Stereospecific Homoallylic Ring Expansions and Contractions[1]

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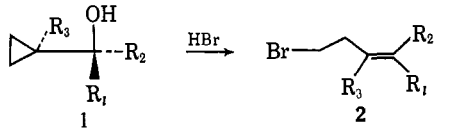
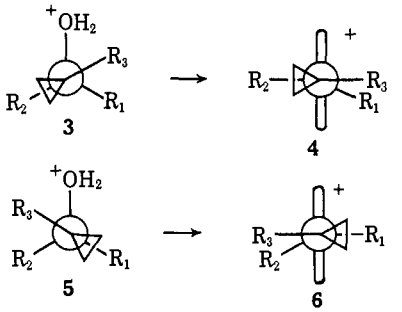
Abstract: The preparations and solvolyses of *syn-* and *anti*-bicyclo[7.1.0]dec-2-yl *p*-nitrobenzoate (*syn-* and *anti*-**16**-OPNB) are described. In 80% acetone–water, *syn*-**16**-OPNB gave hydrocarbons (12%), *syn*-**16**-OH (26%), *cis*-cyclodecen-4-ol (*cis*-**18**-OH) (45%), and *cis*-**18**-OPNB (17%). The *anti-p*-nitrobenzoate gave *anti*-**16**-OH (71%), *trans*-**18**-OH (15%), *trans*-**18**-OPNB (13%), and *trans*-bicyclo[6.2.0]decan-*trans*-9-ol (*trans,trans*-**19**-OH) (1%). Hydrolysis of *cis*-**18**-OBs produced hydrocarbons (25%), *syn*-**16**-OH (30%), and *cis*-**18**-OH (45%), while similar treatment of *trans*-**18**-OBs gave *anti*-**16**-OH (85%), *trans*-**18**-OH (14%), and *trans,trans*-**19**-OH (1%). All of the solvolyses are greater than 99.7% stereoselective. No crossover between *syn* and *anti* reaction pathways was observed. The bicyclo[7.1.0]decane carbon framework is the first in the homologous [*n*.1.0] series which permits an entire set of homoallylic ring expansions and contractions. The stereospecificity is explained in terms of two isomeric, noninterconverting nonclassical homoallylic ions which are generated stereospecifically from *syn–cis* or *anti–trans* precursors.

Stereochemical studies are often invaluable probes for providing information about the nature of reactive intermediates. Cyclopropylcarbinyl to homoallylic isomerizations have been found to be highly stereoselective in several systems.[3] These systems can be divided into two basically different groups. In 1961, Julia and coworkers[3d] reported that isomerizations of **1** to **2** (R_1 = alkyl, R_2 = R_3 = H) were 90–95% stereo-



1 2

selective. Johnson and coworkers[3e] desired to use the method for stereoselective synthesis of trisubstituted double bonds and found when R_1 = alkyl, R_2 = H, and R_3 = CH_3, that formation of **2** was 97% stereoselective. The stereoselectivity found for **1** can be explained in terms of current concepts about cyclopropylcarbinyl cations.[3a] Either **3** or **5** permits participation of the

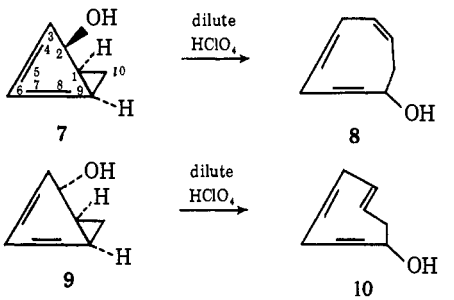


3 4

5 6

cyclopropane ring during ionization. Since R_1 (alkyl) is much larger than R_2 (H) conformer **3** predominates, and **4** is formed in preference to **6**. Once the cyclopropylcarbinyl cation is generated, the relative stereochemistry among R_1, R_2, and R_3 is fixed.[3a,4] Homoallylic product **2** derived from nucleophilic attack at the rear of the cyclopropane ring is the major homoallylic isomer. In this system ionization of the preferred conformer is the basis for stereoselectivity found in the homoallylic product.

Winstein and his coworkers[3b,c] discovered stereospecific cyclopropylcarbinyl to homoallylic isomerizations in a different system, illustrated by the conversion of **7** to **8** and **9** to **10**. It was proposed that ionization



7 8

9 10

gave a homoallylic cation in which positive charge was predominately delocalized to the cyclopropane carbon bearing the allylic substitutent. No products derived from the other, less substituted homoallylic ion were seen. In these systems, the relative orientation of the cyclopropane ring and the leaving group determined the geometry of the homoallylic cation and eventual homoallylic product. Models suggest that sometimes the molecules even twist into *unfavorable conformations* to utilize the more substituted arm of the cyclopropane ring during ionization. If the intermediate in these interconversions is a homoallylic cation, then the reverse cyclizations of **8** to **7** and **10** to **9** should also be stereospecific. This prediction was partially verified by the observation that *cis*-cyclononen-4-yl brosylate gave only *syn*-cyclopropylcarbinyl product.[3a] We now describe work with a system in which a

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(2) (a) This investigation was supported in part by National Institutes of Health Postdoctoral Fellowships 1-F2-GM-29,317-01 and 2-F2-GM-29,317-02 from the Institute of General Medical Sciences; (b) address correspondence to: The Department of Chemistry, University of Utah, Salt Lake City Utah 84112; (c) deceased, November 23, 1969.

(3) (a) C. D. Poulter, E. C. Friedrich, and S. Winstein, *J. Amer. Chem. Soc.*, **92**, 4274 (1970). (b) M. Gåsić, D. Whalen, B. Johnson, and S. Winstein, *ibid.*, **89**, 6382 (1967); (c) D. Whalen, M. Gašić, B. Johnson, H. Jones, and S. Winstein, *ibid.*, **89**, 6384 (1967); (d) M. Julia, S. Julia, and S.-Y. Tchen, *Bull. Soc. Chim. France*, 1849 (1961); (e) S. F. Brady, M. A. Ilton, and W. S. Johnson, *J. Amer. Chem. Soc.*, **90**, 2882 (1968).

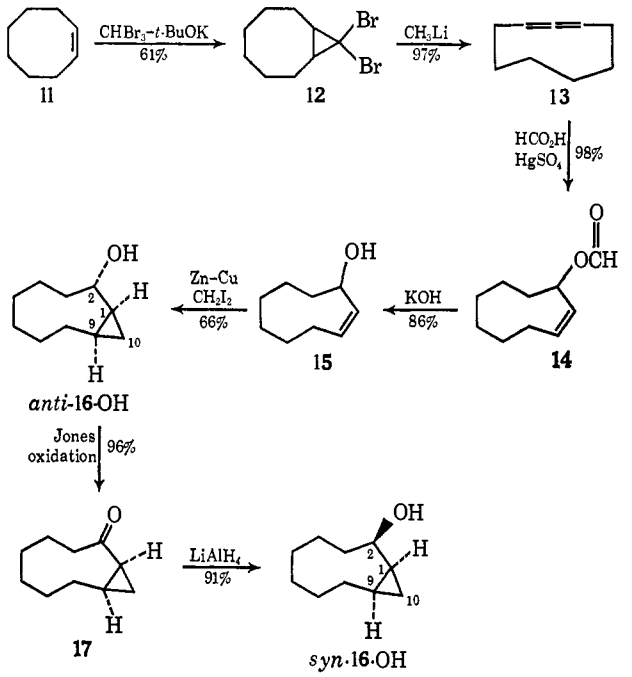
(4) P. von R. Schleyer and V. Buss, *ibid.*, **91**, 5880 (1969).

full set of stereospecific homoallylic ring expansions and contractions is observed.

Results

The synthetic sequence used to prepare *syn*-bicyclo[7.1.0]decan-2-ol (*syn*-**16**-OH) and *anti*-bicyclo[7.1.0]decan-2-ol (*anti*-**16**-OH) is outlined in Scheme I. The

Scheme I



addition of methylene to **15** is highly stereoselective, giving only 0.05% of the *syn* epimer.[5] Oxidation of *anti*-**16**-OH to **17**, followed by reduction with lithium aluminum hydride, gave *syn*-**16**-OH contaminated with less than 1% of its *anti* epimer. The *syn*-cyclopropylcarbinyl alcohol was somewhat sensitive and could not be obtained sufficiently pure, either by column chromatography or glpc, for an acceptable carbon–hydrogen analysis. The *p*-nitrobenzoate derivative was easier to purify and gave the expected combustion results.

We recently discussed several criteria for assigning the stereochemistry at C_2 for 2-bicyclo[6.1.0]nonane derivatives.[3a] The same general principles appear to hold for *syn*- and *anti*-**16**-OH. Methylene addition to **15** with direction by the hydroxyl group gives the *anti* epimer,[5] and hydride attack at the least-hindered face of the carbonyl group reduces ketone **17** to *syn*-**16**-OH. The more hindered hydroxyl group in *syn*-**16**-OH cannot form intermolecular hydrogen bonds as easily as *anti*-**16**-OH. The relative intensity of the 3630-cm^{-1} ir band (free hydroxyl stretch) for *syn*-**16**-OH is significantly greater than for the corresponding band (3610 cm^{-1}) of the *anti* epimer. Also, the neighboring cyclopropane ring shields the proton at C_2 (3.26 ppm) in *anti*-**16**-OH while deshielding the corresponding proton (4.35 ppm) in *syn*-**16**-OH. The resulting chemical-shift difference is 1.09 ppm,[6] which compares nicely with a calculated difference of 0.98–1.17 ppm.[3a]

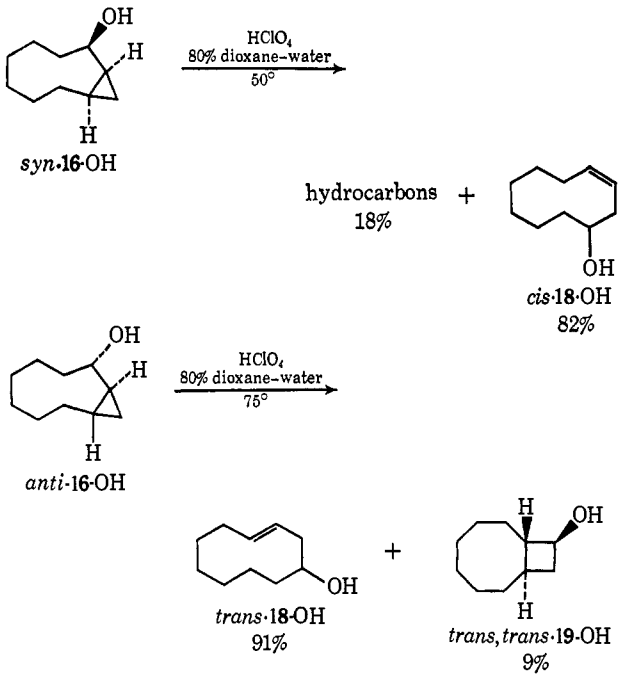
(5) We previously discussed the reasons for stereoselective methylene addition in these systems: C. D. Poulter, E. C. Friedrich, and S. Winstein, *J, Amer. Chem. Soc.*, **91**, 6892 (1969).

(6) Models indicate that the preferred conformations of *syn*- and *anti*-2-bicyclo[6.1.0]nonanes and *syn*- and *anti*-2-bicyclo[7.1.0]decanes are similar.

Dilute perchloric acid in 80% dioxane–water isomerized *syn*-**16**-OH to *cis*-cyclodecen-4-ol (*cis*-**18**-OH) and a mixture of hydrocarbons.[7] The stereochemistry of the double bond was assigned on the basis of ir spectra. Alcohol *cis*-**18**-OH had strong absorptions at 710 and 725 cm^{-1} and no strong bands between 900 and 990 cm^{-1}. On the other hand, *trans*-**18**-OH (*vide infra*) had a strong absorption at 980 cm^{-1}. The ir spectra of these isomers can be compared with those of *cis*-cyclodecene (781, 763, and 706 cm^{-1}) and *trans*-cyclodecene (972 cm^{-1}).[8] An nmr spectrum of *cis*-**18**-OH was consistent with the assigned structure. The chemical-shift difference between the protons at C_1 and C_2 was not large enough at 100 MHz to permit a first-order analysis of the coupling pattern.

Treatment of *anti*-**16**-OH with dilute perchloric acid at 75° gave two isomeric products (Scheme II), which

Scheme II



were easily separated by chromatography on alumina impregnated with silver nitrate. The major isomer (*trans*-**18**-OH) comprised 91% of the mixture. The homoallylic alcohol had an nmr spectrum similar to that for *cis*-**18**-OH and an ir spectrum with a strong band at 980 cm^{-1} (*vide supra*). The affinity which *trans*-**18**-OH exhibited toward silver nitrate during chromatography[9] is also characteristic of *trans* double bonds in medium rings.[10] The minor isomer (9% of the mixture) exhibited ir and nmr spectra very similar to those reported for *trans*-bicyclo[5.2.0]nonan-*trans*-8-ol.[3a,11] On this basis, the minor isomer was assigned

(7) The products assigned as hydrocarbons had short glpc retention times relative to *syn*-**16**-OH and *cis*-**18**-OH. Unfortunately, the hydrocarbon mixture was complex, and the structures of its components have not been determined.

(8) A. T. Bloomquist, R. E. Burge, Jr., and A. C. Sucsy, *J. Amer. Chem. Soc.*, **74**, 3636 (1952).

(9) The easiest way to recover *trans*-**18**-OH was to stir the alumina–silver nitrate column packing with dilute ammonium hydroxide solution and extract the aqueous layer with ether.

(10) A. C. Cope, K. Banholzer, H. Keller, B. A. Pawson, J. J. Whang, and H. J. S. Winkler, *J. Amer. Chem. Soc.*, **87**, 3644 (1965).

(11) The nmr spectrum of *trans,trans*-**19**-OH is also similar to that of *trans*-bicyclo[4.2.0]octan-*trans*-7-ol. We wish to thank Professor Wiberg for a preprint of his full paper: K. B. Wiberg and J. G. Pfeiffer, *ibid.*, **92**, 553 (1970).

Table I. Isomerization Rate Constants in 80% Dioxane–Water, 0.026 *M* $HClO_4$

Alcohol	Temp, °C	10^4k, sec^{-1}
syn-16-OH	25	0.415 ± 0.011
	50	11.0 ± 0.6
	75	183[a]
anti-16-OH	75	5.99 ± 0.18

[a] Extrapolated from rates at 25 and 50°; $\Delta H^{\ddagger}$ = 24.5 ± 0.8 kcal/mol, $\Delta S^{\ddagger}$ = 3.5 ± 3 eu.

was very sensitive to acid. Its rate was measured at 25 and 50° and extrapolated to 75°. The rate constants were calculated by comparing the relative areas of the cyclopropylcarbinyl alcohols with an internal standard as a function of time. The same results were obtained when the relative areas of products and internal standard were compared.

Solvolysis studies of *syn*- and *anti*-16-OPNB were carried out using the sealed ampoule technique. 2,6-Lutidine was used to neutralize the *p*-nitrobenzoic acid generated during solvolysis. Large-scale solvolyses (*ca.* 1 g) were carried out in order to establish structures of the products by correlation of ir and nmr spectra and glpc retention times. After the components of the product mixture had been properly identified, product studies on dilute solutions (0.005–0.01 *M*) were performed. Control experiments established that the products were stable to the reaction conditions. The results are summarized in Scheme III. Rate constants were determined by titration of liberated *p*-nitrobenzoic acid and are listed in Table II. The discrepancy between experimental and theoretical infinity titers and the amounts of homoallylic *p*-nitrobenzoates found in product studies were in excellent agreement.

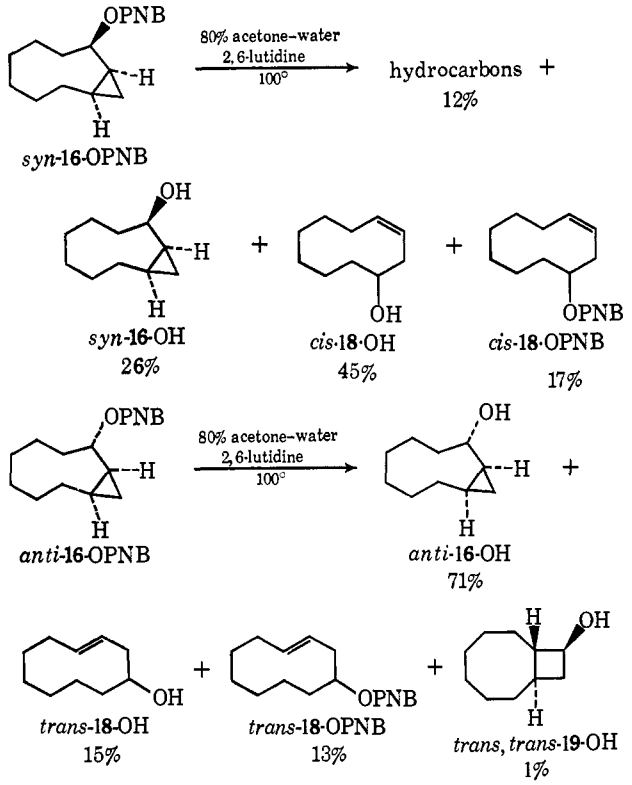
Table II. Solvolysis Rate Constants, 80% Acetone–Water

System	Temp, °C	10^5k, sec^{-1}	$\Delta H^{\ddagger}$, kcal/mol	$\Delta S^{\ddagger}$, eu
syn-16-OPNB	75.0	8.61 ± 0.14	21.6 ± 0.4	−15.5 ± 1.2
	100.0	74.5 ± 3.7		
cis-18-OBs	25.0	0.384 ± 0.009		
anti-16-OPNB	75.0	0.368 ± 0.010	24.9 ± 0.5	−12.3 ± 1.6
	100.0	4.39 ± 0.22		
trans-18-OBs	25.0	310 ± 13		

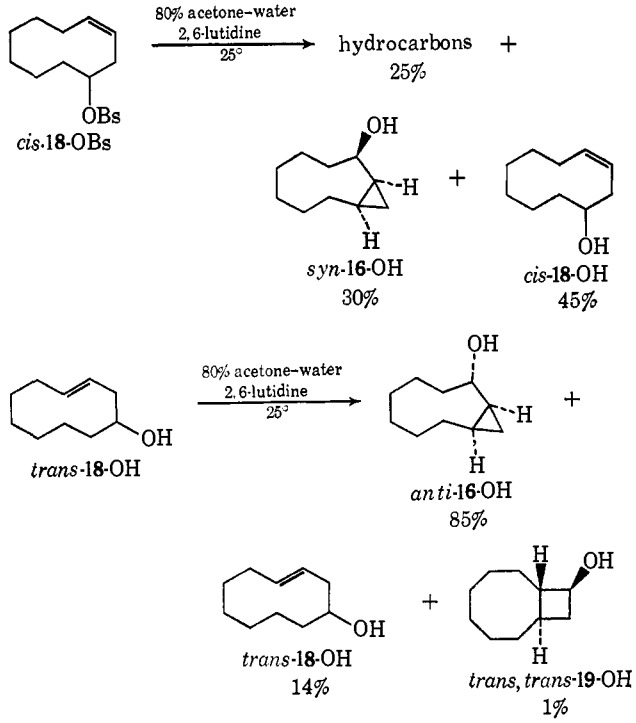
the structure of *trans*-bicyclo[6.2.0]decan-*trans*-9-ol[12] (*trans,trans*-19-OH).

A careful glpc study showed that at least 0.3% of *trans*-18-OH and *trans,trans*-19-OH could have been detected in *cis*-18-OH and *vice versa*. Isomerizations were carried out with carefully purified samples of *syn*- and *anti*-16-OH which contained less than 0.1% of the other epimer. We saw no crossover products between the *syn*- and *anti*-alcohols and conservatively estimate that less than 0.3% occurred. The progress of the isomerizations was followed by glpc. Samples were periodically withdrawn and quenched by vigorous shaking with anhydrous sodium carbonate. The rates of isomerization are listed in Table I. The *syn* epimer

Scheme III



Scheme IV



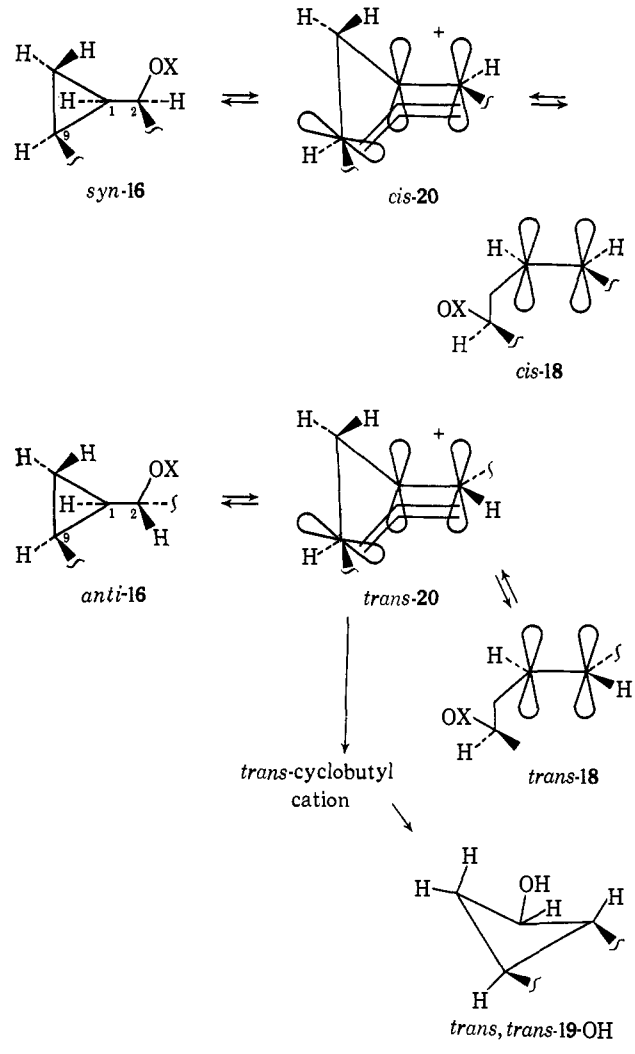
(12) The *trans,trans* isomer is also the expected product from *anti*-16-OH.[3a] The nomenclature of the cyclobutyl ring system has previously been discussed.[3a]

The hydrocarbon products comprised a sizable portion of the products from *syn*-**16**-OPNB and *cis*-**18**-OBs. However, *anti*-**16**-OPNB and *trans*-**18**-OBs gave little, if any, hydrocarbon product. Thus, both brosylates solvolyzed with greater than 99.7% stereoselectivity, with regard to crossover between *syn* and *anti* products. The rate constant of *cis*-**18**-OBs was determined by titration of liberated acid in a conventional manner. The *trans* isomer was too reactive at 25° ($k = 3.10 \times 10^{-3}$ sec^{-1}) for a normal titration. Known concentrations of base (freshly prepared in 80% acetone–water) were added to the solvent along with the indicator in separate test tubes. The tubes were allowed to equilibrate at 25°. A standard amount of *cis*-**18**-OBs in 50 μl of dry acetone was added by syringe to each tube one at a time. The contents were well mixed, and the time required for a color change was measured with a stop watch. The infinity point was determined by conventional titration.[13]

Discussion

The interconversions between *syn*-**16**-OH and *cis*-**18**-OH and between *anti*-**16**-OH and *trans*-**18**-OH represent the first example of a full set of stereospecific homoallylic ring expansions and contractions. Solvolyses of *syn*-**16**-OPNB and *cis*-**18**-OBs gave similar product distributions, as did *anti*-**16**-OPNB and *trans*-**18**-OBs. The ratio of cyclopropylcarbinyl to homoallylic product was slightly higher from *cis*-**18**-OBs and *trans*-**18**-OBs than from the corresponding cyclopropylcarbinyl *p*-nitrobenzoates.[14] These results are only compatible with two noninterconverting, nonclassical homoallylic ions. Scheme V completes the fragmentary results found in other systems.[3a-c] The reasons for expecting stereospecificity in these systems have been discussed in various papers.[3a-c] A few important considerations form the basis of the explanation. Both the cyclopropane ring and the homoallylic double bond are involved in the transition states for ionization. The alkyl group at C_9 in *syn*- or *anti*-**16** stabilizes the incipient homoallylic ion by utilization of the secondary–secondary C_1–C_9 bonding cyclopropane electrons in preference to the C_1–C_{10} secondary–primary electrons. The exact magnitude of the stabilization is difficult to estimate since no products derived from the other possible, less-substituted homoallylic ion were observed. Schleyer and van Dine[15] reported that the rate constant of *cis*-2-methyl-1-hydroxymethylcyclopropane 3,5-dinitrobenzoate is only 8.2 times that of cyclopropylcarbinyl 3,5-dinitrobenzoate. The small rate enhancement caused by the methyl group (and presumably other alkyl substituents) is not sufficiently large to explain the stereospecificity which we observe.[16] We can offer no explanation for this discrepancy other than the possibility that the rate constant reported for cyclopropylcarbinyl dinitrobenzoate (4.30×10^{-7} sec^{-1} at 100° in 60% acetone–water) represented predominant

Scheme V



acyl oxygen cleavage. Another feature essential to Scheme V is retention of stereochemistry between C_1 and C_2 in the homoallylic ions. Both theoretical and experimental data[3a] suggest that the barrier to rotation about the C_1–C_2 bond is high. Stereospecific solvent attack on *cis*- and *trans*-**20** along the reverse path for ionization gives the observed products.

The stereospecificity found for [6.1.0]- and [7.1.0]-cyclopropylcarbinyl systems does not extend to the lower homologs. Based on our current knowledge of medium rings, Scheme V would be expected to be marginal for the [6.1.0] system and fail for [5.1.0], [4.1.0], [3.1.0], and [2.1.0] systems. The strain energy of *trans*-**18** should increase rapidly as the size of the larger ring is decreased. For example, *trans*-cyclooctene is 8 kcal/mol less stable than its *cis* isomer,[17] and *trans*-cycloheptenone[18] is so reactive that it is stable only near liquid nitrogen temperature. The geometry at C_1 and C_2 in *trans*-**20** should approach that of a *trans* double bond. We found that, whereas solvolyses of the [6.1.0] and [7.1.0] systems were stereospecific, those with smaller rings were not.[3a] Careful product studies on the smaller homologs (five-, six-, and seven-membered rings) are not complete, although there is some indica-

(13) A similar procedure has been used by Wiberg and Hess: K. B. Wiberg and B. A. Hess, Jr., *J. Amer. Chem. Soc.*, 89, 3015 (1967).

(14) Similar results were found for *syn*-bicyclo[6.1.0]non-2-yl *p*-nitrobenzoate and *cis*-cyclononen-4-yl *p*-bromobenzenesulfonate.[3a] Differences in temperature and (or) leaving groups are thought to be responsible for different product distributions from the same cation.

(15) P. von R. Schleyer and G. W. van Dine, *J. Amer. Chem. Soc.*, **88**, 2321 (1966).

(16) An additional alkyl substituent at the carbinyl carbon, as in *syn*- and *anti*-**16**-OPNB, could only diminish the effect of the alkyl substituent on the cyclopropane ring.

(17) A. C. Cope, P. T. Moore, and W. R. Moore, *J. Amer. Chem. Soc.*, 82, 1744 (1960).

(18) (a) E. J. Corey, M. Tada, R. La Mahieu, and L. Libit, *ibid.*, 87, 2051 (1965); (b) P. E. Eaton and K. Lin, *ibid.*, 87, 2052 (1965).

tion that more than one nonclassical intermediate may be involved.[11] Several possible explanations, such as equilibration between homoallylic and (or) symmetrical homoallylic cations,[19] cannot be ruled out without additional study. Also, the effect of ion pairing on the stereochemistry of the lower homologs is unknown.[20]

The seven-carbon bridges in *cis*- and *trans*-**20** undoubtedly destabilize the parent isomeric cations. Models indicate that steric interactions are greater for *trans*-**20** than its *cis* isomer. The ring strain of the *trans* cation is much greater when the larger ring is reduced to six carbon atoms. Yet, ionization of *anti*-bicyclo[6.1.0]non-2-yl *p*-nitrobenzoate gives a *trans*-homoallylic intermediate (>99.99%).[3a] In the latter case, the driving force for backside assistance from the more substituted arm of the cyclopropane ring must be considerable. Solvolysis of *trans*-**18**-OBs proceeded about 1000 times faster than solvolysis of its *cis* isomer. The *trans* brosylate is probably somewhat more strained than *cis*-**18**-OBs;[21] however, the strain of a *trans* orientation between C_1 and C_2 is probably magnified at the transition state leading to *trans*-**20**. Thus, it seems unlikely that the strain associated with the *trans* double bond is responsible for the enhanced rate of *trans*-**18**-OBs, since the increased ground-state strain of *trans*-**18**-OBs should be accompanied by increased strain at the transition state leading to *trans*-**20**. The relative orientations between the double bonds and the leaving groups in *cis*- and *trans*-**18**-OBs seem to offer a rational explanation of the kinetic results. The double bond of *trans*-**18**-OBs is properly oriented to assist ionization of the brosylate, while several probable orientations for *cis*-**18**-OBs do not appear to be as favorable for assisting ionization. As the transition state between *trans*-**20** and *trans*-**18**-OH is approached from *trans*-**20**, the C_1–C_2 bond length should shorten considerably. The 7 carbon bridge is large enough to accommodate this development without inducing a large energy difference in the transition state leading to *anti*-**16**-OH and *trans*-**18**-OH. Both isomers are found in the product mixture. When the bridge is reduced to 6 carbon atoms, ring strain at the transition state leading to *trans* homoallylic product apparently becomes so great that none is observed.[3a]

A small amount of cyclobutyl product (*trans,trans*-**19**-OH) was found in the product mixture of *anti*-**16**-OPNB. We feel that *trans*-**20** isomerized stereospecifically to a nonclassical cyclobutyl ion which gave *trans,trans*-**19**-OH, in analogy with the isomerization of *anti*-bicyclo[6.1.0]nonan-2-ol to *trans*-bicyclo[5.2.0]-nonan-*trans*-8-ol.[3a] In the latter case it was demonstrated that at least one cyclobutyl ion was involved, in addition to the *trans*-homoallylic ion. The decrease in cyclobutyl product as the larger bridge is expanded by one carbon atom probably results from a combination of factors. Part of *trans*-**20** is consumed by solvent attack at C_9 to give *trans*-**18**-OH. Also, *trans*-**20** is considerably less strained than its lower homolog, and the relief of strain energy by isomerization to a cyclobutyl cation is not as great.

We would like to emphasize the synthetic utility of stereospecific homoallylic ring expansions for generating either *cis* or *trans* double bonds in medium rings. Starting with *cis*-cyclononen-3-ol (**15**) gram quantities of *cis*-**18**-OH were obtained in an overall yield of 59%, and gram quantities of *trans*-**18**-OH, in an overall yield of 47%. The only sizable losses were incurred during methylene addition to **15**. Each of the homoallylic alcohols could be prepared with less than 1% of the other without resorting to any tedious separations. Homoallylic ring expansions have been used extensively in this laboratory in synthetic sequences for preparation of possible precursors for the heptahomotropilium cation. In theory, trisubstituted double bonds could also be generated stereospecifically from the appropriate α-methylcyclopropylcarbinyl derivative.

Experimental Section[22]

cis-**Cyclononen-3-ol** (**15**). *cis*-Cyclononen-3-ol was prepared by the procedure described by Santelli and coworkers,[23] bp 70–73° (0.3 mm), lit.[23] 62° (0.5 mm).

anti-**Bicyclo[7.1.0]decan-2-ol** (*anti*-**16**-OH).[24] Treatment of 12.0 g (0.086 mol) of **15** with 12.3 g (0.19 mol) of zinc–copper couple and 46.0 g (0.172 mol) of methylene iodide gave 8.66 g (66%) of a colorless, viscous liquid which crystallized in the condenser during distillation: mp 54.5–55.5°; ir (CCl_4) 3610, 3400, 3060, 2990, 2930, 2860, 1440, 1060, 1025, 1005, 963, and 848 cm^{-1}; nmr (CCl_4) 0.11 (1, m, *endo* H at C_{10}), 0.63 and 1.4 (15, m, H at C_1, H at C_3–C_9 and *exo* H at C_{10}), 2.28 (1, s, hydroxyl H), and 3.26 ppm (1, m, H at C_2).

Anal. Calcd for $C_{10}H_{18}O$: C, 77.87; H, 11.76. Found: C, 77.88; H, 11.66.

A 1.992-g (0.013 mol) sample of *anti*-**16**-OH was allowed to react with 2.452 g (0.013 mol) of *p*-nitrobenzoyl chloride in 10 ml of anhydrous pyridine at −5° for 48 hr. Work-up and two recrystallizations from petroleum ether gave 3.401 g (87%) of a pale yellow solid: mp 123.5–124.5°; ir (CCl_4) 3110, 3060, 3000, 2920, 2850, 1715, 1605, 1525, 1343, 1270, 1110, 1095, 940, and 870 cm^{-1}; nmr (CCl_4) 0.04 (1, m, *endo* H at C_{10}) 0.5–2.1 (15, m, H at C_1, H at C_3–C_9, and *exo* H at C_{10}), 4.85 (1, m, H at C_2), and 8.05 ppm (4, s, aromatic H).

Anal. Calcd for $C_{17}H_{21}NO_4$: C, 67.31; H, 6.98; N, 4.62. Found: C, 67.16; H, 6.99; N, 4.36.

Bicyclo[7.1.0]decan-2-one (**17**). A solution of 4.980 g (0.032 mol) of *anti*-**16**-OH in 75 ml of dry acetone was cooled in an ice–methanol bath. To the cold solution was added 9.0 ml of Jones reagent.[25] After 5 min, excess reagent was quenched with 5 ml of 2-propanol. The resulting green suspension was poured into 100 ml of water and the solid green residue was dissolved in an additional 100-ml portion of water. The combined aqueous solutions were extracted with petroleum ether. The combined extracts were washed with saturated sodium bicarbonate solution and dried over anhydrous magnesium sulfate. Solvent was removed at reduced pressure to give 4.76 g (96%) of a colorless liquid. Samples for spectra and combustion analysis were purified by glpc: ir (CCl_4) 3000, 2930, 2860, 1685, 1460, 1452, 1430, 1385, 1370, and 1097 cm^{-1}; nmr (CCl_4) 0.2–2.0 (15, m) and 2.6 ppm (1, m).

Anal. Calcd for $C_{10}H_{16}O$: C, 78.90; H, 10.59; Found: C, 79.02; H, 10.65.

syn-**Bicyclo[7.1.0]decan-2-ol** (*syn*-**16**-OH). To a stirred suspension of 0.429 g (0.045 equiv) of lithium aluminum hydride in 50 ml of dry diethyl ether was added 4.65 g (0.031 mol) of **17**. The

(19) It must be remembered that resonance-stabilized cations in these systems are sufficiently stable to permit some equilibration before solvent collapse. Initial product studies with *syn*- and *anti*-**16**-OPNB in the presence of 0.02 *M* acetate gave up to 10% acetate products. The relative ratios of cyclopropylcarbinyl to homoallylic product were identical for alcohols and acetates.

(20) It is obvious from the amount of internal return to homoallylic product that ion pairing is important in these systems.

(21) *trans*-Cyclodecene is 2.2 kcal/mol less stable than *cis*-cyclodecene in acetic acid at 25°.[17]

(22) The general experimental techniques have been previously described.[3a]

(23) M. Santelli, M. Bertrand, and M. Ronco, *Bull. Soc. Chim. Fr.*, 3273 (1964).

(24) A detailed procedure similar to that used to convert **15** to *anti*-**16**-OH has been described.[3a]

(25) A. Bowers, T. G. Halsall, E. R. H. Jones, and A. J. Lemin, *J. Chem. Soc.*, 2548 (1953).

mixture was allowed to stir for 12 hr before excess hydride was carefully decomposed by dropwise addition of saturated ammonium chloride solution. The addition was continued until the inorganic material precipitated, leaving a colorless ethereal layer. The ether was decanted, and the precipitate was washed with additional portions of ether. The combined ether layers were dried. Solvent was removed at reduced pressure to give 4.30 g (91%) of a colorless liquid: ir (CCl_4) 3630, 3480, 3060, 2990, 2920, 2860, 1510, 1470, 1440, 1078, 1025, 995, and 845 cm^{-1}; nmr (CCl_4) 0.12–1.15 (4, m, H at C_1, C_9 and C_{10}), 1.5 (12, m, H at C_3–C_8), 1.95 (1, s, hydroxyl H), and 4.35 ppm (1, m, H at C_2). The alcohol was quite sensitive and could be stored for long periods only at −15°. Repeated attempts to obtain an analytical sample which gave a combustion analysis within 0.3% for both carbon and hydrogen failed.

Anal. Calcd for $C_{10}H_{18}O$: C, 77.87; H, 11.76. Found: C, 77.36; H, 11.87.

A 2.012-g (0.013 mol) sample of *syn*-**16-OH** was allowed to react with 2.455 g (0.13 mol) of *p*-nitrobenzoyl chloride in 10 ml of dry pyridine at −5° for 72 hr. Work-up and recrystallization from petroleum ether gave 2.499 g (64%) of a pale yellow solid: mp 95–96°; ir (CCl_4) 3110, 3060, 2980, 2920, 2850, 1723, 1525, 1345, 1270, 1110, 1095, and 870 cm^{-1}; nmr (CCl_4) 0.15 (1, m, *endo* H at C_{10}), 0.5–2.4 (15, m, H at C_1, H at C_3–C_9, and *exo* H at C_{10}), 5.70 (1, m, H at C_2), and 8.18 ppm (4, m, aromatic H).

Anal. Calcd for $C_{17}H_{21}NO_4$: C, 67.31; H, 6.98; N, 4.62. Found: C, 67.27; H, 7.02; N, 4.52.

cis-**Cyclodecen-4-ol** (*cis*-**18-OH**). A mixture of 1.100 g (7.2 mmol) of *syn*-**16-OH**, 40 ml of dry dioxane, and 10 ml of 0.129 *N* perchloric acid was stirred at 75° for 1 hr. The solution was poured into 100 ml of water, and the resulting suspension was extracted with pentane. The combined pentane extracts were washed with sodium bicarbonate solution and dried. Solvent was removed at reduced pressure to give 0.990 g (90%) of a colorless oil which crystallized on standing. A 100-mg portion was recrystallized from petroleum ether to give white needles: mp 55.0–57.5°; ir (CS_2) 3620, 3360, 3000, 2980, 2940, 2920, 2900, 2860, 2850, 1650, 1470, 1450, 1440, 1010, 1000, 725, and 710 cm^{-1}; nmr ($CDCl_3$) 1.46 (10, m, H at C_3–C_9), 2.3 (4, m, H at C_3 and C_{10}), 3.75 (1, s, hydroxyl H), 3.8 (1, m, H at C_4), and 5.47 ppm (2, m, H at C_1 and C_2).

Anal. Calcd for $C_{10}H_{18}O$: C, 77.87; H, 11.76. Found: C, 77.86; H, 11.90.

Following a general procedure for preparing reactive brosylates,[3a] 126 mg (0.82 mmol) of *cis*-**18-OH** and 210 mg (0.82 mmol) of *p*-bromobenzenesulfonyl chloride were allowed to stand at −5° for 96 hr. Work-up of the mixture and recrystallization gave white plates (61%): mp 88–89° dec; ir (CS_2) 3000, 2920, 2860, 2840, 1385, 1360, 1270, 1180, 1170, 1060, 1010, 950, 925, 910, 890, 815, 735, and 600 cm^{-1}; nmr ($CDCl_3$) 1.4 (10, m, H at C_5–C_9), 2.2 and 2.5 (4, m, H at C_3 and C_{10}), 4.75 (1, m, H at C_4), 5.43 (2, m, H at C_2 and C_3), and 7.70 ppm (4, m, aromatic H).

Anal. Calcd for $C_{16}H_{21}SO_3Br$: C, 51.47; H, 5.67. Found: C, 51.68; H, 5.89.

trans-**Cyclodecen-4-ol** (*trans*-**18-OH**). Following the procedure described for *cis*-**18-OH**, a mixture of 1.100 g (7.2 mmol) of *anti*-**16-OH** in 40 ml of dioxane and 10 ml of 0.129 *N* perchloric acid was heated at 75° for 12 hr. Work-up of the mixture gave 0.992 g (90%) of a colorless oil, which was composed of two components (91 and 9% by glpc). The mixture was chromatographed on alumina impregnated with 20% (by weight) of silver nitrate. The minor isomer (81 mg) was eluted with 1:10 ether–pentane, and the major isomer was desorbed by stirring the column packing with 10% ammonium hydroxide solution. The aqueous layer was extracted with petroleum ether. The combined extracts were washed with water and dried. Solvent was removed at reduced pressure to yield 629 mg of a colorless oil. Analytical samples were collected by glpc: ir (CS_2) 3620, 3340, 3020, 2920, 2840, 1660, 1450, 1435, 1045, 1010, and 980 cm^{-1}; nmr (CCl_4) 1.38 (10, m, H at C_5–C_9), 2.1 (4, m, H at C_3 and C_{10}), 3.7 (1, m, H at C_4), 4.35 (1, s, hydroxyl H), and 5.47 ppm (2, m, H at C_1 and C_2).

Anal. Calcd for $C_{10}H_{18}O$: C, 77.87; H, 11.76. Found: C, 77.65; H, 11.57.

Following the procedure used to prepare *cis*-**18-OBs**, 159 mg (1.10 mmol) of *trans*-**18-OH** and 281 mg (1.10 mmol) of *p*-bromobenzenesulfonyl chloride were allowed to stand at −5° for 96 hr. Work-up gave 201 mg of a colorless, viscous oil which resisted numerous attempts to induce crystallization: ir (CS_2) 3020, 2920, 2840, 1350, 1270, 1180, 1090, 1060, 1005, 975, and 890 cm^{-1}; nmr ($CDCl_3$) 1.3 and 2.0–2.5 (14, m, H at C_3 and C_5–C_{10}), 4.6 (1, m, H at C_4), 5.4 (2, m, H at C_1 and C_2), and 7.70 ppm (4, d, aromatic H).

trans-**Bicyclo[6.2.0]decan-*trans*-9-ol** (*trans,trans*-**19-OH**). The minor component produced by acid-catalyzed isomerization of *anti*-**18-OH** was isolated by column chromatography. The compound (81 mg) was a colorless oil. Samples for analysis were purified by glpc: ir (CCl_4) 3620, 3320, 2960, 2910, 2840, 1460, 1450, 1440, 1435, 1135, and 1065 cm^{-1}; nmr (CCl_4) 1.1–2.3 (16, m, H at C_1–C_8 and C_{10}), 3.43 (1, m, H at C_9), and 4.27 ppm (1, s, hydroxyl H).

Anal. Calcd for $C_{10}H_{18}O$: C, 77.87; H, 11.76. Found: C, 77.69; H, 11.75.

Acid-Catalyzed Isomerization of *syn*-16-OH and *anti*-16-OH. The general procedure for kinetic and product determinations have been described.[3a] Glpc analyses were carried out with 10 ft × 1/8 in. Carbowax 20M or DEGS columns at 160° (Table III).

Table III. Relative Glpc Retention Times[a]

Compd	Relative time
17	1.00
15	1.36
anti-**16-OH**	1.50[b]
trans,trans-**19-OH**	1.66
syn-**16-OH**	1.72
trans-**18-OH**	1.99
cis-**18-OH**	2.06

[a] On 5% Carbowax 20M, 160°. [b] At 160°, elution took approximately 13 min.

Control experiments established that as little as 0.3% of *anti*-**16-OH**, *trans*-**18-OH**, and *trans,trans*-**19-OH** could be seen in *syn*-**16-OH** and *cis*-**18-OH** and *vice versa*. In all cases no crossover products were detected. Product results are summarized in Scheme II and kinetic results are summarized in Table I.

Kinetic Procedures. Except for *trans*-**18-OBs** the procedures have been described.[3a] The *trans*-brosylate was too reactive at room temperature to permit conventional titration. An 80-μl portion of *trans-18-OBs* was dissolved in 320 μl of dry acetone, and the resulting mixture was kept in a tightly stoppered vial. A 40-μl portion of the solution was added to 5.00 ml of 80% acetone–water and the resulting solution was placed in a 25° bath for 8 hr. One drop of a 1% solution of bromothymol blue in acetone was added. The resulting mixture was titrated with a freshly prepared solution of sodium hydroxide in 80% acetone–water to determine the end point. A zero point with 5.00 ml of 80% acetone–water and 1 drop of indicator was also determined. Then portions of the base solution corresponding to 20–90% of the infinity titer in 10% steps were placed in eight test tubes. The volume was made up to 5.0 ml, and 1 drop of indicator was added. The tubes were stoppered and allowed to equilibrate at 25°. One by one, 40-μl portions of *trans*-**18-OBs** in acetone were added to the solvent, base, and indicator solutions. The contents of the test tubes were well mixed, and the time required for a color change (blue to green) was measured with a stop watch. First-order rate constants were calculated in the usual manner.

Preparative Solvolysis of *syn*-Bicyclo[7.1.0]dec-2-yl *p*-Nitrobenzoate (*syn*-**16-OPNB**). A solution of 1.000 g (3.30 mmol) of *syn*-**16-OPNB** and 1.070 g (10.0 mmol) of 2,6-lutidine in 150 ml of 80% acetone–water was heated at 100° for 150 min (*ca.* 10 half-lives). The solution was poured into saturated sodium chloride solution, and the resulting suspension was extracted with pentane. The combined pentane extracts were washed with water and dried. Solvent was removed at reduced pressure to give 1.231 g of a light yellow oil. Chromatography on Woelm alumina, activity II, gave, in order of elution, 23 mg of hydrocarbons, 139 mg of pale yellow solid, and 379 mg of a mixture of alcohols. The remainder of the sample was 2,6-lutidine. The alcohol mixture consisted of *syn*-**16-OH** (39%) and *cis*-**18-OH** (61%); each was collected by glpc and identified by ir spectra.

The pale yellow solid (*cis*-**18-OPNB**) was recrystallized from petroleum ether: mp 73–74°; ir (CS_2) 3000, 2980, 2920, 2860, 1720, 1600, 1340, 1270, 1110, 1095, and 715 cm^{-1}; nmr (CS_2) 1.1–2.9 (14, m, H at C_3 and C_5–C_{10}), 5.15 (1, m, H at C_4), 5.35–5.75 (2, m, H at C_1 and C_2), and 8.20 ppm (4, s, aromatic H).

Anal. Calcd for $C_{17}H_{21}NO_4$: C, 67.31; H, 6.98; N, 4.62. Found: C, 67.37; H, 6.85; N, 4.64.

Preparative Solvolysis of *anti*-Bicyclo[7.1.0]dec-2-yl *p*-Nitrobenzoate (*anti*-**16-OPNB**). Following the procedure described for *syn*-**16-OPNB**, a solution of 1.001 g (3.31 mmol) of *anti*-**16-OPNB**

and 1.068 g (10.0 mmol) of 2,6-lutidine in 150 ml of 80% acetone–water was heated at 100° for 48 hr (*ca.* 10 half-lives). Work-up gave 1.319 g of a pale yellow oil. Column chromatography separated the residue into three fractions. The minor fraction (138 mg) was a pale yellow solid. The middle fraction (352 mg) was shown by glpc retention times and ir spectra to consist of *anti*-**16**-OH (88%), *trans*-**18**-OH (12%), and *trans,trans*-**19**-OH (1%). The remainder of the sample was 2,6-lutidine.

Recrystallization of the minor fraction from petroleum ether (*trans*-**18**-OPNB) gave 124 mg of a pale yellow solid: mp 54–55°; ir (CS_2) 3020, 2920, 2860, 1720, 1605, 1340, 1270, 1110, 1100, 1015, 980, 870, and 720 cm^{-1}; nmr ($CDCl_3$) 1.2–2.9 (14, m, H at C_3 and C_5–C_{10}), 5.2 (1, m, H at C_4), 5.6 (2, m, H at C_1 and C_2), and 8.16 ppm (4, s, aromatic H).

Anal. Calcd for $C_{17}H_{21}NO_4$: C, 67.31; H, 6.98; N, 4.62. Found: C, 67.22; H, 6.89; N, 4.47.

Analytical Product Solvolyses. Solutions 0.01 *M* in *p*-nitrobenzoate or *p*-bromobenzenesulfonate and 0.02 *M* in 2,6-lutidine were heated at the appropriate temperature for 10 half-lives. Acetone–water (80%) was used in all of the studies. Glpc analyses at 80 and 160° were carried out without prior work-up. The products were identified by glpc retention times, and the results are summarized in Schemes III and IV. Mixtures of 1 equiv of the product alcohols, 1 equiv of *p*-nitrobenzoic acid, and 2 equiv of 2,6-lutidine were heated for the same time periods required for solvolysis of the precursor *p*-nitrobenzoate. Comparison of glpc traces before and after heating established that the products were stable to the reaction conditions.

Studies in Mass Spectrometry. XIII.[1] Stereospecific Electron Impact Induced Fragmentation Processes in Some Tricyclic Diesters

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Abstract: *endo*-Dimethyl esters **1a**, **2a**, **3a**, and **4a** undergo elimination of methanol under electron impact through a seven-centered transition state. Stereoisomeric *exo* diesters **1b**, **2b**, **3b**, and **4b** do not appreciably eliminate methanol. Loss of methoxyl radical from the molecular ion has been observed instead. *trans*-Diesters **1c**, **2c**, **3c**, and **4c** eliminate methanol under electron impact through a five-centered transition state. An additional stereospecific hydrogen migration accompanying retro-Diels–Alder fragmentation has been observed in the *endo* isomers.

The effect of stereochemical factors on the behavior of organic ions produced in the ion source of a mass spectrometer has been of considerable interest since mass spectrometry became a widely used tool in organic structural analysis.[3] Differences in the abundance of certain ions obtained from stereoisomers under electron impact (or photoionization) have been observed in many cases, and attempts have been made to relate these differences to distinctive features of the parent compounds.

One possible argument for the difference in the abundance of certain fragment ions originating from different stereoisomeric parent ions is the existence of sterically controlled fragmentation processes which may be preferred in one of the isomers. This is usually the explanation for the difference in the abundance of the products of rearrangement processes which are believed to occur *via* cyclic transition states.[4] Stereoisomers in which such cyclic transition states are possible without the occurrence of prior skeletal rearrangements can be expected to give rise to more abundant rearrangement ions than those isomers, in which a different group may migrate or skeletal rearrangements must be postulated to enable attainment of a cyclic transition state. Relatively few cases have been reported in which radical difference exists between the mass spectra of stereoisomers.[3]

In the course of our study of the specific double hydrogen migration in the adducts of bi-1-cycloalken-1-yls and *p*-benzoquinone[5] we examined the mass spectra of the three isomeric methyl esters of *endo*-, *exo*-, and *trans*-1,2,3,3a,4,5,5a,6,7,8-decahydroindacen-4,5-dicarboxylic acids, **1a**, **1b**, and **1c**[6] (Figure 1). The mass spectra differed very much in the high mass range in the fragmentation of the carbomethoxy group. While in the case of the *exo* isomer **1b** methoxyl radical CH_3O was lost from the molecular ion (*m/e* 247 ion a_{1b}, abundance ratio $a_{1b}/M^+ = 0.81$), methanol elimination gave rise to very abundant ions in the case of the *endo* (*m/e* 246 ion b_{1a}, abundance ratio $b_{1a}/M^+ = 2.1$) and *trans* (*m/e* 246 ion b_{1c}, abundance ratio $b_{1c}/M^+ = 2.3$) isomers **1a** and **1c** (see Figure 1). Elimination of methanol gave rise to a very low peak in the mass spectrum of the *exo* isomer **1b**. The same was true for the loss of a methoxyl radical from the molecular ion of **1a** and **1c** (see Figure 1).

This different behavior under electron impact was found to be general for the three isomeric forms of homologous diesters **1**–**4** having various rings A and C. All *exo* isomers (series b) exhibit M − 31 ions (M − 32

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