. Stang, and D. J. Raber, *J. Amer. Chem. Soc.*, **92**, 4725 (1970).

(19) The existence of such a borderline situation is consistent with Brown's hypothesis that a spectrum of ions should exist, with "a gradual transition between static classical, equilibrating classical, equilibrating π bridge, and static bridged cations."[3d]

(20) For a clear-cut example, see C. H. DePuy, I. A. Ogawa, and J. C. McDaniel, *J. Amer. Chem. Soc.*, **83**, 1668 (1961).

borderline between those cases which are clearly delocalized and those which have classical structures.[21]

The borderline nature of the ion generated from **3** brings us to the question of the position of this ion in the overall picture of the ions generated from various derivatives of bicyclo[2.2.1]hept-*exo*-2-yl tosylates. If the solvolysis of **3** represents a borderline case, which derivatives yield classical ions and which yield nonclassical? In general, we wish to suggest that derivatives of bicyclo[2.2.1]hept-*exo*-2-yl tosylates bearing substituents in the 1 or 7 position with electron-withdrawing power greater than two 7-methoxyl groups will not yield ions in which the charge will be delocalized in the 1 position in the transition state for ionization of the tosylate function.

Experimental Section[22]

7,7-Dimethoxybicyclo[2.2.1]heptan-*exo*-2-ol (1) and 7,7-Dimethoxybicyclo[2.2.1]heptan-*endo*-2-ol (2). The epimeric alcohols were prepared as previously described by Gassman and Marshall.[6]

7,7-Dimethoxybicyclo[2.2.1]hept-*exo*-2-yl *p*-Toluenesulfonate (3). To a solution of 1.71 g of **1** in 11 ml of pyridine cooled to 0° was added with stirring 2.10 g of *p*-toluenesulfonyl chloride over a period of 20 min. The resulting solution was allowed to stand at 5° for 22 hr and then was mixed with 65 ml of water. The tosylate, which immediately crystallized, was washed with three 25-ml portions of water and dried in a vacuum desiccator overnight to yield 2.52 g (78%) of white crystals, mp 83–87°. Recrystallization from hexane gave an analytical sample, mp 93.0–93.6°. *Anal.* Calcd for $C_{16}H_{22}O_5S$: C, 58.88; H, 6.79; S, 9.82. Found: C, 58.62; H, 6.90; S, 9.90.

7,7-Dimethoxybicyclo[2.2.1]hept-*endo*-2-yl *p*-Toluenesulfonate (4). To a solution of 3.17 g of **2** in 20 ml of pyridine cooled to 0° was added 3.90 g of *p*-toluenesulfonyl chloride over a period of 5 min. The resulting solution was allowed to stand at 5° for 12 hr. The solution was mixed with 300 ml of water and extracted with three 25-ml portions of chloroform. The combined extracts were dried over anhydrous magnesium sulfate and concentrated under reduced pressure to give a crystalline product. Recrystallization from hexane gave 3.38 g (56%) of clear cubes, mp 93.2–94.0°. *Anal.* Calcd for $C_{16}H_{22}O_5S$: C, 58.88; H, 6.79; S, 9.82. Found: C, 58.90; H, 6.80; S, 9.67.

Kinetics Reagents. Anhydrous acetic acid was prepared by refluxing a solution of acetic anhydride and sodium acetate in glacial acetic acid for 24 hr and subsequent fractional distillation in a dry atmosphere. Standard sodium acetate in acetic acid (*ca.* 0.1 *M*) was prepared by the careful addition of anhydrous acetic acid to a solution of anhydrous sodium carbonate in acetic anhydride, such that *ca.* 1% acetic anhydride remained after the water of neutralization was removed, followed by refluxing in a dry atmosphere for 5 hr[23] (calculated to be 1.325 g of anhydrous sodium carbonate and 3.78 g of acetic anhydride diluted to 250 ml with anhydrous acetic acid). Anhydrous ethanol was prepared by the procedure of Fieser.[24] Standard perchloric acid in acetic acid (*ca.* 0.02 *M*) used in titrating acetolysis aliquots was prepared by the careful addition of 70% perchloric acid to a solution of anhydrous acetic acid and acetic anhydride, such that 1% acetic anhydride remained after the water was removed, followed by standing at room temperature for 12 hr[23] (calculated to be 0.7177 g of 70% perchloric acid and 3.72 g of acetic anhydride diluted to 250 ml with anhydrous acetic acid). The molarity of the standard perchloric acid in acetic acid was determined by titrating an aliquot of primary standard of potassium acid phthalate in anhydrous acetic acid using Bromophenol Blue as the indicator. Standard sodium methoxide in methanol used in titrating ethanolysis aliquots was prepared by addition of solid sodium methoxide to anhydrous methanol; the molarity of the resulting titrant was determined by dilution of an aliquot with an excess of water and subsequent titration with standard aqueous hydrochloric acid using phenolphthalein as the indicator.

Anhydrous ethanol was prepared from absolute ethanol as follows. A mixture of 5 g of magnesium turning, 50 ml of absolute ethanol, and a few drops of carbon tetrachloride was heated in a dry atmosphere until a vigorous reaction ensued. When the reaction subsided, 1 l. of absolute ethanol was added and the mixture refluxed for 2 hr. The ethanol was distilled between 78 and 79° in a dry atmosphere.

A solution of dimethylurea buffered ethanol was prepared by dissolving 11.0 g of recrystallized commercial dimethylurea in 500 ml of dry ethanol.

Kinetic Procedure. A 0.02–0.03 *M* solution of tosylate was prepared in a 10-ml volumetric flask with the appropriate solvent. Aliquots of slightly greater than 1 ml were transferred to glass ampoules which had been previously flushed with nitrogen. After sealing, the ampoules were transferred to a constant-temperature bath and a timer was immediately started. At appropriate time intervals an individual ampoule was removed from the bath and plunged into an ice–water bath to quench the reaction. Upon warming to room temperature the ampoule was opened and a 1-ml aliquot was removed with a constant-volume automatic pipet for titration. The aliquot was then titrated with the appropriate titrant using either an indicator or a pH meter to determine the end point.

The end point for the titration of sodium acetate in acetic acid was determined either by the yellow to clear color change of Bromophenol Blue indicator or by titration to a pH which corresponded to the inflection point of the titration curve. *p*-Toluenesulfonic acid in ethanol was titrated with sodium methoxide in methanol using Bromophenol Blue indicator.[25]

All kinetic data were processed by computer.

Product Analysis of the Acetolysis of 7,7-Dimethoxybicyclo[2.2.1]-hept-*exo*-2-yl *p*-Toluenesulfonate (3). A solution of 0.476 g of **3** and 0.140 g of anhydrous sodium acetate in 20 ml of anhydrous acetic acid was heated at 100.00° for 114 min. The solution was cooled and poured into ice–water, and the acetic acid was neutralized *via* the addition o fsolid sodium carbonate. The slightly basic solution was extracted with six 100-ml portions of ether. The combined ethereal extracts were dried over anhydrous magnesium sulfate, the drying agent was removed by filtration, and the solution was concentrated under reduced pressure. The residue was distilled to yield 0.270 g (66%) of a clear liquid, bp 90–100° (0.5 mm), whose infrared spectrum was identical with that for the *exo*-acetoxy ketal, **9**. This product was reduced with lithium aluminum hydride in ether to form the ketal alcohol, since the ketal acetates (**9** and **10**) could not be separated by vpc. The crude alcohol mixture proved to consist of 95.5% of the exo alcohol **1** and 4.5% of the endo alcohol **2**. An independent experiment proved that a pure sample of the *exo*-acetoxy ketal **9** could not account for the *endo*-hydroxy ketal **2**.

When the acetolysis product mixture from **3** was analyzed by vpc prior to distillation, a 71% yield of the mixture of **9** and **10** was established. In addition, approximately 12% of a third component was detected.[26] Lithium aluminum hydride reduction of the crude solvolysis product mixture prior to distillation gave the expected mixture of **1** and **2** and a mixture of *syn*- and *anti*-7-*exo*-2-dihydroxybicyclo[2.2.1]heptane.

Product Analysis of the Acetolysis of 7,7-Dimethoxybicyclo-[2.2.1]hept-*endo*-2-yl *p*-Toluenesulfonate (4). A solution of 0.730 g of **4** and 0.206 g of anhydrous sodium acetate in 30 ml of anhydrous acetic acid was heated at 100.00° for 1950 min. This solution was worked up and distilled as above to yield 0.220 g of

(21) The nature of such borderline cases is extremely hard to evaluate because the intermediate chemical behavior gives all of the biased observers something which fits their preferred theory.[3]

(22) All melting points and boiling points are uncorrected. Nuclear magnetic resonance spectra were run on a Varian Model A-60 spectrometer and all chemical shifts were measured using tetramethylsilane as an internal standard. Mass spectral analyses were obtained on an AEI-MS9 mass spectrometer. Infrared spectra were taken on a Perkin-Elmer Model 137 sodium chloride prism spectrophotometer and all spectra were calibrated relative to the 6.238-μ band in polystyrene. Near-infrared spectra were obtained on a Cary Model 14 spectrophotometer. Vapor phase chromatograms were run on an F&M Corporation Model 810 chromatograph or an Aerograph Hy-Fi, 600 D. Microanalyses were obtained from Scandinavian Microanalytical Laboratory, Herlev, Denmark, Max-Planck-Institut fur Kohlenforschung, and a few were obtained on an F&M Corporation Model 800 Carbon-Hydrogen-Nitrogen Analyzer. Computer programs were run on an IBM-7094 computer using the Ohio State University system.

(23) P. D. Bartlett and W. P. Giddings, *J. Amer. Chem. Soc.*, **82**, 1240 (1960).

(24) L. F. Fieser, "Experiments in Organic Chemistry," 3rd ed, D. C. Heath, Boston, Mass., 1957, p 285.

(25) S. G. Smith, A. H. Fainberg, and S. Winstein, *J. Amer. Chem. Soc.*, 83, 618 (1961).

(26) It was established by vpc analysis that this third component was not **13**.

a yellow-tinted product which proved to consist of 29% of **12**, 16% of **11**, and 55% of **13**. The overall yield of these three products from **4** was 70%. Each of the products was collected by preparative vpc (15% didecyl phthalate on Chromosorb P) and was identified by comparing its infrared spectrum with that of an authentic sample. Independent experiments under identical acetolysis conditions proved that **9**, **10**, **11**, **12**, **13**, **14**, and **15** were not interconvertible with any of the (other) solvolysis products.

exo-**2-Acetoxy-7,7-dimethoxybicyclo[2.2.1]heptane (9).** To a solution of 4.30 g of the *exo*-hydroxy ketal **1** in 40 ml of pyridine was added dropwise 2.8 g of acetyl chloride with swirling. After standing for 15 min, the resulting mixture was poured over 400 ml of water and extracted with four 50-ml portions of ether. The combined extracts were dried over anhydrous magnesium sulfate, filtered, concentrated under reduced pressure, and distilled to give 4.76 g (89%) of **9**, bp 83–85° (0.6 mm). Redistillation gave an analytical sample, bp 104–105° (6 mm), n^{26}D 1.4587. *Anal.* Calcd for $C_{11}H_{18}O_4$: C, 61.66; H, 8.47. Found: C, 61.51; H, 8.50.

endo-**2-Acetoxy-7,7-dimethoxybicyclo[2.2.1]heptane (10).** Treatment of the *endo*-hydroxy ketal **2** as above gave an 89% yield (1.66 g) of the endo acetate **10** which crystallized when cooled. An analytical sample was prepared by redistillation, bp 67° (0.3 mm). A sample recrystallized from hexane gave white flakes, mp 29.0–30.1°. *Anal.* Calcd for $C_{11}H_{18}O_4$: C, 61.66; H, 8.47. Found: C, 61.39; H, 8.49.

Nortricyclanone (12). An authentic sample of **12** was prepared as previously described.[10]

exo-**2-Acetoxybicyclo[2.2.1]heptan-7-one (13).** An authentic sample of **13** was prepared as previously described.[6]

7,7-*exo*-**2-Trimethoxybicyclo[2.2.1]heptane (15).** A mixture of 4.02 g of the *exo*-hydroxy ketal **1**, 5 g of sodium hydride, and 100 ml of dry tetrahydrofuran was stirred under reflux for 22 hr. The stirring mixture was allowed to cool, and 25 g of methyl iodide was added. After the mixture was stirred at room temperature for 6 hr, 10 ml of water was added cautiously. The resulting mixture was washed with saturated sodium chloride solution until no more solids were carried out with the washings, dried over anhydrous magnesium sulfate, filtered, concentrated under reduced pressure. and distilled to yield 3.94 g (91%) of a clear oil, bp 73–77° (1.5 mm). A portion was purified *via* preparative vpc (15% didecyl phthlate on Chromosorb P) and subsequent distillation to give an analytical sample, bp 75° (1.4 mm), n^{25}D 1.4581. *Anal.* Calcd for $C_{10}H_{18}O_3$: C, 64.49; H, 9.74. Found: C, 64.55; H, 9.75.

exo-**2-Methoxybicyclo[2.2.1]heptan-7-one (11).** A mixture of 2.86 g of **15** and 20 ml of 5% sulfuric acid was stirred vigorously at room temperature for 18 hr and then extracted with two 50-ml portions of ether. The combined ethereal extracts were dried over anhydrous magnesium sulfate, filtered, concentrated under reduced pressure, and distilled to yield 1.96 g (91%) of a clear liquid, bp 78–80° (1.5 mm). A portion was purified *via* preparative vpc (15% didecyl phthalate on Chromosorb P) and subsequent distillation to give an analytical sample, bp 80–81° (1.4 mm), n^{26}D 1.4690. *Anal.* Calcd for $C_8H_{12}O_2$: C, 68.54; H, 8.63. Found: C, 68.56; H, 8.63.

Product Analysis of the Ethanolysis of 7,7-Dimethoxybicyclo-[2.2.1]heptan-*exo*-2-yl *p*-Toluenesulfonate (3). A solution of 153 mg of tosylate **3** in 10 ml of 0.25 *M* dimethylurea in absolute ethanol was heated at 130° for 1 hr. After the solution was cooled to room temperature, the acid generated was titrated to the Bromophenol Blue end point with 1.965 ml of 0.1214 *M* sodium methoxide in methanol. The basic solution was poured into 50 ml of water and the aqueous solution was extracted four times with 25-ml portions of ether. The combined ether extracts were washed twice with 15-ml portions of water, dried over anhydrous magnesium sulfate and filtered, and the solvent was distilled through a 12-in. Vigreux column. The crude oil was transferred to a vial containing 37.2 mg of *N,N*-dimethylaniline which was used as a standard. Vapor phase chromatograms were run on a 10-ft, 10% SE-30 column programmed at 100° for 10 min followed by an increase of 2°/min to 150°. For four runs the yields averaged 91%. Product compositions (also an average of four runs) were **16** (11%), **17** (22%), **18** (65%), and **19** (2%).

The identity of the products was determined by comparison of the infrared spectra of the isolated compounds with those of authentic samples. Vpc retention times of the solvolysis mixture on 10% SE-30, 5% PDEAS, and 15% Carbowax 20M compared favorably with those of authentic samples. The vpc of the solvolysis mixture enriched with the authentic samples showed appropriate increases in peak heights and areas.

Product Analysis of the Ethanolysis of 7,7-Dimethoxybicyclo-[2.2.1]heptan-*endo*-2-yl *p*-Toluenesulfonate (4). A solution of 235 mg of tosylate **4** in 10 ml of 0.25 *M* dimethylurea in absolute ethanol was heated for 1.5 hr at 130°. The solution was cooled and the liberated acid was titrated to the Bromophenol Blue end point with 3.270 ml of 0.1214 *M* sodium methoxide in methanol. The basic solution was poured into 75 ml of water and the solution was extracted five times with 25-ml portions of ether. The combined ether solutions were washed twice with 25-ml portions of water, dried over anhydrous magnesium sulfate, filtered, and the solvent was removed by distillation through a 12-in. Vigreux column. The crude product mixture was transferred to a vial containing 37.4 mg of *N,N*-dimethylaniline which was used as a standard. Vpc yields were determined on a 10-ft 10% SE-30 column with the temperature programmed at 100° for 10 min followed by an increase of 2°/min to 150°. For five runs the yields averaged 77%. Product compositions (also an average of five runs) were **16** (8%), **17** (12%), **18** (57%), **19** (5%), and **22** (18%).

The identity of the products was determined by comparison of vpc retention times of the solvolysis mixture with those of authentic samples on a 10-ft 10% SE-30 column, a 15-ft 5% PDEAS column, and a 10-ft 15% Carbowax 20M column. Vapor phase chromatograms on the same three columns of the solvolysis mixture enriched with authentic samples showed appropriate peak area increases.

Stability of 7,7-Dimethoxy-2-*exo*-ethoxybicyclo[2.2.1]heptane (21) to Ethanolysis. A solution of 0.222 g (0.0011 mol) of ketal ether, **21**, and 0.191 g of anhydrous *p*-toluenesulfonic acid in 10 ml of absolute ethanol was refluxed for 42 hr. The solution was poured into 25 ml of water and extracted with three 25-ml portions of ether. The combined ether extracts were dried with anhydrous magnesium sulfate and filtered, and the solvent was removed by distillation. The vpc of the crude product (0.182 g) showed only one product. Isolation of this product by preparative vpc and comparison of its ir, nmr, and vpc retention times with the major product from the ethanolysis of tosylates **3** and **4** showed them to be identical. The nmr showed that the dimethyl ketal, **21**, had exchanged with solvent to form *exo*-2,7,7-triethoxybicyclo[2.2.1]heptane (**18**).

Stability of 7,7-Dimethoxybicyclo[2.2.1]heptene to Ethanolysis. A solution of 3.0 g (19.5 mmol) of 7,7-dimethoxybicyclo[2.2.1]hept-2-ene[27] and 0.1 g of anhydrous *p*-toluenesulfonic acid in 50 ml of absolute ethanol was refluxed for 12 hr. The mixture was poured into 100 ml of 5% sodium bicarbonate and the solution was extracted three times with 50-ml portions of ether. The combined ether extracts were dried with anhydrous magnesium sulfate and filtered, and the solvent was removed by distillation. The product was distilled to yield 2.3 g of 7,7-diethoxybicyclo[2.2.1]heptene. The nmr clearly showed that the dimethyl ketal had exchanged with solvent.

Stability of 2,2-Dimethoxytricyclo[2.2.1.0^{3,5}]heptane (14) to Ethanolysis. A solution of 59.6 mg (0.387 mmol) of ketal **14** and 38.2 mg of anhydrous *p*-toluenesulfonic acid in 10 ml of 0.25 *M* DMU in dry ethanol was heated at 110° for 2.5 hr. The solution was poured into 50 ml of saturated aqueous sodium bicarbonate and the resulting mixture was extracted four times with 25-ml portions of ether. The combined ether extracts were washed twice with 25-ml portions of water, dried over anhydrous magnesium sulfate, and filtered, and the solvent was removed on a rotary evaporator. The crude product was transferred to a vial containing 26.0 mg of standard (*N,N*-dimethylaniline), and vpc analyses were determined. The major product, 2,2-diethoxytricyclo[2.2.1.0^{3,5}]heptane, which was identified by comparison of vpc retention times with an authentic sample, was formed in 64% yield and greater than 95% purity. Trace amounts of 5-*exo*-ethoxynorcamphor were also detected.

Stability of 7,7-Dimethoxybicyclo[2.2.1]heptan-*exo*-2-ol *p*-Toluenesulfonate (3) to Ethanolysis. A solution of 0.1752 g of **3** in 10 ml of 0.25 *M* DMU in absolute ethanol was heated in a sealed ampoule for 2 hr (1 half-life) at 90°. The resulting solution was poured into 50 ml of saturated aqueous sodium bicarbonate and followed by extraction with three 25-ml portions of ether. The combined ether extracts were dried with anhydrous magnesium sulfate and filtered, and the solvent was removed on a rotary evaporator. The resulting semisolid[28] was recrystallized from Skelly F to yield a crystalline

(27) P. G. Gassman and J. L. Marshall, *Org. Syn.*, **48**, 68 (1968).

(28) From the semisolid nature of the material at this stage, it was not possible to determine whether some ketal exchange had occurred. In the case of the ethanolysis of **4**, the substantial amount of **23**, which was formed, indicated that solvolysis occurred at least as rapidly as ketal exchange in the case of the tosylates.

solid whose melting point (90.5–91.0°), mixture melting point (90.0–91.0°), and ir were identical with the starting tosylate (**3**).

7,7-Dimethoxy-*exo*-2-ethoxybicyclo[2.2.1]heptane (21). To a solution of 2.0 g (0.0116 mol) of ketal alcohol (**1**) in 35 ml of dry dimethylformamide was added 0.86 g of 55% NaH in mineral oil. After foaming had subsided, 3.6 g of ethyl iodide was added followed by stirring overnight. To this solution, 35 ml of water was added and the resulting mixture was extracted three times with 25-ml portions of ether. The combined ethereal extracts were washed with a 25-ml portion of water and then dried over anhydrous magnesium sulfate. The solution was filtered and the solvent removed on a rotary evaporator. The crude product was distilled *in vacuo* to yield 1.1 g (47%) of the desired product, **21**, bp 74–75° (4 mm), n^{24}D 1.4547. *Anal.* Calcd for $C_{11}H_{20}O_3$: C, 65.97; H, 10.07. Found: C, 66.22; H, 10.10.

***exo*-2-Ethoxybicyclo[2.2.1]heptan-7-one (19).** A solution of 3.0 g (0.0150 mol) of ketal ether, **21**, and 15 ml of 5% sulfuric acid was stirred at room temperature for 12 hr. The solution was extracted three times with 10-ml portions of ether and the combined ether extracts were dried over anhydrous magnesium sulfate. The solution was filtered and the solvent removed by distillation through a 12-in. Vigreux column. The resulting crude product was distilled *in vacuo* to yield 1.64 g (71%) of **19**, bp 87–88° (3 mm), n^{27}D 1.4639. *Anal.* Calcd for $C_9H_{14}O_2$: C, 70.10; H, 9.15. Found: C, 69.91; H, 9.22.

***exo*-3,7,7-Triethoxybicyclo[2.2.1]heptane (18).** A solution of 0.871 g (0.00436 mol) of **21** and 0.4 g of anhydrous *p*-toluenesulfonic acid in 50 ml of absolute ethanol was stirred at reflux for 14 hr. The solution was poured into 50 ml of 5% sodium bicarbonate. The aqueous solution was then extracted three times with 25-ml portions of ether. The combined ether extracts were dried over anhydrous magnesium sulfate and filtered, and the solvent was removed by distillation through a 12-in. Vigreux column. Distillation of the product *in vacuo* yielded 0.714 g (71%) of **18**, bp 89–90° (3 mm), n^{27}D 1.4460. *Anal.* Calcd for $C_{13}H_{24}O_3$: C, 68.38; H, 10.59. Found: C, 68.18; H, 10.93.

2,2-Diethoxytricyclo[2.2.1.0^{3,5}]heptane (16). A solution of 3.0 g (0.0278 mol) of nortricyclanone (**12**) and 0.2 g of IR-120 ion exchange resin (strongly acidic) in 20 ml of triethyl orthoacetate and 50 ml of absolute ethanol was stirred at reflux for 12 hr. The solution was filtered and the solvent removed by distillation. The crude product was then distilled through a 12-in. Vigreux column to yield 4.1 g (81%) of **16**, bp 127–130° (86 mm), $n^{26.6}$D 1.4515. *Anal.* Calcd for $C_{11}H_{18}O_2$: C, 72.49; H, 9.96. Found: C, 72.17; H, 10.09.

***exo*-5-Ethoxybicyclo[2.2.1]heptan-2-one (17).** A solution of 5.2 g of *p*-toluenesulfonic acid monohydrate in 100 ml of benzene was refluxed for 20 min and the water was removed azeotropically. The remaining benzene was stripped off on a rotary evaporator and 3.3 g of nortricyclanone (**12**) was added along with 50 ml of absolute ethanol. The solution was refluxed for 12 hr, after which the mixture was poured onto 100 ml of 10% aqueous sodium bicarbonate. The mixture was extracted three times with 50-ml portions of ether and the combined ether extracts were dried over anhydrous magnesium sulfate. After filtration of the ether solution, the solvent was removed by distillation through a 12-in. Vigreux column and the crude product was distilled *in vacuo* to yield 3.4 g of **17**, bp 97–99° (10 mm), $n^{22.8}$D 1.4671. *Anal.* Calcd for $C_9H_{14}O_2$: C, 70.10; H, 9.15. Found: C, 70.09; H, 9.15.

Acknowledgment. We are indebted to the Petroleum Research Fund, administered by the American Chemical Society, for Grant No. 1670-A1 which supported this investigation.

Steric Effects in Bicyclic Systems. IV. Base-Catalyzed Enolization of Bicyclo[2.2.2]octan-2-one, Bicyclo[2.2.1]heptan-2-one, and Bicyclo[2.1.1]hexan-2-one[1]

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Abstract: Deuterium exchange of bicyclic ketones in 2:1 (v/v) dioxane–D_2O catalyzed by NaOD was measured by a mass spectrometric technique developed for this purpose. Second-order rate constants (M^{-1} sec^{-1}) at 25.0° and activation parameters ΔH^* (kcal mol^{-1}) and ΔS^* (eu) were determined as follows: bicyclo[2.2.2]octan-2-one (**1**) 3.03×10^{-2}, 13.1, and −21; bicyclo[2.2.1]heptan-2-one (**2**) 5.58×10^{-2}, 14.0, and −17 (exo); 8.26×10^{-5}, 17.1, and −20 (endo); and bicyclo[2.1.1]hexan-2-one (**3**) 6.04×10^{-6}, 17.8 and −23. The rate of base-catalyzed bromination of cyclohexanone was found to exceed that of **1** by a factor of 3.1 in water at 10.0°. The secondary isotope effect k_D/k_H for deuteration of **1** was 0.94 ± 0.04 at 25.0°. These results are interpreted as showing that the rates reflect the relative facility of proton abstraction from the different sites, and that the principal factors governing the rates of attack are the angle strain generated in the resulting enolates, which favors reactivity in the series **1** > **2** > **3**, and the greater steric blocking of access of the base to the reaction site by a two-carbon bridge as opposed to a one-carbon bridge, which favors reactivity in the series *exo*-**2** > *endo*-**2**, and **3** > **1**.

Bicyclic ring systems have been widely used as substrates for the examination of organic reactions, particularly the steric requirements of those reactions.[3] These compounds are attractive for this purpose because of their relatively fixed geometries, and because their molecular dimensions have been

(1) Address correspondence concerning this work to the University of Toronto. For part III, see ref 2a. Portions of this work were reported in preliminary communications, ref 2b,c. Supported in part by the U. S. Public Health Service, the Petroleum Research Fund, administered by the American Chemical Society, and the National Research Council of Canada.

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