The relatively small $H_{15\alpha-16\alpha}$ coupling is explained by the through-space interactions between the carbon–hydrogen orbitals of the C_{15}–C_{16} fragment and the orbitals about the methylene bridge in the highly puckered envelope of ring D of the steroids. It is shown on basis of a comparison between the observed coupling constants and those calculated by means of a generalized Karplus equation[10] for rings A, B, and C and the application of the laws of pseudorotation for ring D, that the conformations derived from the solid-state data or MM2 calculations corresponds with the conformation of these steroids in solution.

Experimental Section

The steroids 17β-hydroxy-19-nor-5α,17α-pregn-20-yn-3-one (5α-R) and 17β-hydroxy-19-nor-5β,17α-pregn-20-yn-3-one (5β-R), generous gifts from Schering, A. G. (Berlin), were dissolved in CD_3OD (ca. 15 mg mL^{-1}).

NMR Spectroscopy. ^1H NMR spectra were recorded on a Bruker WM-500 NMR spectrometer interfaced to an ASPECT-2000 computer and a real-time pulser board. Chemical shifts (δ) were measured relatively to the residual methanol peak and converted to the standard Me_4Si scale by adding 3.38 ppm. ^{13}C NMR spectra were recorded on a Bruker WM-200WB spectrometer operating at 50.3 MHz also equipped with an ASPECT-2000 computer and a real-time pulser board. Chemical shifts were measured relatively to the central peak of the methanol multiplet and converted to the Me_4Si scale (δ_{CH_3OH} 49.3). For further experimental details see ref 3 and references cited therein.

Computation Methods. The structure of 5α-R and 5β-R were calculated by means of general valence force field methods using the computer program MM2.[4,5] For reasons described elsewhere,[10] the hydrogen atoms were removed from the minimized structure and their positions were recalculated from the remaining heavy atom skeleton by using standard methods[10,25] (i.e. methylene hydrogens have a local C_{2v} symmetry with a H–C–H bond angle of 107.6°; methine hydrogens on tertiary sp^3 carbon atoms are fixed in positions having equal bond angles to the other three non-hydrogen substituents; the C–H bond length is 1.105 Å).

The crystal structure data of 5α-R were taken from Rohrer et al.[8] Only the data pertaining to the heavy atoms were used since it is well-known that hydrogen atom coordinates from X-ray diffraction data are at least 1 order of a magnitude less precise than coordinates obtained for heavy atoms (due to the low scattering power and the noncoincidence of bonding electrons and nucleus in the case of hydrogens). The hydrogen atoms were fixed to the crystal structure skeleton following the guidelines given in the preceding paragraph.

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Registry No. 5α-R, 52-79-9; 5β-R, 28044-91-9.

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2-Bicyclo[3.2.0]heptyl and 7-Norbornyl Cations

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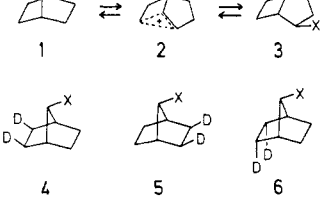
The structure and reactivity of 2-bicyclo[3.2.0]heptyl and 7-norbornyl cations have been probed with the aid of optically active, deuterium-labeled, and methyl-substituted precursors. Bicyclo[3.2.0]heptyl-6,7-d_2 and 6-methyl- and 7-methylbicyclo[3.2.0]heptyl substrates rearranged with >98% inversion at the migration origin to give *anti*-7-norbornyl products. Optically active 2-methylbicyclo[3.2.0]heptyl substrates afforded 1-methyl-7-norbornanol of >98% ee. Anti–syn leakage is characteristic of 7-norbornyl substrates and may be due to k_Δ,k_c competition. Several carbocations have been shown to undergo "same-side bridge-flipping" (**2a** ⇄ **2b**), leading to partial racemization of the parent system and to structural isomerization of others. Bridge-flipping has not been observed with 2-methylbicyclo[3.2.0]heptyl substrates, owing to stabilization of the carbocation by Me. The product distributions cannot be rationalized in terms of open (classical) ions. Bridged (nonclassical) intermediates provide an internally consistent interpretation of our data.

Considerable effort has been expended to explore the $C_7H_{11}^+$ manifold.[1] Controversy regarding the structure of the 2-norbornyl cation continues to receive much attention.[2] The 7-norbornyl cation, posing similar problems, has been studied less extensively. In 1958 Winstein et al.[3] observed that acetolyses of either 7-norbornyl brosylate (1-OBs) or *exo*-2-bicyclo[3.2.0]heptyl brosylate (3-OBs) led to similar product distributions (1-OAc: 3-OAc ≃ 95:5).



The bridged ion **2** was proposed as a common intermediate,

(1) For a novel $C_7H_{11}^+$ cation, generated from bicyclo[3.2.0]heptane-*endo*-2-diazonium ions, see: Kirmse, W.; Siegfried, R.; Streu, J. *J. Am. Chem. Soc.* **1984**, *106*, 2465.

(2) Several recent reviews include: (a) Barkhash, V. A. *Top. Curr. Chem.* **1984**, *116*, 1. (b) Grob, C. A. *Acc. Chem. Res.* **1983**, *16*, 426; Angew. Chem., Int. Ed. Engl. **1982**, *21*, 87. (c) Brown, H. C. *Acc. Chem. Res.* **1983**, *16*, 432; "The Nonclassical Ion Problem" (with comments by Schleyer, P. v. R.); Plenum Press: New York, 1977. (d) Olah, G. A.; Prakash, G. K. S.; Saunders, M. *Acc. Chem. Res.* **1983**, *16*, 440. Olah, G. A. *Chem. Scr.* **1981**, *18*, 97. (e) Walling, C. *Acc. Chem. Res.* **1983**, *16*, 448. (f) Kirmse, W. *Top. Curr. Chem.* **1979**, *80*, 125. (g) Sargent, G. D. In "Carbonium Ions"; Olah, G. A.; Schleyer, P. v. R., Eds.; Wiley-Interscience: New York, 1972; Vol. III, Chapter 24.

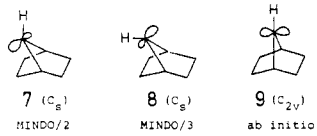
(3) Winstein, S.; Gadient, F.; Stafford, E. T.; Klinedinst, P. E. *J. Am. Chem. Soc.* **1958**, *80*, 5895.

0022-3263/85/1950-4187$01.50/0

on the basis of the fact that the 2-bicyclo[3.2.0]heptyl acetate formed was exclusively the exo isomer **3**-OAc. Solvolyses of the deuterated precursors **4** (X = OTs, OBs, and OTf) revealed not only that the 7-norbornyl products were predominantly the anti isomers **4**-OR (retention of configuration) but that ca. 10% of the syn isomers **5**-OR were also present.[4-6]

Neither the nature of the 7-norbornyl cation nor the mechanism of stereochemical "leakage" (**4** → **5**) have been clearly established. The solvolytic rate of 1-OTs[7] conforms to the Foote–Schleyer correlation.[8,9] The γ-isotope effects in **4**-OTf (1.024) and **6**-OTf (1.011) were found to be small.[6] Although these data indicate little, if any, anchimeric assistance, they do not exclude the intervention of **2**. Quantum mechanical calculations give different structures for the 7-norbornyl cation. MINDO/2[10] and MINDO/3[11,12] produce bent (C_s) geometries while ab initio (STO-3G) procedures prefer the symmetrical (C_{2v}) structure.[12] In the absence of full geometry optimization (C_s symmetry had been imposed in most of these calculations) the relative energy of **2** could not be assessed.

The predominant retention of configuration in a range of different solvents is more readily explained in terms of **8** than of **9**.[6] However, difficulties arise in acounting for

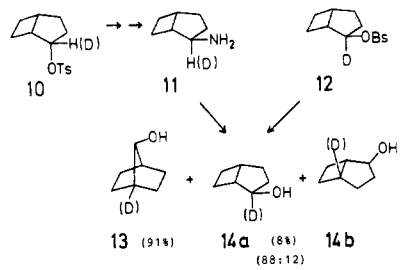


the inverted product (**5**-OR). If bridge-flipping in **8** competed with nucleophilic capture, the fraction of **5**-OR should not be independent of solvent and temperature.[6] The same argument excludes solvolytic displacement (k_s) as a possible source of **5**-OR. The values for Q′ (1.01) and m (1.03)[13] also indicate that the solvolysis of 1-OTf is not influenced by solvent nucleophilicity.

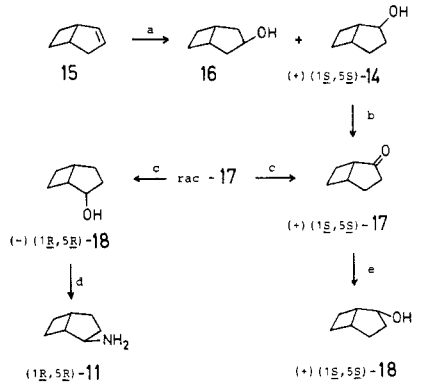
Results and Discussion

Bicyclo[3.2.0]heptane-*exo*-2-diazonium Ions. The low symmetry (C_1) of 2-bicyclo[3.2.0]heptyl derivatives benefits mechanistic studies. Optical activity and differential labeling may be employed to probe the structure of intervening carbocations. Since **3**-OBs produced 83% of 1-OBs by internal return and only 17% of solvolysis products,[3] we chose diazonium ion precursors. Bicyclo[3.2.0]heptan-*exo*-2-amine (**11**) was readily obtained from *endo*-2-bicyclo[3.2.0]heptyl tosylate (**10**) by azide displacement (86%), followed by reduction with lithium aluminum hydride (64%). Nitrous acid deamination of **11** in dilute perchloric acid (pH 3.5) gave an unexceptional 92:8 ratio of 7-norbornanol (**13**) and *exo*-2-bicyclo[3.2.0]-heptanol (**14**). When the reaction sequence was repeated with [2-^{2}H]-**10**, the 7-norbornanol thus obtained carried deuterium exclusively (±1 %) at the bridgehead (^{2}H NMR). The deuterium in [^{2}H]-**14** was distributed among positions 2 (δ 3.83) and 5 (δ 2.80) in an 88:12 ratio

Scheme I



Scheme II[a]



[a] a: (i) Diisopinocampheylborane, diglyme, 30 °C, 14 h; (ii) 3 N NaOH, 30% H_2O_2, 1 h. **16**:**14** = 40:60, isolated yield (preparative GC) of **14** 21%, ee 82%. b: PCC, CH_2Cl_2, room temperature, 12 h, 94% yield. c: Fermenting yeast, 96 h, **17**:**18**:**14** = 55:41:1; **17** isolated yield (GC) 18%, ee 63%; **18** isolated yield (GC) 16%, ee 80%. d: (i) TsCl, py, −20 °C to room temperature, 12 h; (ii) NaN_3, Me_2SO, 80 °C, 24 h; (iii) $LiAlH_4$, Et_2O, room temperature, 16 h; (iv) HCl (gas), overall yield of **11**·HCl 21%. e: $LiAlH_4$, Et_2O, room temperature, 6 h, 94%.

(**14a**:**14b**)[14] (Scheme I). In a related study of the acetolysis of the labeled brosylate **12**, some loss of 2-^{2}H in **14** had been noted, but the amount and the position of the relocated deuterium was not established.[16]

Optically active **11** was approached by two routes (Scheme II). Asymmetric addition of di-3-pinanylborane[17] to bicyclo[3.2.0]hept-2-ene (**15**)[18] gave *exo*-3- and *exo*-2-bicyclo[3.2.0]heptanol, **16**:**14** = 40:60. After separation by GC (+)-(1*S*,5*S*)-**14** was isolated in 21% yield and 82% enantiomeric excess (ee). The optical purity was determined by GC on glass capillaries coated with optically active polypropylene glycol.[19] The enantiomers of *endo*-2-bicyclo[3.2.0]heptanol (**18**) were cleanly separated, whereas the peaks of (+)- and (−)-**14** overlapped seriously. Therefore, **14** was converted into **18** by PCC oxidation and $LiAlH_4$ reduction for enantiomeric analysis. The (1*S*,5*S*) configuration was assigned to (+)-bicyclo[3.2.0]heptan-2-one (**17**) on the basis of its circular dichroism (positive $\Delta\epsilon$).[20] Alternatively, fermenting yeast reduction of racemic **17** (45% conversion) afforded (−)-(1*R*,5*R*)-**18** (80% ee) and (+)-(1*S*,5*S*)-**17** (63% ee). Optically active **11** was obtained from optically active **18** via tosylate and azide. The optical purity of **11** was determined by GC of its *N*-(trifluoroacetyl)-(*S*)-prolyl amides.[21]

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(13) Bentley, T. W.; Schleyer, P. v. R. *J. Am. Chem. Soc.* **1981**, *103*, 5466.

(14) The previous assignment[15] of 1-H and 5-H in **14** had to be reversed. With the aid of two-dimensional ^{1}H NMR (COSY) *endo*-2-H was found to couple weakly ($J \leq 1$ Hz) with 1-H (δ 2.50) but not with 5-H (δ 2.80).
(15) Svensson, T. *Chem. Scr.* **1973**, *3*, 171; **1974**, *5*, 20.
(16) Funke, B.; Winstein, S. *Tetrahedron Lett.* **1971**, 1477.
(17) Zweifel, G.; Brown, H. C. *Org. React. (N.Y.)* **1963**, *13*, 34.
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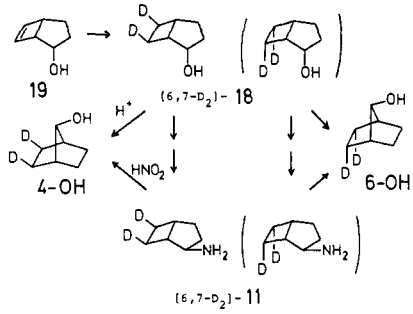
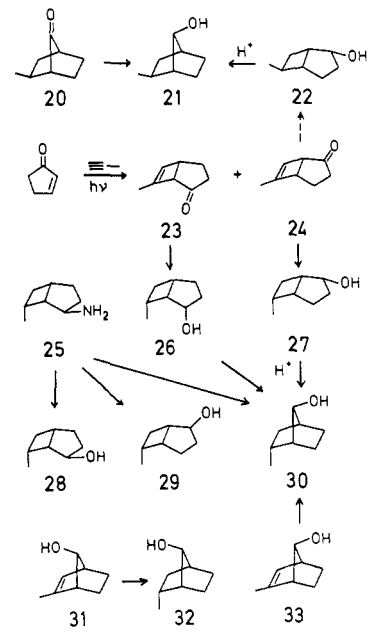
(19) Kirmse, W.; Siegfried, R. *J. Am. Chem. Soc.* **1983**, *105*, 950.
(20) Snatzke, G.; Wiartalla, R., unpublished results.

Scheme III



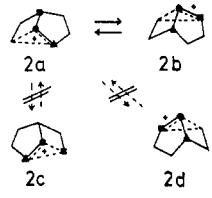
Scheme IV



Nitrous acid deamination of (1*R*,5*R*)-**11** (80.4 ± 0.9% ee) produced (1*R*,5*R*)-**14** (62.4 ± 1.6% ee) with 78% net retention (22% racemization). We note that inversion (11%) and deuterium relocation (**14b**, 12%) agree within experimental error.

The observed ratio of racemization and deuterium relocation might be explained by intervention of the symmetrical (C_{2v}) 7-norbornyl cation (**9**). [1-^{2}H]-**9** would lead to **14a,b** in a 1:1 ratio, and any products derived from **9** would be racemic. The potential role of **9** was explored with the aid of 6,7-$^2H_2$-labeled bicyclo[3.2.0]heptyl derivatives. Deuteration of bicyclo[3.2.0]hept-6-en-*endo*-2-ol (**19**) with $^2H_2$ and Pd–C catalyst was exo selective, but the ^{2}H NMR spectrum of [$^2H_2$]-**18** revealed an impurity assumed to be the *endo*-[6,7-$^2H_2$] isomer. Acidolysis (5 N H_2SO_4 in HOAc, 100 °C, 22 h) of [$^2H_2$]-**18** produced 4-OH (^{2}H NMR δ 1.50) contaminated with 7% of **6**-OH (δ 1.2). Within the limits of detection (1%), no syn-deuterated product (**5**-OH, δ 1.82) was found. Identical results were obtained by nitrous acid deamination of the *exo*-amine [6,7-$^2H_2$]-**11** (Scheme III).

Most remarkably, the anti → syn leakage associated with the solvolyses of 7-norbornyl sulfonates **4** and **5**[4-6] is not observed with 2-bicyclo[3.2.0]heptyl precursors. Our data exclude a significant contribution of the symmetrical 7-norbornyl cation **9**. Partial racemization and deuterium relocation may then be attributed to "bridge-flipping", **2a** ⇄ **2b**. Various modes of bridge-flipping have been con-



sidered previously.[4,15,16] "Front-side-flipping", **2a** ⇄ **2c**, and "cross-side-flipping", **2a** ⇄ **2d**, lead to anti → syn leakage and are therefore eliminated. "Same-side-flipping", **2a** ⇄ **2b**, emerges from our study as the only reorganization of **2** (see below for a more explicit discussion).

6- and 7-Methylbicyclo[3.2.0]hept-2-yl Substrates. In order to confirm the conclusions of the preceding paragraph we introduced methyl groups either at C-6 or at C-7 or the bicyclo[3.2.0]heptyl substrates. Photocycloaddition of propyne to 2-cyclopentenone yielded **23** and **24** in a 3:1 ratio, as reported by Swenton et al.[22] Hydrogenation of **24** apparently gave a single saturated ketone,[22] but subsequent reduction with lithium aluminum hydride resulted in a mixture of three alcohols, **22**, **27**, and **29** (12.3:86.5:1.2). Inversion of the major component, presumed to be *endo*-6-methylbicyclo[3.2.0]heptan-*endo*-2-ol (**27**), via tosylate and acetate led to the analogous *exo*-2-ol (**29**). The third alcohol (12.3%) was tentatively assigned as *exo*-6-methylbicyclo[3.2.0]heptan-*endo*-2-ol (**22**). Acid-catalyzed rearrangement of **27** and **29** gave *endo*-2-methyl-*anti*-7-norbornanol (**30**) while **22** produced *exo*-2-methyl-*anti*-7-norbornanol (**21**). Comparison with authentic samples served to identify the *anti*-7-norbornanols and to exclude the presence of analogous syn isomers. Hydrogenation of the known[23] 2-methyl-2-norbornen-7-ols **31** and **33** afforded **32** and **30**, respectively. Ashby and Noding[24] obtained **21** by reduction of *exo*-2-methyl-7-norbornanone (**20**) under equilibrating conditions (Meerwein–Ponndorf–Verley) whereas $LiAlH_4$ produced the syn isomer (Scheme IV).

In contrast to our observations with **24**, hydrogenation of **23**, followed by reduction with $LiAlH_4$, provided pure (>99%) *endo*-7-methylbicyclo[3.2.0]heptan-*endo*-2-ol (**26**). Acid-catalyzed rearrangement of **26** yielded exclusively *endo*-2-methyl-*anti*-7-norbornanol (**30**); no syn isomer (**32**) was found. Equilibrating conditions favor 7-norbornanols to the virtual exclusion of bicyclo[3.2.0]heptan-2-ols.[25] In order to detect bridge-flipping we required a kinetically controlled reaction. Conversion of **26** into *endo*-7-methylbicyclo[3.2.0]heptan-*exo*-2-amine (**25**) was achieved via tosylate and azide. Nitrous acid deamination of **25** gave *endo*-7- (**28**, 3.1%) and *endo*-6-methylbicyclo[3.2.0]heptan-*exo*-2-ol (**29**, 2.5%) in addition to **30** (94%). An upper limit of 0.3% for **32** was established by GC. The ratio of bicyclo[3.2.0]heptan-2-ols to 7-norbornanols agrees very well with that of the parent system. The proportion of bridge-flipping seems to be enhanced, despite the absence of anti → syn leakage.[26] Bridged ions of type **2** readily explain the configuration and distribution of the products.

(21) Halpern, B.; Westley, J. W. *Chem. Commun.* **1966**, 34. Pereira, W. E.; Halpern, B. *Aust. J. Chem.* **1972**, *25*, 667. Westley, J. W.; Evans, R. H.; Blount, J. F. *J. Am. Chem. Soc.* **1977**, *99*, 6057.

(22) Shih, C.; Fritzen, E. L.; Swenton, J. S. *J. Org. Chem.* **1980**, *45*, 4462.

(23) Gassman, P. G.; Andrews, J. P.; Patton, D. S. *J. Chem. Soc., Chem. Commun.* **1969**, 437.

(24) Ashby, E. C.; Noding, S. A. *J. Org. Chem.* **1977**, *42*, 264.

(25) According to force field calculations (MM1), norbornane (ΔH_f° = −13.3 kcal/mol) is much more stable than bicyclo[3.2.0]heptane (ΔH_f° = 4.5 kcal/mol): Maier, W. F.; Schleyer, P. v. R. *J. Am. Chem. Soc.* **1981**, *103*, 1891.

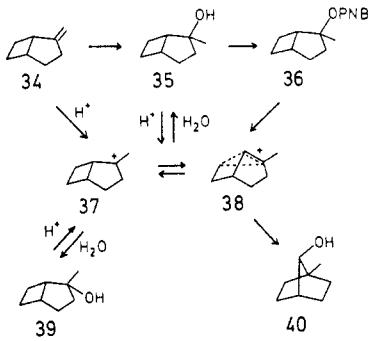
(26) An early report on the acetolysis of 4,4,6-trimethylbicyclo-[3.2.0]hept-2-yl tosylate also indicates stereospecific formation of the appropriate 7-norbornanol: Lewis, S. C.; Whitham, G. H. *J. Chem. Soc. C* **1967**, 274.

Table I. Kinetically Controlled Product Distributions Obtained from 2-Methylbicyclo[3.2.0]hept-2-yl (34, 36), 1-Methyl-7-norbornyl (41, 43, 45), and 5-Methylbicyclo[3.2.0]heptyl (54) Substrates

precursor	conditions	products, % 35	39	40	49
34	70% aq dioxane, 0.3 N H_2SO_4	91.1	3.8	5.1	
36	50% aq acetone, reflux	96.6	1.7	1.7	
41	70% aq acetone, reflux	91.6	3.3	5.1	
41	70% aq dioxane, reflux	90.4	4.2	5.4	
43	$HClO_4$, pH 3.5, $NaNO_2$	78.9	0.6	18.4	2.1
43	$HClO_4$–Et_2O, $NaNO_2$	74.6	0.8	21.3	3.3
45	0.2 N NaOH, hν (Pyrex)	77.4	0.6	20.6	1.4
54	$HClO_4$, pH 3.5, $NaNO_2$	24.0	0.1	69.0	5.8[a]

[a] 0.9% 5-methylbicyclo[3.2.0]heptan-*endo*-2-ol (**51**).

Scheme V



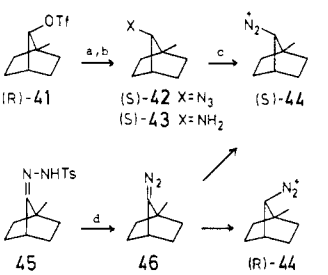
2-Methylbicyclo[3.2.0]hept-2-yl Substrates. Conversion of bicyclo[3.2.0]heptan-2-one (**17**) into 2-methylenebicyclo[3.2.0]heptane (**34**), *endo*-2-methylbicyclo[3.2.0]heptan-*exo*-2-ol (**35**), and *exo*-2-methylbicyclo[3.2.0]heptan-*endo*-2-ol (**39**) was achieved by conventional methods.[27] We have previously reported that acidolysis (HOAc, 0.5 N H_2SO_4, 16 h, room temperature) of **34**, **35**, and **39**, followed by $LiAlH_4$ reduction, gave 1-methyl-7-norbornanol (**40**) as the only alcohol in 70–98% yield.[27] Starting from (1*S*,5*S*)-**17** (ee 82.0 ± 0.9%, cf. Scheme II), we obtained **40** without loss of enantiomeric purity (ee 81.6 ± 0.8%, estimated by GC on optically active polypropylene glycol). The 4-nitrobenzoate **36** solvolyzed in aqueous acetone to give **35** (96.6%), **39** (1.7%), and **40** (1.7%) (Scheme V). Owing to eventual *O*-acyl cleavage, the solvolysis of **36** might lead to erroneous results, exaggerating the proportion of **35**. Therefore the hydration of **34** was performed under mild conditions, avoiding significant rearrangement of **35**. Again, **35** was the predominant product (91%, cf. Table I).

The high yield of **35** from the kinetically controlled reactions of **34** and **36** reflects the stabilization of positive charge at the methyl-substituted carbon. The formation of some *endo*-alcohol **39** suggests the open tertiary cation **37** as an intermediate. On the other hand, the enantiomeric purity of **40** obtained under thermodynamic control points to a bridged (**38**) or bent 1-methyl-7-norbornyl cation. In contrast to the parent and 7-methyl systems, **38** does not undergo bridge-flipping. The reorganization of **38** in analogy to **2a** → **2b** would be endothermic, leading to a less stable isomer (**47**, see below for the reverse process, **47** → **38**).

1-Methyl-7-norbornyl Substrates. A racemic mixture of 1-methylnorbornane-7-diazonium ions (**44**) was readily generated by photolysis of 1-methyl-7-norbornanone tosylhydrazone (**45**)[28] in aqueous sodium hydroxide. The photolysis of tosylhydrazone anions generates diazo compounds,[29] i.e., **46**, which are protonated by hydroxylic solvents to give diazonium ions and products derived therefrom.[30] Optically active **44** is accessible by diazotization of the analogous amine. 1-Methyl-7-norbornanol (**40**), ee 82%, prepared from (*S*)-bicyclo[3.2.0]heptan-2-one (**17**) according to Scheme V, was converted into triflate **41**. Displacement of the triflate with hexadecyltributylphosphonium azide in toluene, followed by $LiAlH_4$ reduction of **42**, afforded 1-methyl-7-norbornylamine (**43**) (Scheme VI). The solvolysis of **41** and the nitrous acid deamination of **43** gave alcohols of similar enantiomeric purity (Table II), but of opposite configuration, thus proving clean inversion in the azide displacement step. To our knowledge, this is the first record of an S_N2 displacement at 7-norbornyl sulfonates. Other "reluctant" substrates have been subjected to inverting displacement under similar conditions, e.g., 2-norbornyl brosylates, 2-adamantyl tosylates, and cyclopropyl triflates.[31]

Solvolyses of 1-methyl-7-norbornyl trilfate (**41**) gave product distributions (Table I) in close agreement with those obtained from 2-methylbicyclo[3.2.0]heptyl precursors **34** and **36**. Obviously, identical intermediates are approached from both sides and C-2(6) of **41** migrates

Scheme VI[a]



[a] (a) Hexadecyltributylphosphonium azide, toluene, 90 °C, 56%; (b) $LiAlH_4$, Et_2O, 73%; (c) $HClO_4$–H_2O (pH 3.5), $NaNO_2$; (d) 0.5 N NaOH, *hν* (Pyrex).

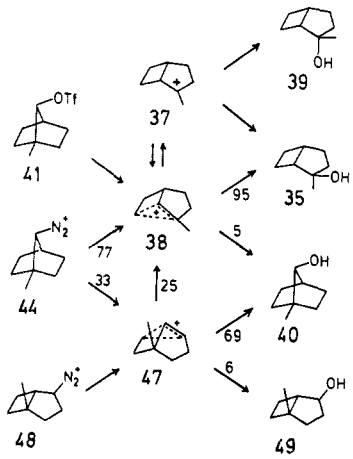
Table II. Enantiomeric Excess (% ee) of Alcohols Obtained from (*R*)-41 and (*S*)-43[a]

precursor	conditions	35	40	49
41	70% aq acetone, reflux	101 ± 3[b]	93 ± 2	
41	40% aq dioxane, reflux	93 ± 3[b]	91 ± 2	
43	$HClO_4$–Et_2O, $NaNO_2$	95 ± 5[c]	88 ± 1	94 ± 3
43	$HClO_4$–Et_2O, $NaNO_2$	98 ± 1[b] 91 ± 5[c]	90 ± 2	92 ± 3

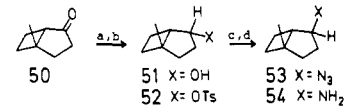
[a] Corrected for the ee (82 ± 1) of **40** used in the preparation of **41** and **43**. [b] Indirect estimate via acid-catalyzed isomerization of **35** to **40**. [c] Direct estimate by GC on optically active PPG.

(27) Kirmse, W.; Streu, J. *Synthesis* **1983**, 994.
(28) Kirmse, W.; Streu, J. *Chem. Ber.* **1984**, *117*, 3490.
(29) Dauben, W. G.; Willey, F. G. *J. Am. Chem. Soc.* **1962**, *84*, 1497.
(30) For a review, see: Ando, W. In "The Chemistry of Diazonium and Diazo Groups"; Patai, S., Ed.; Wiley-Interscience: Chichester, 1978; Part I, p 362.
(31) Banert, K.; Kirmse, W. *J. Am. Chem. Soc.* **1982**, *104*, 3766. Banert, K. *Chem. Ber.* **1985**, *118*, 1564.

Scheme VII



Scheme VIII[a]



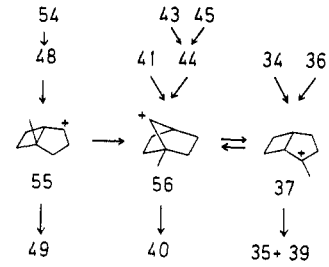
[a] (a) $LiAlH_4$, Et_2O, 90%; (b) TsCl, py, 99%; (c) NaN_3, Me_2SO, 80 °C, 24 h, 67%; (d) $LiAlH_4$, Et_2O, 64%.

exclusively. The diazonium ion **44** showed less discrimination, giving rise to some 5-methylbicyclo[3.2.0]heptan-*exo*-2-ol (**49**), the product of C-3(5) migration, and to a larger fraction of 1-methyl-7-norbornanol (**40**) (Scheme VII). The close agreement of acidic (**43**) and alkaline (**45**) dediazoniations excludes acid-catalyzed rearrangement of the tertiary alcohol **35** as a significant source of **40**. Moreover, ion-pair collapse is not a likely route to **40** in view of the similar results obtained from aqueous and two-phase (dilute $HClO_4$–Et_2O) deaminations of **43**. In suitable cases the presence of ether accentuates retention of structure and configuration as the diazotic acid (RN=NOH) is extracted into the less polar organic phase. Substantial effects of ion pairing have been found with short-lived diazonium species, giving rise to stable carbocations, e.g., 1-phenylethyl.[32] Since 7-norbornyl substrates dissociate slowly, random solvation of **44** should precede decomposition, as observed with 1-alkanediazonium species.[32]

The stereochemical data obtained with optically active substrates have been collected in Table II. The analytical method of choice was GC on optically active PPG.[19] While satisfactory separation of the enantiomers of **40** and **49** was achieved, the peaks of **35** partially overlapped. Therefore, preparative isolation of **35** + **39**, followed by acid-catalyzed rearrangement to **40**, replaced or complemented the direct analysis of **35**. The ≥90% enantiomeric excess of all products indicates that symmetrical 1-methyl-7-norbornyl cations intervene to a minor extent, if at all. The differences in optical purity of **35**, **40**, and **49** do not exceed the experimental errors sufficiently to deserve comment.

5-Methylbicyclo[3.2.0]heptane-*exo*-2-diazonium Ions. For further insights into the partitioning of the diazonium ion **44** and into the bridge-flipping of the cation **47**, 5-methylbicyclo[3.2.0]heptan-*exo*-2-amine (**54**) was synthesized from 5-methylbicyclo[3.2.0]heptan-2-one (**50**)[33] according to Scheme VIII. The nitrous acid deamination of **54** gave even larger fractions of **40** and **49** than that of

Scheme IX



43, as expected (Table I). With the aid of the product distribution obtained from **54**, partitioning factors may be derived for **38**, **44**, and **47** which reproduce the data of Table I within experimental error (Scheme VII).

Our figures are entirely reasonable. It is widely recognized that diazonium ions discriminate but weakly among neighboring groups.[34] Streitwieser's compressed energy scale of diazonium ion decomposition provides a consistent explanation.[35] The partitioning factor of 11.5 assigned to **47** agrees with that of the parent ion **2** (**13**:**14** = 13), ring strain being a dominant factor.[25] With **38**, the strain effect is outbalanced by charge stabilization, thus reversing the product ratio. (Secondary–tertiary carbocation systems not involving differences in strain energy give tertiary alcohols exclusively, cf. 2-methyl-2-norbornyl.) Owing to the stabilization of **38**, the exothermic **47** → **38** transformation occurs more readily (25%) than the degenerate bridge-flipping of **2** (11–12%).

Structure of the Carbocations. Bridged (nonclassical) ions have been used persuasively in previous schemes to rationalize the stereochemistry and distribution of the products. Alternative open (classical) ion formulations must now be considered. Symmetrical 7-norbornyl cations are clearly excluded by our data, except for a minor contribution to the solvolyses of 7-norbornyl substrates. Bent 7-norbornyl cations, however, cannot be discounted on the basis of stereochemical evidence. The question arises whether the pair of bridged intermediates (**38**, **47**) shown in Scheme VII could be replaced by a set of open, chiral carbocations (**55**, **56**, **37**) (Scheme IX). Our answer is no. We argue that Scheme IX is inconsistent with the product distributions recorded in Table I. In terms of Scheme IX, the similar **35**:**40** ratios obtained from **34** and **41** indicate rapid equlibration of **56** and **37**. On the other hand, **55** must rearrange irreversibly to give **56** (no **49** was found in the solvolysis of **41**, but the deamination of **54** afforded **35** and **40**). It follows that the **35**:**40** ratios from all substrates should be identical. This is clearly not the case. The divergent **35**:**40** ratios require at least tow different precursors to **40**. The bridged ions **38** and **47** fulfill this requirement uniquely well. Structure **56** may be viewed as the transition state of the **47** → **38** "bridge-flipping".

Conclusions

On the basis of the results obtained in the present work, we conclude the following:

(1) The carbocations generated from 2-bicyclo[3.2.0]-heptyl precursors are highly anti selective. Anti–syn leakage is characteristic of 7-norbornyl substrates and may be due to k_Δ,k_c competition. This assumption would explain the smaller leakage of 1-methyl-7-norbornyl triflate (**41**) as compared to the parent system.[6]

(32) Gold, B.; Deshpande, A.; Linder, W.; Hines, L. *J. Am. Chem. Soc.* **1984**, *106*, 2072 and references cited therein.
(33) Cargill, R. L.; Wright, B. A. *J. Org. Chem.* **1975**, *40*, 120.
(34) For reviews, see: Collins, C. L. *Acc. Chem. Res.* **1971**, *4*, 315. Kirmse, W. *Angew. Chem.* **1976**, *88*, 273; *Angew. Chem., Int. Ed. Engl.* **1976**, *5*, 251. Kirmse, W. *Top. Curr. Chem.* **1979**, *80*, 275.
(35) Streitwieser, A., Jr. *J. Org. Chem.* **1957**, *22*, 861. Streitwieser, A., Jr.; Schaeffer, W. D. *J. Am. Chem. Soc.* **1957**, *79*, 2888.

(2) The carbocations undergo reorganizations exchanging C-2 with C-5 (bicyclo[3.2.0]heptyl numbering) without exchanging C-3,4 with C-6,7. This process, "same-side bridge-flipping", leads to partial racemization of the parent system and to structural isomerization of others. No bridge-flipping is found with 2-methylbicyclo[3.2.0]heptyl substrates from which the most stable ion is formed directly.

(3) Attempts to rationalize the product distributions in terms of open ions lead to serious discrepancies. In contrast, bridged intermediates provide an internally consistent interpretation of all data. Open, bent 7-norbornyl cations appear to represent transition states of bridge-flipping rather than intermediates.

It is remarkable that 2-bicyclo[3.2.0]heptyl and 7-norbornyl cations conform to the stereochemical criteria of bridging in spite of a supposed energy gap between the contributing structures.[36] More elaborate theoretical investigations are clearly desirable.

Experimental Section

General Methods. Melting points were determined on a Kofler hot-stage apparatus and are uncorrected. Specific rotations were obtained on a Perkin-Elmer 141 polarimeter. ^1H NMR spectra were recorded in $CDCl_3$ on Bruker WP-80, WM-250, and AM-400 instruments. ^2H NMR spectra were recorded on a Bruker WM-250 (38.39 MHz) or a Bruker AM-400 (61.42 MHz) spectrometer. High-pressure liquid chromatography (HPLC) was performed on a LDC instrument with 25 × 1.5 cm silica gel columns (Si 60, 5 μm, Macherey and Nagel), gas chromatography (GC) was performed on a Siemens Sichromat equipped with glass capillary columns. The preparation and operation of glass capillaries coated with optically active PPG has been described previously.[19]

Bicyclo[3.2.0]heptan-*exo*-2-amine (11). Bicyclo[3.2.0]heptan-*endo*-2-ol[15] (2.0 g, 18 mmol) was treated with tosyl chloride (3.8 g, 20 mmol) in anhydrous pyridine at −20 °C to give 4.3 g (91%) of tosylate **10**. A solution of the crude tosylate in Me_2SO (70 mL) and 2.0 g (31 mmol) of sodium azide were heated to 80 °C for 24 h. The reaction mixture was poured onto ice–water and extracted with ether. The organic layer was washed with water, dried over $MgSO_4$, and evaporated. The crude azide (1.9 g, 14 mmol, 86%) and $LiAlH_4$ (2.0 g, 53 mmol) in ether were stirred overnight at room temperature. Excess $LiAlH_4$ was hydrolyzed by dropwise addition of water. The solution was filtered, dried over K_2CO_3, and concentrated to ca. 50 mL. Anhydrous hydrogen chloride was introduced, and the precipitate was recrystallized from ethyl acetate–ethanol (1.3 g, 64%, mp 272–274 °C). The hydrochloride was treated with aqueous potassium hydroxide, and the amine was extracted with ether and purified to 99.8% by preparative GC (4.5-m Carbowax–KOH, 90 °C): ^1H NMR (C_6D_6) δ 0.67 (2 H, s, NH_2), 1.0–2.4 (9 H, m), 2.5–2.9 (1 H, m), 2.95 (1 H, d, J = 4 Hz). Anal. Calcd for $C_7H_{13}N$: C, 75.62; H, 11.78; N, 12.60. Found: C, 75.67; H, 11.74; N, 12.62.

A solution of 80 mg of **11** in 80 mL of water was adjusted to pH 3.5 (glass electrode) with dilute perchloric acid. Sodium nitrite (0.25 g) was added, and stirring was continued for 18–24 h. The products were extracted with ether, treated with $LiAlH_4$ to remove alkyl nitrites, and analyzed by GC on three different columns. In addition to **13** (91.0%) and **14** (8.1%), a small amount (0.8%) of bicyclo[3.2.0]heptan-*endo*-2-ol was observed. This alcohol may be an artifact, arising from the reduction of ketone **17**. Ketones are minor byproducts in many deamination reactions. The combined yield (by internal standard) was 65–71%.

The synthesis of [2-^2H]**11** started from bicyclo[3.2.0]heptan-2-one (**17**) and $LiAlD_4$ and was exactly analogous to that of **11**. The alcohols obtained by nitrous acid deamination of [2-^2H]**11** (1.20 g) were separated by preparative GC (4.5-m Carbowax–KOH, 90 °C) to give isolated yields of 46 mg (5%) of [^2H]**14** (^2H NMR δ 3.8 and 2.8; 88:12)[14] and 0.58 g (63%) of [^2H]**13** (^2H NMR δ 1.9; ≥98.5%).

(1*R*,5*R*)-**11** was prepared analogously from optically active *endo*-alcohol **18** (see below). The enantiomeric excess of **11** (82 ± 1%) was determined by GC of the *N*-(trifluoroacetyl)-(*S*)-prolyl amides.[21] Alcohol **14** from the nitrous acid deamination of (1*R*,5*R*)-**11** was isolated by preparative GC and oxidized by excess pyridinium chlorochromate[37] (6 g of PCC in 20 mL of CH_2Cl_2). The resulting ketone **17** was reduced ($LiAlH_4$, Et_2O) to the *endo*-alcohol **18**, and the optical purity of **18** (ee 62.4 ± 1.6%) was determined by GC on optically active PPG.

Optically Active Bicyclo[3.2.0]hept-2-yl Derivatives. Bicyclo[3.2.0]hept-2-ene (**15**)[18] was prepared by Wolff–Kishner reduction of bicyclo[3.2.0]hept-2-en-6-one[28] (56% yield). To a solution of sodium borohydride (2.8 g, 74 mmol) and of (+)-α-pinene (26.3 g, 0.19 mol; $[\alpha]_D$ 46.5°; ee 90%) in diglyme (40 mL) was added at 0 °C a solution of 14.1 mL of $BF_3{\cdot}OEt_2$ in 10 mL of diglyme. After the mixture was stirred at 0 °C for 6 h, **15** (9.0 g, 96 mmol) was added, and stirring was continued for 14 h at 30 °C. NaOH (3 N, 31 mL) and 30% H_2O_2 (31 mL) were then added with cooling. After 1 h the reaction mixture was diluted with water and extracted with ether. The organic layer was washed with aqueous ammonium iron(II) sulfate and water and then dried over $MgSO_4$. Evaporation of the solvent and distillation afforded a fraction, bp 65–90 °C (20 mmHg), containing ca. 40% **14**, 30% **16**, and 30% isopinocampheol. Most of the isopinocampheol, bp 105 °C (10 mmHg) remained in the residue. The alcohols **14** (2.2 g, 21%) and **16** (1.6 g, 15%) were isolated by preparative GC (4.5-m Carbowax–KOH, 110 °C).

PCC oxidation of **14** by the standard procedure,[37] followed by short-path distillation, yielded 2.04 g (94%) of (+)-bicyclo[3.2.0]heptan-2-one (**17**). A sample of 99.7% purity, obtained by preparative GC, was used for optical rotation and CD measurements: $[\alpha]^{19}_D$ 29.87° (neat, l = 0.1 dm); CD (acetonitrile) λ_{max} 302.6 (Δε +1.47), 200.6 (Δε +0.67). On the basis of the octant rule, the 1*S*,5*S* configuration was assigned to (+)-**17**.[20] The optical purity of this sample (ee 82.0 ± 1.8%) was estimated by reduction ($LiAlH_4$, Et_2O) to the *endo*-alcohol **18**, followed by GC of **18** on optically active PPG.

Saccharose (60 g), baker's yeast (8.0 g), and water (150 mL) were stirred for 30 min. Bicyclo[3.2.0]heptan-2-one (**17**)[15] (2.0 g) was then added. Stirring was continued with addition of more saccharose (40 g), yeast (5 g), and water (50 mL) after 24, 48, and 72 h. Progress of the reaction was monitored by GC. After 96 h, the reaction mixture containing 55% of **17**, 44% of **18**, and 1% of **14** was separated by centrifugation (ca. 40 min at 4000 rpm) and continuous extraction of the viscous liquid with ether (24 h). The extracts were dried over $MgSO_4$ and evaporated. Preparative GC (4.5-m Carbowax–KOH, 120 °C) of the residue yielded 0.32 g (16%) of **18** (ee 80.4 ± 1.8%) and 0.36 g (18%) of (+)-**17** (ee 63 ± 2%). PCC oxidation of **18** gave (−)-(1*R*,5*R*)-**17**, $[\alpha]^{20}_D$ −27.75° (neat, l = 0.1 dm).

[6,7-$^2H_2$]Bicyclo[3.2.0]hept-2-yl Substrates. The attempted deuteration of bicyclo[3.2.0]hex-6-en-2-one ($^2H_2$, 10% Pd–C, room temperature, atmospheric pressure, ethyl acetate) led to incorporation of more than two ^2H, presumably by partial exchange of 3-H. The analogous deuteration of bicyclo[3.2.0]hept-6-en-*endo*-2-ol (**19**) proceeded quantitatively. However, the ^2H NMR spectrum of [6,7-$^2H_2$]**18** showed signals at δ 1.41 (4%), 1.81 (49%), and 2.16 (47%). The minor component is assumed to be *endo*-[6,7-$^2H_2$]**18**. Labeled **18** (60 mg) was treated with 3 mL of 5 N H_2SO_4 in acetic acid (100 °C, 22 h). The reaction mixture was diluted with water and extracted with ether. The ether extracts were washed with aqueous $NaHCO_3$, dried over $MgSO_4$, and treated with $LiAlH_4$. Standard workup yielded 51 mg (73%) of [$^2H_2$]-7-norbornanol: ^2H NMR δ 1.12 (7%), 1.50 (93%). No other products were detected by GC. The assignment of the NMR signals rests on the spectra of 4-OH[6] (exo,anti) (^2H NMR δ 1.50) and 5-OH[6] (exo,syn) (^2H NMR δ 1.82). The endo,anti protons of 4-OH (δ 1.12) and the endo,syn protons of 5-OH (δ 1.21) are readily identified in the ^1H NMR spectra by their lack of geminal coupling.

(36) According to STO-3G calculations of isodesmic reactions, the 2-bicyclo[3.2.0]heptyl ($\Delta H_f°$ = 205.9 kcal/mol) and 7-norbornyl ($\Delta H_f°$ = 198.6 kcal/mol) cations differ by 7.3 kcal/mol: Würthwein, E. U., unpublished results.

(37) Corey, E. J.; Suggs, J. W. *Tetrahedron Lett.* **1975**, 2647.

(38) Rey, M.; Huber, U. A.; Dreiding, A. S. *Tetrahedron Lett.* **1968**, 3583.

Labeled **18** was converted into [6,7-$^2H_2$]**11**, following the procedures for the synthesis of **12**. The ^2H NMR spectrum of [$^2H_2$]**13** from the nitrous acid deamination of [6,7-$^2H_2$]**11** was identical with that of [$^2H_2$]**13** from the acid-catalyzed rearrangement of [6,7-$^2H_2$]**18**. The spectrum of [$^2H_2$]**14** from the deamination of [6,7-$^2H_2$]**11** was compared with that of [6,7-$^2H_2$]**14**, prepared by inversion of [6,7-$^2H_2$]**10** [(a) Et_4NOAc, acetone, 100 °C, 11 h; (b) $LiAlH_4$). Although some deviations were noticed, the resolution was insufficient for an analysis of deuterium relocation.

6- and 7-Methylbicyclo[3.2.0]hept-2-yl Substrates. Photocycloaddition of propyne (14.6 g, 0.35 mol) to 2-cyclopentenone (3.0 g, 36 mmol) (CH_2Cl_2, −78 °C, 13 h, 87% conversion), followed by preparative GC (4.5-m Carbowax–KOH, 130 °C) gave **23** (0.67 g, 15%; purity 99.4%) and **24** (0.20 g, 4.5%; purity 97.9%).[22] Hydrogenation of **23** to give *endo*-7-methylbicyclo[3.2.0]heptan-2-one,[22] followed by reduction with $LiAlH_4$, afforded *endo*-7-methylbicyclo[3.2.0]heptan-*endo*-2-ol (**26**) (91%). The crude **26** contained 1.4% of the exo isomer **28** and was purified to 100% by preparative GC (1-m Carbowax, 120 °C): ^1H NMR δ 1.20 (CH_3, d, J = 6 Hz), 1.1–2.8 m (9 H), 2.8 (OH, s), 4.25 (2-H, apparent q, J = ca. 8 Hz). Anal. Calcd for $C_8H_{14}O$: C, 76.14; H, 11.18. Found: C, 76.10, H, 11.02.

Tosylation of **26**, following the procedure for **10**, yielded the analogous tosylate (90%). Treatment of the tosylate (0.20 g, 0.7 mmol) with tetraethylammonium acetate (1.0 g) in acetone (7 mL) for 11 h at 100 °C and subsequent reduction with $LiAlH_4$–ether led to *endo*-7-methylbicyclo[3.2.0]heptan-*exo*-2-ol (**28**) (31 mg, 32%): ^1H NMR δ 0.87 (CH_3, d, J = 6.8 Hz), 1.0–2.9 m (9 H), 2.7 (OH, s), 4.21 (2-H, apparent d, J = 3 Hz). Anal. Calcd for $C_8H_{14}O$: C, 76.14; H, 11.18. Found: C, 76.04; H, 11.17. Acid-catalyzed rearrangement of either **26** or **28** (1 N H_2SO_4 in acetic acid, 100 °C, 21 h) gave **30** (see below) as the only product detectable by GC.

The major portion of the tosylate was converted into *endo*-7-methylbicyclo[3.2.0]heptan-*exo*-2-amine (**25**), as described for **11**. The yield of recrystallized hydrochloride, mp 248 °C dec, was 22%: ^1H NMR [of **25**·HCl] (D_2O) δ 0.80 (CH_3, d, J = 6 Hz), 0.9–1.3 m (1 H), 1.4–3.0 m (8 H), 3.68 (2-H, d, J = 4 Hz); ^1H NMr [of **25**] (C_6D_6) δ 0.71 (NH_2, s), 0.82 (CH_3, d, J = 6 Hz), 0.9–2.9 m (9 H), 3.20 (2-H, d, J = 3 Hz). Anal. Calcd for $C_8H_{16}ClN$: C, 59.43; H, 9.97; N, 8.66. Found: C, 59.49; H, 9.94; N, 8.62. The nitrous acid deamination of **25** (for conditions, etc., see **11**), gave **28** (3.1 ± 0.5%), **29** (2.5 ± 0.2%), **30** (94.0 ± 0.5%), **32** (0.3 ± 0.2%), and **26** (0.1 ± 0.1%). The figures are average values from six deaminations, analyzed by GC on three different capillary columns.

Hydrogenation of **24** led to an apparently homogeneous 6-methylbicyclo[3.2.0]heptan-2-one,[22] but subsequent reduction with $LiAlH_4$ resulted in a mixture of **22** (12.0%), **26** (2.1%), **27** (84.7%), and **29** (1.2%). While **26** stems from a contamination of **24** with **23** (see above), **22** is obviously due to moderately selective hydrogenation of **24**. The major components, *endo*-6-methylbicyclo[3.2.0]heptan-*endo*-2-ol (**27**) and its *exo*-6-methyl isomer (**22**), were isolated by preparative GC (2-m Carbowax, 120 °C): ^1H NMR [of **27**] δ 0.90 (CH_3, d, J = 6 Hz), 1.3–2.2 m (8 H), 2.4–2.8 (m 2 H), 4.12 (2-H, dt, J = 9, 6 Hz). Anal. Calcd for $C_8H_{14}O$: C, 76.14; H, 11.18. Found: C, 76.07; H, 11.13; ^1H NMR of **22** δ 0.8–2.3 m (9 H) [superimposed on δ 1.12 (CH_3, d, J = 7 Hz)], 2.5–2.9 (m, 1 H), 4.2 (2-H, apparent q, J = 8 Hz).

Inversion of **27** via tosylate and acetate (cf. **26** → **28**) yielded *endo*-6-methylbicyclo[3.2.0]heptan-*exo*-2-ol (**29**): ^1H NMR δ 0.84 (CH_3, d, J = 6 Hz), 1.40 (OH, s), 1.65–3.0 m (9 H), 3.97 (2-H, d, J = 3 Hz). Anal. Calcd for $C_8H_{14}O$: C, 76.14; H, 11.18. Found: C, 76.22; H, 11.22.

Acid-catalyzed rearrangement of either **27** or **29** (1 N H_2SO_4 in acetic acid, 100 °C, 21 h) gave *endo*-2-methyl-*anti*-7-norbornanol (**30**), whereas analogous treatment of **22** gave the *exo*-2-methyl-*anti*-7-norbornanol (**21**). Authentic samples of **21** and of its syn isomer were prepared according to Ashby and Noding.[24] A mixture of 2-methyl-2-norbornen-7-ols (**31**, **33**) was obtained by reduction of 2-methyl-2-norbornen-7-one[23] and separated by preparative GC (2-m Carbowax–KOH, 120 °C). Hydrogenation (Pd–C, ethyl acetate, atmospheric pressure) of **33** gave **30**: ^1H NMR δ 0.53 m (1 H), 0.8–1.3 (m, 2 H) [superimposed on δ 0.88 (CH_3, d, J = 6 Hz)], 1.35–2.05 (m, 6 H), 2.30 (OH, s), 3.83 (7-H, s, br). Anal. Calcd for $C_8H_{14}O$: C, 76.14; H, 11.18. Found: C, 76.24; H, 11.12. Analogous hydrogenation of **33** afforded *endo*-2-methyl-*syn*-7-norbornanol (**32**): ^1H NMR δ 0.60 (m, 1 H), 0.8–2.5 (m, 8 H) [superimpozed on δ 0.97 (CH_3, d, J = 6 Hz) and 1.27 (OH, s)], 3.92 (7-H, s, br). Anal. Calcd for $C_8H_{14}O$: C, 76.14; H, 11.18. Found: C, 76.01; H, 11.27.

2-Methylbicyclo[3.2.0]hept-2-yl Substrates. Application of the reported synthesis of 2-methylenebicyclo[3.2.0]heptane (**34**)[27] to (1*S*,5*S*)-bicyclo[3.2.0]heptan-2-one (82% ee) gave 62% of (1*S*,5*S*)-**34**, $[\alpha]^{19}_D$ 19.90° (neat, l = 0.1 dm). Acid-catalyzed addition of acetic acid to (1*S*,5*S*)-**34** (0.5 N H_2SO_4 in HOAc, room temperature, 18 h), followed by deacetylation with $LiAlH_4$, yielded 68% of (7*R*)-1-methyl-7-norbornanol (**40**) (81.6 ± 0.8% ee, estimated by GC on optically active PPG). "Mild" hydration of **34** (0.3 N H_2SO_4 in 70% aqueous dioxane, room temperature 6 h) gave *endo*-2-methylbicyclo[3.2.0]heptan-*exo*-2-ol (**35**) as the major product (91.1%), along with the epimeric tertiary alcohol **39** (3.8%) and **40** (5.1%).

endo-2-Methylbicyclo[3.2.0]heptan-*exo*-2-ol p-nitrobenzoate (**36**) was obtained by a reported general procedure.[39] To **35** (1.1 g, 8.7 mmol) in THF (20 mL) was added *n*-butyllithium (1.6 # in hexane, 6.2 mL). After 30 min at room temperature, *p*-nitrobenzoyl chloride (1.8 g, 9.7 mmol) in THF (10 mL) was added, and the mixture was heated at reflux for 1 h. The resulting solution was diluted with ether and washed with aqueous $NaHCO_3$ and with water. The organic phase was dried over $MgSO_4$ and evaporated under reduced pressure. The residue was recrystallized from pentane to give a low yield (0.12 g, 5%) of **36**: mp 98–99 °C; ^1H NMR δ 1.4–2.7 (8 H, m) [superimposed on δ 1.70 (CH_3, s)], 2.8–3.0 (1 H, m), 3.1–3.4 (1 H, m), 8.2 (4 H, m); IR ($CDCl_3$) $\nu_{C=O}$ 1710 cm^{-1}. Anal. Calcd for $C_{15}H_{17}NO_4$: C, 65.44; H, 6.22; N, 5.09. Found: C, 65.33; H, 6.38; N, 5.12.

A solution of **36** (70 mg, 0.3 mmol) and of potassium carbonate (0.50 g) in acetone–water (1:1, 12 mL) was heated at reflux for 45 h. The reaction mixture was diluted with ether and extracted with water. The organic layer was dried over $MgSO_4$, concentrated, and analyzed by GC (see Table I).

1-Methyl-7-norbornyl Substrates. 1-Methyl-7-norbornanone tosylhydrazone (**45**)[28] was photolyzed in 0.2–2.0 N NaOH (medium-pressure mercury arc, pyrex vessel). The product distribution (Table I) was independent of the concentration of base; hydrocarbons were formed to less than 1%. The combined yield of alcohols, estimated by GC with the aid of an internal standard, was 72–78%.

A general procedure by Schleyer et al.[40] was followed for the preparation of 1-methyl-7-norbornyl triflate (**41**). A solution of **40** (0.42 g, 3.3 mmol) in anhydrous ether (3 mL) and anhydrous pyridine (7.6 mL) was cooled to −15 °C and treated in a dropwise fashion with trifluoromethanesulfonic anhydride (2.52 g, 8.9 mmol). Stirring was continued overnight at −20 °C. The reaction mixture was diluted with ether and extracted with water. The organic phase was then dried over $MgSO_4$ and concentrated under reduced pressure. The crude triflate (0.56 g, 65%) was separated from minor amounts of unreacted **40** by preparative GC (0.5-m SE 30, 70 °C) to give 0.27 g (32%) of pure **41**: ^1H NMR δ 1.13 (CH_3, s), 1.25–2.1 (8 H, m), 2.4 (1 H, br s), 4.60 (1 H, s).

Solvolyses of **41** were performed at reflux temperature in acetone–water (9:4, 8 h) and dioxane–water (9:4, 4 h) in the presence of 2 equiv of calcium carbonate. The reaction mixtures were saturated with sodium chloride and extracted with ether. The combined extracts were dried over $MgSO_4$, concentrated, and analyzed by GC on three different columns (Table I). In the case of (*R*)-**41**, the individual product peaks, after having been separated on achiral columns, were transferred onto optically active PPG. Since the enantiomers of **35** overlapped partially, **35** was isolated by preparative GC (4.5-m Carbowax–KOH, 120 °C) and converted into **40** by acid-catalyzed rearrangement. The procedure was analogous to the **34** → **40** rearrangement, and the data are recorded in Table II.

A solution of 0.21 g (0.8 mmol) of triflate **41** in 30 mL of anhydrous toluene was treated with 0.52 g (1.1 mmol) of hexadecyltributylphosphonium azide,[41] and the resulting mixture was

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heated at 90 °C for 15 h. Progress of the reaction was monitored by IR ($Q^+N_3^-$ 2000 cm^{-1}, **42** 2100 cm^{-1}). Most of the toluene was then evaporated at 70 °C (300 mmHg). Short-path distillation of the residue [100 °C (< 0.01 mmHg)] afforded 69 mg (56%) of **42**, contaminated with traces of toluene. A solution of the crude **42** in 10 mL of ether was added dropwise to a suspension of 0.5 g of $LiAlH_4$ in 30 mL of ether. The mixture was then stirred for 20 h at room temperature before being quenched by dropwise addition of water. The precipitate was filtered and washed with ether. Anhydrous hydrogen chloride was then passed into the combined ethereal solutions. The precipitate was filtered and recrystallized from ethyl acetate–ethanol to give 95 mg (73%) of **43**·HCl, mp 221 °C sublimed. 1-Methylbicyclo[2.2.1]heptan-7-amine (**43**) was obtained from the hydrochloride with 5 N NaOH, extracted with ether, and purified by preparative GC (4.5-m Carbowax–KOH, 105 °C): ^{1}H NMR (C_6D_6) δ 0.75 (NH_2, s), 0.94 (CH_3, s), 1.0–1.6 (7 H, m), 1.7–2.1 (2 H, m), 2.43 (1 H, s). Anal. Calcd for $C_8H_{15}N$: C, 76.73; H, 12.07; N, 11.19. Found: C, 76.69; H, 12.12; N, 11.26.

The enantiomeric purity of optically active **43**, obtained from (*R*)-**40** via **41**, was determined by GC of the *N*-(trifluoroacetyl)-(*S*)-prolyl amides.[21] Within experimental error (±2%), the ee of **43** was found to be identical with that of **40**. The deaminations of **43** (12–20 mg) in water (10 mL) were performed as described for **11**. Ether (5 mL) was added in some runs in order to minimize the acid-induced rearrangement of **35**. Product distributions (Table I) and optical purities (Table II) were estimated as described for the solvolyses of **41**. The peak ratios on optically active PPG indicated that **40** from the deamination of **43** (*S*:*R* = 87:13) and **40** from the solvolysis of **41** (*S*:*R* = 12:88) had opposite configurations.

5-Methylbicyclo[3.2.0]heptan-*exo*-2-amine (54). 5-Methylbicyclo[3.2.0]heptan-2-one (**50**)[33] was processed to the amine **54** via *endo*-alcohol **51**[42] (90%), tosylate **52** (99%), and azide **53** (67%), as described for the parent compound (**11**). Reduction of **53** with $LiAlH_4$, followed by introduction of HCl, afforded 64% of **54**·HCl: mp 246–250 °C dec; ^{1}H NMR [of **54**] (C_6D_6) δ 0.65 (NH_2, s), 0.9–2.2 (9 H, m), 2.93 (1 H, d, J = 4.4 Hz). Anal. Calcd for $C_8H_{15}N$: C, 76.73; H, 12.07; N, 11.19. Found: C, 76.77; H, 12.11; N, 11.23.

The nitrous acid deamination for **54** was performed in analogy to that of **11**. Products **35**,[27] **39**,[27] **40**,[27] **49**,[33] and **51**[33] were analyzed by GC (Table I) and identified by comparison on three different columns. An authentic sample of **49** was prepared from **51** via **52** by the standard inversion procedure (see above for **26** → **28**).

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Products and Reaction Routes in the Diozonolysis of 2,3-Dimethyl-1,3-butadiene in Methanol

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Treatment of 2,3-dimethyl-1,3-butadiene (**1**) with 2 molar equiv of ozone in methanol afforded the abnormal products acetic acid (**12**) and methyl acetate (**13**), which resulted from cleavage of both the double bonds and the single bond of the conjugated diene system. In model experiments it was shown that the reaction proceeds stepwise by formation of an α,β-unsaturated methoxy hydroperoxide (**3**) in the first and a α-keto methoxy hydroperoxide (**8**) in the second ozonolysis step. The latter undergoes spontaneous decomposition at ambient temperatures to give rise to the abnormal cleavage products **12** and **13**. This cleavage is accompanied by emission signals in the ^{1}H NMR spectrum which are indicative of the occurrence of acetyl radicals and hence suggest at least a partial radical-type cleavage of the α-keto methoxy hydroperoxide **8**.

Considering the importance of compounds having conjugated diene systems, including both natural and synthetic products, surprisingly little is known about their ozonolysis. In fact, not even a subchapter has been devoted to this theme in Bailey's recent comprehensive review on ozone chemistry.[2] The scarce reports in the literature are mainly concerned with the description of non-peroxidic stable end products of mono-[3-7] and of diozonolysis reactions[8-13] of acyclic and of cyclic diene compounds. By contrast, the nature of peroxidic intermediates has in most cases not been elucidated. Furthermore, the scattered data available do not provide a unifying view of the course of such reactions. Thus, in some cases it was reported that diozonolysis of a diene system followed a conventional pattern and resulted in the cleavage of the double bonds only, whereas in other cases abnormal reactions have been observed, in which the carbon skeleton has been cleaved both at the double bonds and at the central single bond.

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