added and allowed to warm at room temperature. $MgSO_4$ (1 g) was added to remove water and filtered off. Removal of the solvent, followed by filtration through a silica gel column (pentane), gave **31** (173 mg, 77%), which was sublimed at 80 °C (3 Torr). **31**: colorless crystals, mp 81.5–82.0 °C; ^1H NMR (90 MHz, CCl_4) δ 2.20 (br s, 8 H), 1.59 (br s, 12 H); ^{13}C NMR (22.5 MHz, CCl_4) δ 152.0, 114.8, 34.6, 27.5, 26.1; MS, m/z 188 (M^+); UV, λ_{max} (cyclohexane) 272 nm (log ϵ 3.84), 265 (3.83); IR (CCl_4) 2933, 2853, 1450, 1346, 1225 cm^{-1}. Attempted elemental analysis of **31** was unsuccessful because of its instability to atmospheric oxygen. The butatriene **31** can be stored in CCl_4 or hexane solution under argon.

Reaction of 31 with $Ni(CO)_2(PPh_3)_2$. To a solution of 942 mg (5 mmol) of **31** in benzene (150 mL) were added 640 mg (1 mmol) of $Ni(CO)_2(PPh_3)_2$ and 512 mg (2 mmol) of PPh_3. The mixture was heated to reflux under nitrogen for 3 days. The reaction mixture was filtered through a short silica gel column (benzene) and chromatographed on silica gel (hexane) to give the [4]radialene **30** (134 mg, 14%).

Codimerization of 17 and 29 with $Ni(PPh_3)_4$. To a suspension of $Ni(PPh_3)_4$ prepared from $NiBr_2(PPh_3)_2$, PPh_3, and zinc [1.49 g (2 mmol), 1.05 g (4 mmol), and 1.31 g (30 mmol), respectively] were added 725 mg (2 mmol) of **17** and 884 mg (2 mmol) of **29**. The resulting mixture was stirred under argon at room temperature for 50 h and then filtered. The filtrate was passed through a short alumina column and then chromatographed on silica gel to give **19** (6%), **26** (28%), and **30** (14%). Pure sample of these compounds were obtained by further separation using preparative TLC.

Reaction of 33 with $Ni(PPh_3)_4$. To a suspension of $Ni(PPh_3)_4$ prepared from $NiBr_2(PPh_3)_2$, PPh_3, and zinc in benzene (7 mL), [373 mg (0.5 mmol), 263 mg (1 mmol), and 328 mg (5 mmol), respectively] was added 550 mg (1.1 mmol) of **33** in one portion. The mixture was stirred at room temperature for 24 h and worked up in a similar manner used for **29** to give a mixture of (*E*)- and (*Z*)-**34**[30] (19 mg, 27%).

Reaction of 36 with $Ni(PPh_3)_4$. To a suspension of $Ni(PPh_3)_4$ prepared from $NiBr_2(PPh_3)_2$, PPh_3, and zinc in benzene (30 mL) at 50 °C [1.51 g (2 mmol), 1.06 g (4 mmol), and 1.31 g (20 mmol), respectively] was added 680 mg (2 mmol) of **36** in one portion. The mixture was stirred at 50 °C for 21 h and worked up to give **6** (207 mg, 60%).

Acknowledgment. We thank Dr. C. Kabuto for X-ray analysis of **19** and Professor M. Kobayashi for helpful advice on the interpretation of Raman spectra. We also thank Professors K. Sonogashira and A. Nakamura for helpful discussions.

Static Structure of a Regular Intermediate Controls the Course of the Thermal 1,3-Sigmatropic Rearrangement of 6-Methylenebicyclo[3.1.0]hex-2-enyl Derivatives[1]

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Abstract: The rearrangements of derivatives of the title structure bearing oxygen substituents at C_4 occur at measurable rates in the temperature range 50–100 °C in benzene solution. The products are 2-methylenebicyclo[3.1.0]hex-3-enes substituted at C-6. The stereochemistry of these processes shows the intervention in each case of a true intermediate. Either stereoisomer of the 4-methoxy reactant gives the same 97:3 mixture of 6-*endo*- and 6-*exo*-methoxy products. Similar results are observed starting with the 4-*endo*-methoxy-4-*exo*-methyl reactant, which gives largely the 6-*endo*-methoxy product. In the case of the rearrangement of optically active ethylene ketal of bicyclo[3.1.0]hex-3-en-2-one, the rearranged cyclopropanone ketal is devoid of optical activity (>99% racemized), and the starting material is recovered 12% racemized. These data suggest the intermediacy of a symmetrical achiral biradical intermediate, which lives long enough to lose mechanistic memory of its origin and which cyclizes to rearrangement product about 6.5 times as fast as it cyclizes back to starting material.

Structural or stereochemical symmetrization experiments traditionally have provided one of the most decisive means of mechanistic investigation. The power of this method comes from the conviction that a statically or dynamically symmetrical intermediate in a symmetrical environment would necessarily give equal quantities of two or more symmetry-related products.[2] A similar criterion pertains to quasi-symmetrical intermediates, which give identical product distributions from two or more different precursors. These criteria are especially strong in their exclusionary form,[3] in which the observation of a biased product distribution is taken as compelling evidence *against* a symmetrical (or quasi-symmetrical) intermediate.

Although a number of effectively symmetrical intermediates have been brought to light, especially in the field of carbocation chemistry,[3a,b,4] the literature of thermal rearrangements is notably lacking in such examples. In part, this may be ascribed to the difference in lifetime of the intermediates: If the stereochemical test of carbocation symmetry depends upon an intermolecular capture in solution, the carbocation presumably must live at least as long as the time (of the order of nanoseconds) needed for diffusive encounters with the capturing nucleophile. In contrast, a biradical in a thermal unimolecular reorganization may have

(1) Preliminary communication: Pikulin, S.; Berson, J. A. *J. Am. Chem. Soc.* **1985**, *107*, 8274.

(2) (a) True symmetry is not achieved in most such studies, since "symmetrization", when detected by isotopic position labeling, for example, is perturbed by kinetic or equilibrium secondary isotope effects. Even when the experimental design proposes racemization via an achiral species as the criterion, the "electro-weak advantage" associated with parity nonconservation prevents strict equality of the amounts of enantiomeric products.[2b] Although the isotope effects cannot be ignored, the parity effect will be indetectably small in most mechanistic studies. (b) Mason, S. F. *Nouv. J. Chim.* **1986**, *10*, 739, and references cited therein. (c) Although in the absence of dynamical effects, a symmetrical intermediate is required to give equal amounts of two or more isotopomers or enantiomers, the converse is not necessarily true; that is, "reaction symmetry" does not imply structural symmetry of an intermediate.[2d,e] (d) Burwell, R. L.; Pearson, R. G. *J. Phys. Chem.* **1966**, *70*, 300. (e) Salem, L.; Durup, J.; Bergeron, G.; Cazes, D.; Chapuisat, X.; Kagan, H. *J. Am. Chem. Soc.* **1970**, *92*, 4472.

(3) (a) For an early example, see the refutation of tricyclene as an intermediate in the carbonium ion chemistry of the camphene/isobornyl solvolysis system: Meerwein, H.; van Emster, K. *Ber. Disch. Chem. Ges.* **1920**, *53*, 1815. (b) Review: Berson, J. A. In *Molecular Rearrangements*, de Mayo, P., Ed.; Interscience: New York, 1963; Vol. I, Chapter 3, pp 115, 149. (c) Review: Berson, J. A. *Angew. Chem. Int. Ed. Engl.* **1968**, *10*, 779.

(4) (a) Bartlett, P. D. *Nonclassical Ions*; Benjamin: New York, 1965. (b) Brown, H. C. (with comments by Schleyer, P. v. R.) *The Nonclassical Ion Problem*; Plenum: New York, 1977.

0002-7863/88/1510-8500$01.50/0

little or no barrier to intramolecular ring closure and may live only a few picoseconds. Bond formation in the biradical therefore may compete effectively with internal rotations, conformational isomerizations, and even redistributions of internal energy. A potentially symmetrical intermediate may then be represented by a point or region of multidimensional space on the reaction energy surface, but full symmetrization may not be achieved. Even carbocations may display "memory effects" if the structure is appropriate for a fast *intramolecular* exit of the intermediate before symmetrization.[3c]

In the specific case of sigmatropic rearrangements, several models have been put forward to explain incomplete symmetrization in individual cases. One of these proposes a memory effect operating through competing ring-closure and conformational interconversions among biradical species.[5a] Another invokes the "principal of least motion", in which the favored pathway corresponds to the minimum change of atomic coordinates.[6] A third suggests that the choice of reaction pathway is controlled to a significant extent by dynamic effects in which trajectories favored by conservation of momentum tend to carry the atoms through the point of symmetry representing the biradical preferentially to one of several potential symmetry-related products.[7] Finally, the possibility is raised that, in some cases, biradicals themselves do not occur as discrete intermediates but rather that the products are instead controlled by competition among direct concerted reactions.[8,9]

Regardless of which of these models is closest to the truth of any individual reaction mechanism, a plausible corollary of each of them is that symmetrization should be favored by stabilization of the hypothetical symmetrical intermediate. This inference depends in turn upon another assumption, namely that the "stabilization" of the intermediate not only would lower its heat of formation relative to that of some standard reference but also would lower the barrier to its formation from the reactant and raise the barriers to its collapse to products. In other words, a structural change leading to a more "stable" intermediate might be imagined to correspond to digging a deeper hole in the energy surface. Such an assumption is merely a heuristic device, since in general there is no rigorous justification for it. Its consequences, however, are readily deduced for the case of mechanistic models based upon classical energy-surface considerations, which predict increased symmetrization under the control of conventional transition-state factors. For the case of models controlled by momentum dynamics, one expects a similar result. Qualitatively, a deeper hole should damp momentum effects by forcing the reacting molecules to spend a longer time in the hole, thereby allowing the internal energy to distribute itself into more degrees of freedom. In fact, Carpenter has confirmed this expectation by trajectory calculations designed to test the point in a model system.[7]

Nevertheless, few, if any, experimental verifications of the expected stabilization/symmetrization behavior are to be found in the literature of thermal rearrangement reactions.[6b,10,11] The dearth of such instances in the face of concordant predictions from both types of models is cause for surprise. It is not immediately obvious whether the difficulty lies with the models or the experiments. Since little previous work had been explicitly intended to study this matter, our goal became the construction of a candidate molecule for sigmatropic rearrangement that would incorporate a purposive structural modification into a substrate type already known to give incomplete symmetrization. The modification would be designed to stabilize the putative biradical intermediate and, we hoped, would lead to complete symmetrization.[1]

Scheme I

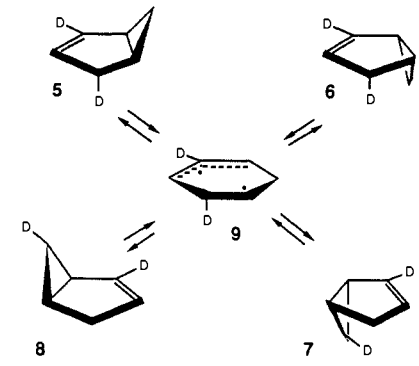
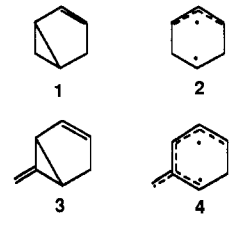


Table I. Products from the Gas-Phase Thermal Rearrangement of Bicyclo[3.1.0]hex-2-ene **5**[8]

	products, %			
reaction time, s	**5**	**6**	**7**	**8**
14.4	81.9	6.7	1.8	9.5
23.8	68.4	11.2	5.6	14.8
48.7	54.4	15.9	10.2	19.6

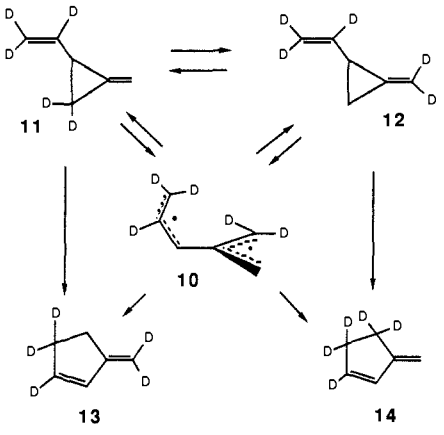
Experimental Design. The bicyclo[3.1.0]hex-2-ene system **1** had been extensively investigated and shown to rearrange by pathways that preserved asymmetry in three separate cases involving different substitution patterns,[5,8] despite the opportunity for symmetrization provided by the allylic biradical intermediate **2**. We proposed to change this structure by attachment of an



exocyclic methylene group at C-6 to give the substrate **3**, whose corresponding biradical is the vinyltrimethylenemethane (VTMM) **4**. To make a rough guess at the stabilization associated with this alteration, we note that the π-delocalization energy of the VTMM biradical **4** in the simple Hückel approximation[12] is 1.675β relative to 1,3-butadiene as a reference, whereas that of allyl radical is 0.828β relative to ethylene as a reference. Thus, the VTMM **4** benefits from π-delocalization by about 0.85β more than does the allylic biradical **2**. If the traditional "aromatic" β-value of 18 kcal/mol is appropriate to this case, the extra stabilization energy amounts to about 15 kcal/mol. An alternative estimate can be based on the assumption that the difference in endothermicities of formation of the biradicals **2** and **4** from the reactants **1** and **3**, respectively, is the same as that of the difference in endothermicities of formation of the respective transition states for rearrangement, i.e., the difference in the Arrhenius activation energies. From the E_a values for alkyl-substituted derivatives of **1**[5] and **3**, 43 and <24 kcal/mol, respectively, this difference is >19

(5) (a) Doering, W. v. E.; Schmidt, E. K. G. *Tetrahedron* **1971**, *27*, 2005. (b) Swenton, J. S.; Wexler, A. *J. Am. Chem. Soc.* **1971**, *93*, 3066.
(6) (a) Altmann, J. A.; Tee, O. S.; Yates, K. *J. Am. Chem. Soc.* **1976**, *98*, 7132. (b) See, however: Berson, J. A. In *Rearrangements in Ground and Excited States*; de Mayo, P., Ed.; Academic: New York, 1980; Essay 5. (c) Klärner, F.-G.; Yaslak, S.; Wette, M. *Chem. Ber.* **1979**, *112*, 1168. (d) Klärner, F.-G.; Brassel, B. *J. Am. Chem. Soc.* **1980**, *102*, 2469.
(7) Carpenter, B. K. *J. Am. Chem. Soc.* **1985**, *107*, 5730.
(8) Cooke, R. S.; Andrews, U. H. *J. Am. Chem. Soc.* **1974**, *96*, 2974.
(9) (a) Berson, J. A.; Salem, L. *J. Am. Chem. Soc.* **1972**, *94*, 8917. (b) Berson, J. A. *Acc. Chem. Res.* **1972**, *5*, 406.
(10) Gajewski, J. J. *Hydrocarbon Thermal Isomerizations*; Academic: New York, 1981.
(11) A converse form of this argument can be used to predict that stabilization of the *product* (be it a following intermediate or a stable species), should *shorten* the lifetime of the potentially symmetrical intermediate, and thereby permit the observation of *enhanced* preservation of asymmetry ("memory effect"). This has been verified experimentally in sequential rearrangements of carbonium ions: See inter alia: (a) Berson, J. A. ref 3c. (b) Berson, J. A.; McKenna, J. M.; Junge, H. *J. Am. Chem. Soc.* **1971**, *93*, 1296, and references cited therein. (c) Berson, J. A.; Foley, J. W. *J. Am. Chem. Soc.* **1971**, *93*, 1297, and references cited therein.
(12) Heilbronner, E.; Straub, E. *Hückel Molecular Orbitals*; Springer-Verlag: Heidelberg, 1966.

Scheme II



kcal/mol. The latter estimate includes differential strain effects in addition to π-delocalization.

That the thermal sigmatropic rearrangement of the bicyclo[3.1.0]hex-2-ene system does not use the potentially available opportunity for complete symmetrization is perhaps most clearly seen in the study by Cooke and Andrews of the pyrolysis (318 °C) of the labeled substrate **5** (Scheme I), which gives the products **6–8**.[8] Table I shows the distribution observed.

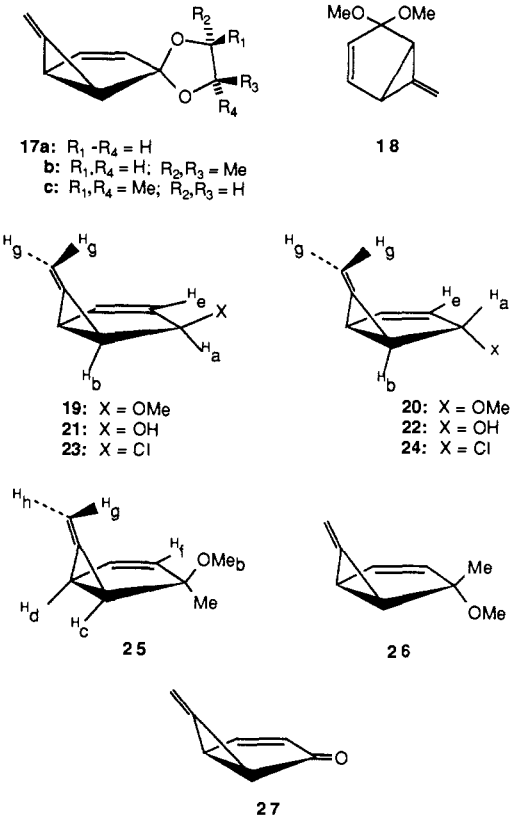
As Scheme I shows, were the symmetrical species **9** an obligatory intermediate, the three products **6–8**, each of which necessarily would be formed from it by mechanistically equivalent pathways, would appear in equal amounts (almost imperceptibly biased by a secondary isotope effect). Table I shows, however, a clear predominance of product **8**, which results from rearrangement with retention of configuration of the migrant carbon. Moreover, one cannot hypothesize that this results from a separate mechanism (**5** → **8** via some other pathway) concurrent with the one employing symmetrical intermediate **9**, since in that case products **6** and **7** should have been formed in equal amounts, whereas Table I shows that the amount of **6** clearly exceeds that of **7**.

Of the several cases in which VTMM intermediates have been considered in the rearrangements of vinylmethylenecyclopropanes,[13] the one most relevant to the symmetrization issues under consideration here is that of the deuteriated compound **11** (Scheme II) studied by Gilbert and Higley.[14] These authors showed that the thermal rearrangement of **11** led to the methylenecyclopentenes **13** and **14** in approximately equal amounts, a result that is consistent with an intermediate having the (static or time-averaged) symmetry of the VTMM biradical **10**. (Note that **10** in this context would consist of two mutually orthogonal allylic radicals joined at C-2 of one and C-1 of the other.) Unfortunately, as Gilbert and Higley recognized, **10** is not an obligatory sole intermediate, because the starting material **11** undergoes a deuterium-scrambling process (interconversion with **12** by a methylenecyclopropane rearrangement) in competition with the vinylcyclopropane rearrangement to **13** and **14**. Thus, a substantial fraction of the label scrambling in the latter two rearranged products is attributable to a reaction that may be independent of the vinylcyclopropane rearrangement itself. Of course, it may be that the **11–12** scrambling and the vinylcyclopropane rearrangement both occur through the common intermediate **10** (see Scheme II), but this has not been established.

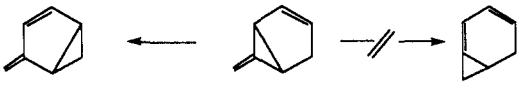
Modification of the substrate structure by incorporation of the VTMM unit into a ring, as in **4**, seemed to promise a means of avoiding the methylenecyclopropane rearrangement of the type that had led to the scrambling observed in the case of **11**, since the strain energy of the product would make the corresponding process **3** → **15** sharply uphill. Paradoxically, a disadvantage of this proposal is the extreme facility with which hydrocarbons of the 6-methylenebicyclo[3.1.0]hex-2-ene series, e.g. **3**, undergo the

(13) Review: Berson, J. A. in ref 6b.
(14) Gilbert, J. C.; Higley, D. P. *Tetrahedron Lett.* **1973**, 2075.

Chart I



desired vinylcyclopropane rearrangement to those of the 2-methylenebicyclo[3.1.0]hex-3-ene series, e.g. **16**.[15,16]



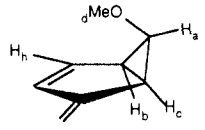
In fact, to our knowledge, the parent hydrocarbon has never been prepared as a persistent material. To facilitate the kinetic characterization of the system, we chose to work with bicyclo[3.1.0]hex-2-ene derivatives bearing oxygen substituents at C-4. Substances of this class have been prepared[17,18] and are reasonably stable at room temperature. The temperature dependence of the rate of the 1,3-sigmatropic rearrangement of the ethylene ketal **17a** (Chart I),[18,19] for example, gives the Arrhenius parameters E_a = 27.7 kcal/mol and log A = 12.1 (A in s^{-1}), which correspond to a half-life of about 90 min at 105 °C. We now have studied the stereochemistry of the rearrangement of **17a** and several closely related derivatives: the diastereomeric pair of butanediol ketals **17b** and **17c**, the dimethyl ketal **18**, and the epimeric pairs of secondary (**19** and **20**) and tertiary (**25** and **26**) methyl ethers. The experimental design includes the (testable) assumption that the rotational conformation of the substituents at C-4 will not be a factor in preserving asymmetry of the intermediate. For didactic reasons, we describe the results for the secondary ethers (**19** and **20**) first. We also have made a brief examination of the pyrolysis chemistry of the two chlorides, **23** and **24**.

Synthesis of Methyl Ethers 19 and 20. Reduction of ketone **27**[17a,18] with diisobutylaluminum hydride, as expected,[20,21] is both

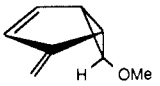
(15) See, especially: Newman, M. S.; Vander Zwan, M. S. *J. Org. Chem.* **1974**, *39*, 761.
(16) See also: Rey, M.; Huber, U. A.; Dreiding, A. S. *Tetrahedron Lett.* **1973**, 4403.
(17) (a) Rule, M.; Matlin, A. R.; Dougherty, D. A.; Hilinski, E. F.; Berson, J. A. *J. Am. Chem. Soc.* **1979**, *101*, 5098. (b) Seeger, D. E.; Hilinski, E. F.; Berson, J. A. *Ibid.* **1981**, *101*, 720.
(18) Rule, M.; Matlin, A. R.; Seeger, D. E.; Hilinski, E. F.; Dougherty, D. A.; Berson, J. A. *Tetrahedron* **1982**, *38*, 787.
(19) Matlin, A. R.; Ph.D. Thesis, Yale University, New Haven, CT, 198..

regiospecific and stereospecific. The major product is the endo alcohol **21**, which is formed in a 13:1 mixture with the epimeric exo isomer **22** in 78% yield. Methylation (NaH/MeI) of this material followed by preparative gas chromatography (GC) gave the *endo*-methyl ether **19**, >99% pure. The stereochemical assignment was anticipated by analogy to the results of reductions of model bicyclic enones[21] and was confirmed by ^{1}H NMR spectroscopy, with coupling analysis and nuclear Overhauser effects, as is described in the Experimental Section.

Entry into the exo series was effected by Luche reduction[22] ($NaBH_4/CeCl_3$) of ketone **27**, which gave a slight preference (1.2–1.5:1) for the exo alcohol **22**. Mild acid-catalyzed stereoequilibration (5% H_2SO_4, 30 min) of such a mixture followed by methylation and preparative GC gave the *exo*-methyl ether **20**, almost free of the endo isomer **19** but containing 10–20% of the cyclopropyl methyl ether rearrangement products **28** and **29**.



28



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Rearrangement of either the *endo*- or the *exo*-methyl ether, 19 or 20, in benzene-d_6 gave predominantly the *endo*-cyclopropyl methyl ether **28**, together with small amounts of the exo isomer **29**. The rates were monitored by ^{1}H NMR spectroscopy over a range of temperatures, from which data the Arrhenius equations (1) and (2) were derived.

$$k'_{19} = 10^{13.3} \exp(-26600\ (\text{cal/mol})/2.303RT) \quad (1)$$

$$k'_{20} = 10^{13.4} \exp(-24700\ (\text{cal/mol})/2.303RT) \quad (2)$$

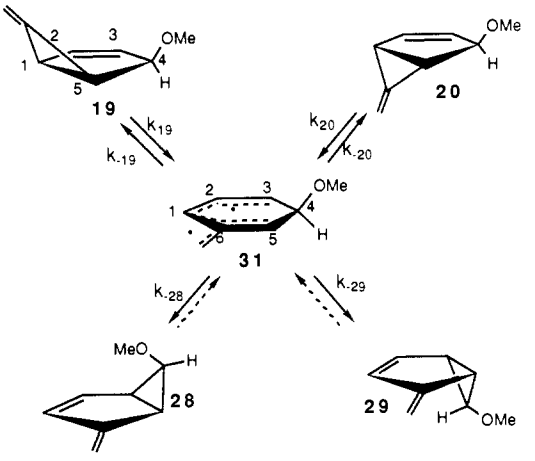
The cumulative effect of oxygen substitution at C-4 in slowing the rearrangement can be seen from the relative rates of the series hydrocarbon **16**, *exo*-methyl ether **20**, *endo*-methyl ether **19**, dimethyl ketal **18** (see below), and ethylene ketal **17a**, which have the values very fast, 1589, 79, 1.7, and 1. Since the substitution is not at the bridgehead, which is the site of the carbon–carbon bond that is broken in the rearrangement, these effects are remarkable. We defer a discussion of their possible causes.

Although the activation energies of the two methyl ethers do not differ greatly, the practical consequences for handling the isomers may be appreciated from the rate ratio at 70 °C, k'_{20}/k'_{19} = 20. Thus, the rate of rearrangement of the 6-methylenebicyclo[3.1.0]hex-2-enyl system depends strongly not only on the number of C-4 oxygens but also on the configuration at that site.

Moreover, the rearrangement is highly stereoselective, as has been mentioned. For example, exhaustive pyrolysis of either *endo*- or *exo*-methyl ether, **19** or **20**, in benzene-d_6 at 54 °C gave the rearranged cyclopropyl methyl ethers *endo*-**28** and *exo*-**29** in a ratio of 97:3, as determined by ^{1}H NMR spectroscopy and GC analysis. This ratio changed only slightly, to 95:5, in a pyrolysis of **19** carried out at 100–140 °C. Stereochemical assignments to **28** and **29** were made by NMR experiments described in the Experimental Section.

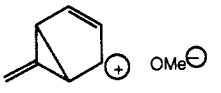
The formation of the same products in identical ratios from the two epimeric ethers could in principle signify a common intermediate (see Scheme III) or, alternatively, interconversion of the products or starting materials under the reaction conditions. Control experiments showed that the rearrangement products **28** and **29** did not interconvert. Similarly, no conversion of starting exo substrate **20** to its endo isomer **19** (for example, by double epimerization at the bridgehead positions) could be observed during any of the runs. It is less easy to demonstrate that the reaction in the opposite direction, i.e., of endo starting ether **19** to exo ether **20**, is absent, since the rearrangement of **20** is so fast

Scheme III



that it would not have accumulated. Nevertheless, it seems likely, by analogy to the cases of the ketals **17a–c** and **18**, that **19** → **20** is not an important reaction and that the reason for the formation of the same products in exactly the same ratios from the two epimeric ethers is the intervention of a common intermediate.

The requirements on the structure of the intermediate imposed by the experiments described so far would be met by an ion pair, e.g. **30**, hypothetically derived from either substrate. However,



30

although the starting structure would be heterolytically active, conceivably even in so poor an ionizing medium as benzene, the ion-pair mechanism is rendered highly unlikely by the observation that the rearrangements of **19** and **20** proceed smoothly in solvent CD_3OH, without incorporation of any deuterium in the rearrangement product.

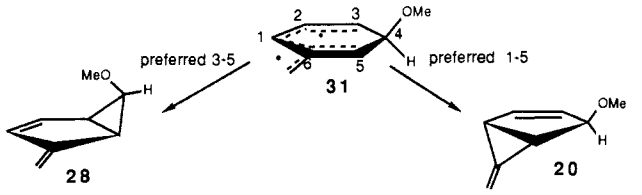
Instead, the results all point to the intervention of the vinyltrimethylenemethane biradical **31** as the common intermediate (Scheme III), free of conformational memory or dynamical constraints. An alternative hypothesis of two pairs of competitive pathways, **19** → **28** + **29** and **20** → **28** + **29**, without a common intermediate, is less satisfactory, since it would imply identical competition ratios in processes with entirely different geometric requirements for reactive atomic motions.

The ring-closure reaction of the biradical intermediate **31** is remarkably stereoselective. This is immediately obvious for the product-determining step, in which closure occurs at positions C-3 and C-5 (6-methylenebicyclo[3.1.0]hex-2-ene numbering), forming the *endo*-cyclopropyl methyl ether **28** with a preference, k_{-28}/k_{-29}, of about 21-fold over the exo isomer **29** at 100 °C. Moreover, although the ratio k_{-20}/k_{-19} of recyclization of **31** to the 6-methylenebicyclo[3.1.0]hex-2-ene structures, **20** and **19**, is not directly available because the reaction was not observed, it may, nevertheless, be deduced from the data. Thus, it is easy to show that, for the mechanism of Scheme III, the mechanistic ratio of rate constants, k_{20}/k_{19}, for formation of the intermediate **31** is equal to the phenomenological ratio of rate constants for the rearrangements, k'_{20}/k'_{19}. From the data already given, this ratio has the value 16 at 100 °C. The acid-catalyzed equilibration of the alcohols showed that the exo isomer **22** is more stable than the endo isomer **21**. On the reasonable assumption that the same relationship would apply to the corresponding ethers **20** and **19**, microscopic reversibility then would require that the ring-closure rates be in the ratio $k_{-20}/k_{-19} > 16$ (see Figure 1).

The stereoselectivities of the ring closures of the biradical **31** may be summarized as follows.

Thus, closure at C-1–C-5 to reconstitute the 6-methylenebicyclo[3.1.0]hex-2-ene structure prefers to place the methoxy group exo (**20**), whereas closure at C-3–C-5 to give the cyclopropyl methyl ether prefers to place it endo (**28**). The effects are sub-

(20) Cf. inter alia: Wilson, K. E.; Seidner, R. T.; Masamune, S. *J. Chem. Soc. D* **1970**, 213.
(21) Cf. inter alia: South, M. S.; Liebeskind, L. S. *J. Org. Chem.* **1982**, *47*, 3815.
(22) Luche, J.-L. *J. Am. Chem. Soc.* **1978**, *100*, 226.



stantial in both cases. At present, qualitative rationalizations of this peculiar behavior must be considered speculative, but we hope that the result, as well as the (probably related) rearrangement rate effects described above, will stimulate quantum computational activity.

Rearrangement of the Tertiary Methyl Ether 25. To investigate the possible role of steric effects on these rearrangements, we have prepared the tertiary methyl ether **25** via the alcohol **33** by the sequence shown in Scheme IV. The reaction of ketone **27** with methyllithium is highly stereoselective for exo attack, giving the *endo*-hydroxy compound **33**. In the analogous secondary case, acid-catalyzed epimerization served to convert the *endo*-hydroxy isomer **21** to the exo compound **22**, but this reaction failed in the tertiary case, where the only identified product was the allylic isomer **35** instead of the desired tertiary *exo*-methoxy epimer **34**. With only one of the tertiary ethers available, a test for a common intermediate by the method used in the secondary series was infeasible, but the study of **25** itself nevertheless afforded some useful information.

Thermal 1,3-sigmatropic rearrangement of the tertiary *endo*-methoxy compound **25** in benzene-d_6 proceeded smoothly to give the homofulvene tertiary methyl ethers **36** and **37**. The *endo*-methoxy isomer dominated the product mixture: At 59 and 100–129 °C, the product distributions **36**/**37** were 97:3 and 96:4, respectively, closely matching the results in the secondary case. Moreover, the Arrhenius parameters, E_a = 26.8 kcal/mol and log A (in s^{-1}) = 13.6, observed for **25** are identical within experimental error to those observed for the secondary *endo*-methoxy compound **19**. The most reasonable interpretation of the product and rate data is that the extra methyl group in the tertiary system does not change the mechanism of the rearrangement; that is, it is likely that a vinyltrimethylenemethane biradical **38**, analogous to **31**, is an intermediate in the rearrangement of tertiary ether **25** (Scheme V).

If this is true, it also must be true that the observed endo stereoselectivity in the ring closure at C-3–C-5 of the biradical **31** in the secondary series (Scheme III) is not a consequence of simple steric bulk of the methoxy group. Had a steric repulsion between *exo*-OMe and some other part of the molecule been the determining factor there, one would have expected the methyl group in the tertiary system **25** to have perturbed the product distribution in the direction of *exo*-methoxy product **37**, since the steric effect of methyl is greater than that of methoxy. Moreover, the same kind of argument can be invoked to support the suggestion that the 20-fold advantage in rearrangement rate enjoyed by the *exo*-methyl ether **20** over its endo isomer **19** in the secondary series is not primarily of steric origin.

Rearrangements of the Diastereomeric 2,3-Butanediol Ketals 17b–c. The optically active diastereomeric pair of ketals **17b** and **17c** had been prepared previously by Matlin[18,19] in a synthetic sequence employing (2*R*,3*R*)-(−)-2,3-butanediol. Although the application of these diastereomers to the present problem in principle could have used racemic materials, the racemic 2,3-butanediol samples available to us invariably contained enough of the meso isomer to introduce a significant contaminant into the derived ketals. Scheme VI is formulated with the now anticipated common intermediate biradical **39**. Like the previously postulated species **31** and **38**, biradical **39** is formally quasi-symmetric rather than fully symmetric, but its departure from true symmetry is of a subtle kind that depends only upon a syn or anti relationship of two remote groups, $=CH_2$ and CH_3. This should impose at most a very small selectivity on the stereochemistry of the ring closure to the potential rearrangement products **40** and **41**.

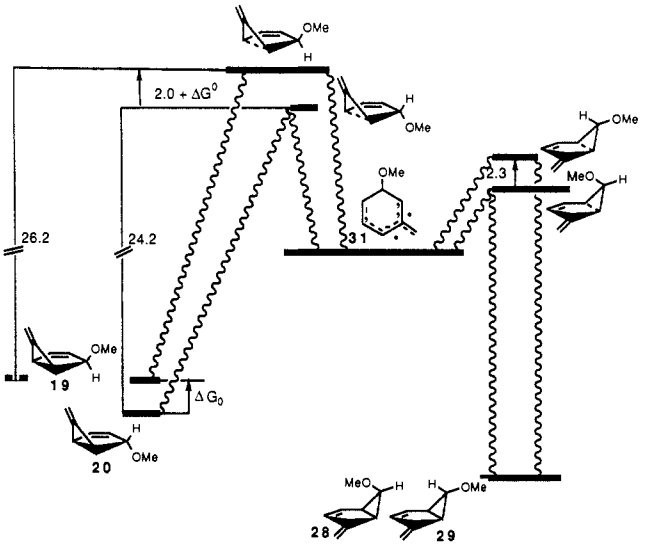
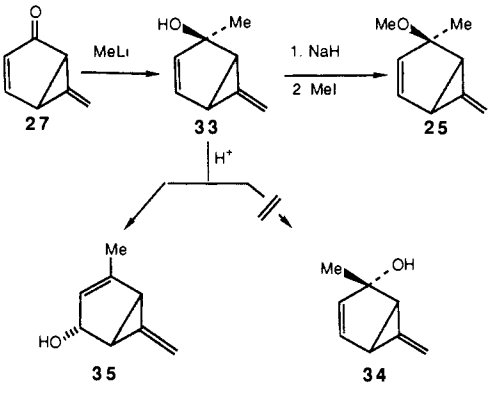
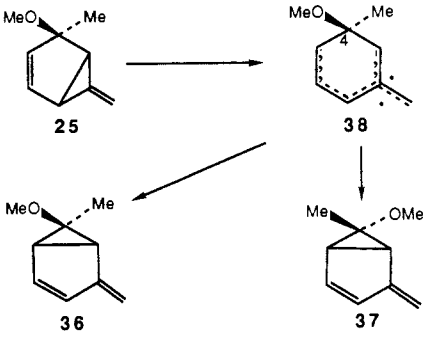


Figure 1. Free energy surface for the rearrangements of the methyl ethers **19** and **20**. The structural formulas are shown in boldface numerals. Energies in kilocalories per mole are shown in plain type. It is assumed arbitrarily that the cyclopropyl methyl ethers **28** and **29** are equienergetic. The reaction pathways are shown in wiggly lines.

Scheme IV



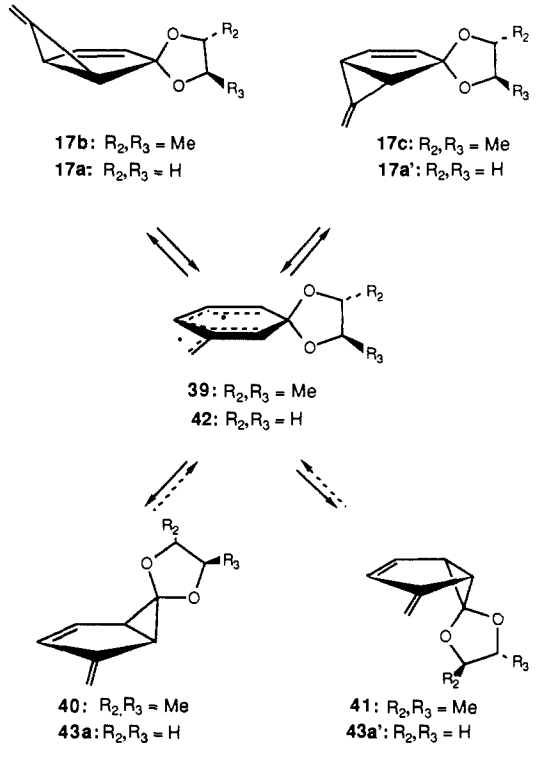
Scheme V



Pyrolysis of benzene-d_6 solutions of three different mixtures of **17b** and **17c** gave mixtures of **40** and **41** in identical ratios, which also approached the expected 1:1 value closely (^{1}H NMR analysis). These results are those anticipated from the mechanism involving the quasi-symmetric intermediate **39** of Scheme VI.

Rearrangements of the Ethylene and Dimethyl Ketals 17a and 18. A much more sensitive mechanistic test is provided by the ethylene ketal **17a**, whose rearrangement could pass through the truly symmetrical vinyltrimethylenemethane biradical **42** (Scheme VI). Confirming earlier work,[18,19] we found that, in the racemic series, pyrolysis of **17a** in benzene-d_6 for 3–4 half-lives of conversion at various temperatures between 80–120 °C gave the cyclopropanone ketal **43a–43a′** (racemic mixture) as the only product, with near-quantitative material balance (^{1}H NMR analysis). Longer heating caused the formation of unknown

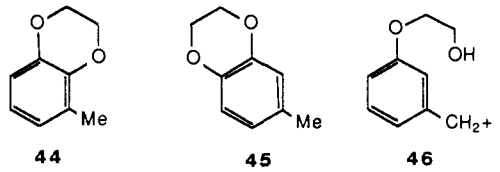
Scheme VI



(presumably polymeric) products.

A similar rearrangement was observed to occur in $CDCl_3$ solvent at almost the same rate as the one in benzene-d_6: At 87.8 °C, k_{CDCl_3} and $k_{benzene}$ had the values 1.59×10^{-5} and 2.14×10^{-5} s^{-1}, respectively, the latter value being extrapolated from the kinetic data of Matlin.[19]

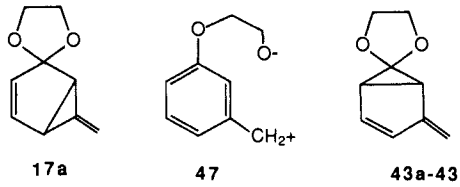
Again, the cyclopropanone ketal **43a–43a'** was the only product detected after 1 half-life, but prolonged heating afforded not only some polymeric material but also small amounts (5–10%) of additional product(s) with sharp NMR resonances in the aromatic region. These minor products were not observed in benzene-d_6. They could not be isolated by preparative GC directly from the reaction mixture, but after hydrogenation to reduce the diene **43a–43a'**, about 5% yield of a product was isolated whose ^1H NMR spectrum was consistent with that of one of the dioxanes **44** or **45**.



44 **45** **46**

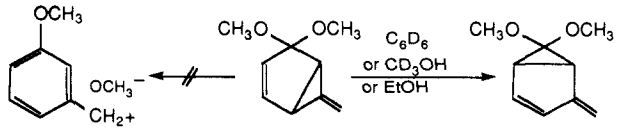
One of several conceivable mechanisms for the formation of a dioxolane in $CDCl_3$ would be initiated by an adventitious acidic impurity in the solvent. Protonation of the substrate **17a** could lead to the benzyl cation intermediate **46**, which by unexceptional steps, could give **44** or **45**.

One might entertain the idea that rearrangement **17a** → **43a–43a'** could occur by a variant of this mechanism, via the zwitterion **47**, by cyclization at the ether ipso position.



17a **47** **43a-43a' enantiomers**

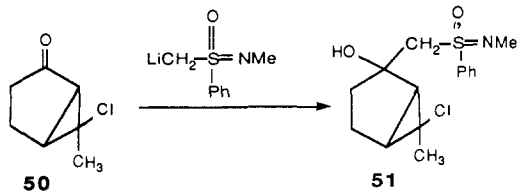
However, the study of a model compound makes this an implausible hypothesis. Thus, the dimethyl ketal **18** rearranges in the usual way in benzene-d_6 to the cyclopropanone dimethyl ketal **48**. The same rearrangement occurs in CD_3OH or EtOH solvent, without significant incorporation of solvent into the ketal function as CD_3O or EtO groups. The ion-pair **49**, corresponding to the hypothetical zwitterion **47** in the cyclic ketal case, would have assured massive incursion of OCD_3 or OEt residues.



49 **18** **48**

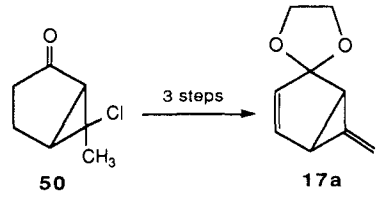
For the detection of the now anticipated symmetrical intermediate **42**, we proposed to study the rearrangement of optically active ethylene ketal **17a** (Scheme VI). If the rearrangement pathway were required to pass through **42**, the product would be racemic, that is, a 1:1 mixture of **43a** and **43a'**. Moreover, to the extent that **42** returns to **17a** and **17a'**, the starting material may racemize during the rearrangement. The sensitivity of the experiment depends upon the analysis of the relative enantiomeric purities of the starting material and product.

Optical activation of a precursor of the ketal **17a** was effected by the general sulfoximine-mediated resolution method of Johnson,[23a,b] using (+)-(*S*)-*N*,*S*-dimethyl-*S*-phenylsulfoximine. The lithium salt of this reagent reacted with the mixture of methyl chloro ketones **50**[18,19] to give a diastereomeric mixture of four hydroxy sulfoximines **51**.



50 **51**

Separation of the two major diastereomers of **51** by column chromatography, followed by vacuum pyrolysis of each regenerated enantiomerically enriched samples of **50**, which then were processed through the steps of ethylene ketalization, bromination, and double dehydrohalogenation to give the enantiomers **17a** and **17a'**.



50 **17a**

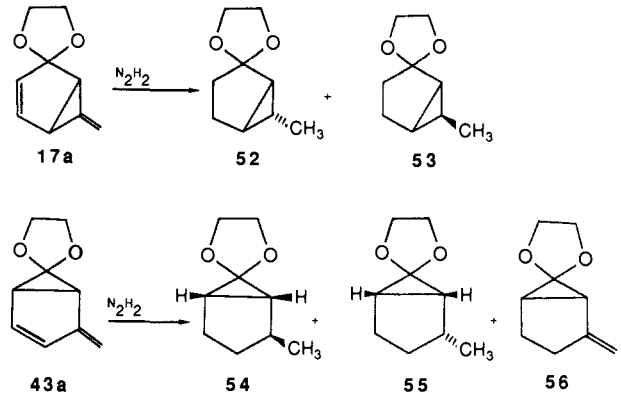
Using the chiral lanthanide shift reagent $Eu(hfc)_3$,[24] we found that a sample of **17a**, $[\alpha]_{365} = -1176°$, had an enantiomeric excess (ee) of 66 ± 2%, whereas a sample of $[\alpha]_{365} = +1436°$ had an ee of 78 ± 2%. These data correspond to rotations of −1782° and +1831° for the enantiomerically pure compounds, values that agree to within 3%.

Because the rearrangement product, the cyclopropanone ketal **43a–43a'**, polymerized with extreme ease, it was not practical to separate it from unreacted starting material **17a** for a direct determination of enantiomeric purity. On the subsequently verified assumption that reduction of the total reaction mixture would lead to separable derivatives of the reactant and product, we studied such transformations in the racemic series. Catalytic (EtOAc solvent, PtO_2, Pd/C, $Pd/BaSO_4$, or Rh/Al_2O_3 catalyst) hydrogenation, especially of **43a–43a'**, proceeded abnormally,[25] but

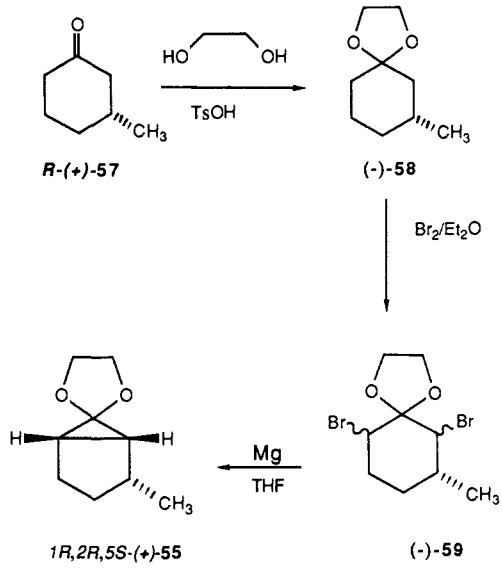
(23) (a) Johnson, C. R.; Zeller, J. R. *J. Am. Chem. Soc.* **1982**, *104*, 4021. (b) *Tetrahedron* **1984**, *40*, 1225, and references cited therein. (c) Optical activation of **27** by GC separation of the optically active 2,3-butanediol ketals of the precursor **50** has been achieved previously,[18,19] but the yields are too low to be of practical value in the present studies.

(24) For a review, see: Sullivan, G. R. *Top. Stereochem.* **1978**, *10*, 287.

Scheme VII



Scheme VIII



diimide reduction of the two ketals gave useful results. The reactant **17a** gave nearly equal amounts of the saturated bicyclic ketals **52** and **53**, whereas the rearrangement product **43a** gave, in addition to both saturated materials **54** and **55** in 1.2:1 ratio, about 10–20% of the partially hydrogenated compound **56** (Scheme VII).

A standard of enantiomeric purity for the rearrangement product **43a** was established by independent synthesis of one of its diimide reduction products, the endo epimer **55**, from (+)-(*R*)-3-methylcyclohexanone (**57**), whose absolute configuration and maximum rotation are known.[25] These transformations are modeled upon a known[26] bicyclo[3.1.0]hexane synthesis by transannular elimination and are depicted in Scheme VIII.

The dibromo ketal **59**, although of uncertain configuration at the bromine-substituted positions, was crystalline and diastereomerically homogeneous by ^1H and ^{13}C NMR spectroscopy. The ring closure was highly stereospecific for the endo product **55** and afforded only a trace of the *exo*-methyl epimer **54**, which could be removed by double-pass preparative GC. In this way, enantiomerically pure (+)-(1*R*,2*R*,5*S*)-**55**, $[\alpha]_{365} = +219°$, was obtained from commercially available (+)-(*R*)-**57** of 100% ee.

Thermal rearrangement of optically active **17a**, $[\alpha]_{365} = -1176°$ (66 ± 2% ee), 0.05 M in benzene solution, was allowed to proceed at 88.1 °C for 24.33 h, after which time conversion to **43a–43a'** had reached 78%. The pyrolysate was subjected to diimide reduction as described for the racemic series, and the reduction products were separated by preparative GC. The first three emergent products were **55**, **54**, and **53**. Their optical rotations were determined at five wavelengths and corrected for small amounts of cross-contamination. The results given here pertain to rotations measured at the 365-nm Hg line, but similar conclusions follow from the other data (see the Experimental Section).

Since enantiomerically pure **55** has $[\alpha]_{365} = 219°$, the maximum specific rotation of **55** obtained from reduction of rearrangement product **43a–43a'** in the present experiment, which starts at the level of 66% ee, is 0.66 × 219 = 145°. The observed value for the specific rotation of **55** was −0.13°, with a probable error of ±1°. The rearrangement of **17a** to **43a–43a'** thus occurs with loss of more than 99% of enantiomeric purity. Within experimental error, this result conforms to the behavior expected to the mechanism of Scheme VI, in which all of the rearrangement is funneled through the symmetrical intermediate **42**.

If the formation of the achiral intermediate **42** from starting material **17a** is reversible, some racemization of the remaining **17a** should be observed. The reduction product **53** contains this information. When prepared from starting material **17a** of 66% ee, **53** showed $[\alpha]_{365} = -62.8°$, whereas the sample of **53** obtained from the rearrangement mixture showed $[\alpha]_{365} = -55.7°$. We believe that the implied 12% diminution in ee of the recovered **17a** probably is real. If it is interpreted as the result of return of the biradical **42** to **17a** (Scheme V) and if the reaction **43a–43a'** → **42** is irreversible, which would be consistent with our experimental observation of overall unidirectionality of **17a** to **43a–43a'**, then the partitioning of the intermediate **42** is simply given by the ratio % rearrangement of **17a**/% racemization of **17a** = 78/12 = 6.5/1. Thus interpreted, the data indicate that biradical **42** closes to the cyclopropanone ketal rearrangement product **43a–43a'** faster than it does to the methylenecyclopropane **17a**, which would simply correspond to more rapid formation of the more stable cyclization product from the intermediate.

The partial racemization of **17a** corresponds to inversion of configuration at both bridgehead positions. This reaction is at least formally (and perhaps mechanistically) similar to the reaction **5** → **6** (Scheme I), which produces an amount of **6** in excess of that predicted by the hypothetical symmetrical intermediate in the experiment of Cooke and Andrews[8] (Table I). At present, there is no direct evidence that rules out an alternative interpretation that would invoke a separate dynamically controlled momentum-conserving pathway for *enantiomerization* of **17a**, in which some of the molecules of **17a** manage to avoid the funnel leading to the symmetrical intermediate **42**. Note, however, that no such momentum effects can be at work in the *rearrangement* mechanism, where symmetrization of the product **43a–43a'** is complete. Scheme VI, therefore, can be considered as the mechanistic hypothesis of minimum complexity needed to explain all of the experimental results. In particular, the preference for rearrangement with retention of configuration of the migrant carbon seen in other bicyclo[3.1.0]hex-2-ene rearrangements[5a,8] has been obliterated in the rearrangement of the 6-methylenebicyclo[3.1.0]hex-2-enes of the present work, as we had hoped. Apparently, the change to a vinyltrimethylenemethane structure deepens the energy well containing the symmetrical intermediate sufficiently to compel all the rearrangement trajectories to pass through it.

Table II. Columns for Gas Chromatography

column	description
A	15 ft × 1/4 in. 5% OV-101[a]
B	2 ft × 1/4 in. 5% OV-101[a]
C	3 ft × 1/4 in. 5% OV-101[a]
D	8 ft × 1/4 in. 2% Carbowax 20M[b]
E	15 ft × 1/4 in. 15% Carbowax 20M[a]
F	3 ft × 1/4 in. 15% Carbowax 20M[a]
G	3 ft × 1/8 in. 15% Carbowax 20M[c]
H	12 ft × 1/8 in. 15% Carbowax 20M[b]

[a] On Anakrom ABS 100/120 mesh. [b] On Chromasorb P AW/DCMS 80/100 mesh. [c] On Chromasorb W/DCMS 100/120 mesh.

Experimental Section

Procedures, reagents, kinetic data, and instrumental details are described in ref 25, pp 160 ff. Columns for GC are listed in Table II.

(25) Cf.: Pikulin, S. Ph.D. Thesis, Yale University, New Haven, CT, 1986; pp 84 ff.

(26) Garbisch, E. W., Jr. *J. Org. Chem.* **1965**, *30*, 2109.

Chromatographic conditions are reported in the following order: oven temperature, injector temperature, detector temperature, and retention time. Reaction temperatures for pyrolysis were held to ±1° (0.1° in the kinetic runs) except where otherwise noted. GC/mass spectral (GC/MS) data are reported in the following order: initial column temperature (°C), time at initial temperature (min), temperature program rate (°C/min), final temperature, and retention time (min). Mass spectral data are reported as follows: *m/e*, relative abundance, and fragment lost from parent ion. Methane was used as the reactant gas in the chemical ionization mode MS.

2-*endo*- and 2-*exo*-Hydroxy-6-methylenebicyclo[3.1.0]hex-3-ene (21 and 22). Method A (DIBAL-H Reduction).[20] A solution of 2.0 g (18.9 mmol) of 6-methylenebicyclo[3.1.0]hex-3-en-2-one (**27**)[17-19] in dry pentane (200 mL) was prepared in a 500-mL round-bottomed flask equipped with a stir bar, pressure-equalized addition funnel, and N_2 inlet. The solution was stirred and cooled to −10 °C with an ice/salt/water bath. Diisobutylaluminum hydride (1.0 M, 25 mL, 25 mmol) in hexanes was added dropwise via the addition funnel while the reaction temperature was maintained between −5 and 0 °C. After the addition was complete (40–60 min), the reaction mixture was stirred for 1 h at 0 °C and then quenched with 150 mL of 20% sodium potassium tartrate. The two-phase mixture was filtered, the layers were separated, and the aqueous layer was extracted with ether (1 × 50 mL). The combined organic layer were washed with H_2O (2 × 25 mL) and with brine (1 × 50 mL). The organic phase was dried over Na_2SO_4 and filtered, and the solvent was removed in vacuo. The residue was distilled in vacuo to give 1.60 g (78%) of **21** and **22**, bp 30 °C (0.25 mmHg), as a 13:1 endo/exo mixture by ^1H NMR. This material, which invariably contained isobutanol contaminant, was unstable at room temperature but could be stored indefinitely at −20 °C with only minimal decomposition.

Method B (Luche Reduction).[22] In a 125-mL Erlenmeyer flask equipped with a stir bar was placed 1.0 g (9.4 mmol) of **27** and a solution of cerium trichloride heptahydrate (3.6 g, 9.7 mmol) in 25 mL of methanol. With stirring, 400 mg (10.6 mmol) of sodium borohydride was added slowly over a 5-min period. During this addition vigorous hydrogen evolution was observed. The mixture was stirred for 15 min, and then 75 mL of H_2O was added. The solution was filtered and extracted with ether (2 × 50 mL). The combined extracts were washed with H_2O (1 × 25 mL) and brine (1 × 25 mL). The organic phase was dried over Na_2SO_4 and filtered, and the solvent was removed in vacuo. The residue was distilled in vacuo to give 800 mg (79%) of **21** and **22** as a 1.5:1 exo/endo mixture by ^1H NMR. Repetition of this procedure at 0 °C afforded **21** and **22** as a 1.2:1 endo/exo mixture.

^1H NMR (250 MHz, $CDCl_3$): (endo alcohol **21**) δ 5.95 (dd, 1 H, C-4 proton), 5.36 (m, 4 H, C-2, C-3, and C-7 protons), 2.38 (m, 2 H, bridgehead methines), 1.7 (br s, 1 H, OH); (exo alcohol **22**) δ 6.16 (m, 1 H, C-4 proton), 5.63 (m, 1 H, C-3 proton), 5.12 (partially resolved t, 1 H, C-7 proton), 5.06 (t, 1 H, C-7 proton), 4.50 (br unresolved m, 1 H, C-2 proton), 2.56 (m, 1 H, C-1 or C-5 proton), 2.32 (m, 1 H, C-5 or C-1 proton), 1.7 (br s, 1 H, OH).

^{13}C NMR (62.9 MHz, $CDCl_3$): (**21**) δ 140.1 (s, C-6), 134.9 (d, C-3 or C-4), 132.4 (d, C-4 or C-3), 101.3 (t, C-7), 81.0 (d, C-2), 28.1 (d, C-1 or C-5), 22.7 (d, C-4 or C-3); (**22**) δ 139.1 (s, C-6), 136.3 (d, C-3 or C-4), 130.5 (d, C-4 or C-3), 98.8 (t, C-7), 78.2 (d, C-2), 30.0 (d, C-1 or C-5), 27.3 (d, C-5 or C-1).

GC/MS (50, 1, 20, 200, 2.00) **21** + **22**: *m/e* 108 (17%, M), 107 (9%, −H), 80 (46%, $-C_2H_4$ or CO), 79 (100%, −CHO), 78 (15%, $-CH_2O$), 77 (68%, $-CH_3O$).

IR (neat) **21** + **22**: 3400 cm^{-1}.

2-*exo*-Hydroxy-6-methylenebicyclo[3.1.0]hex-3-ene (22). A solution of **21** and **22** (1.0 g, exo/endo ratio 1.5:1) in 100 mL of diethyl ether was treated with 100 mL of 5% H_2SO_4, and the mixture was stirred at room temperature. The reaction was monitored by ^1H NMR until complete disappearance of **21** (about 30 min). The layers were then separated, and the aqueous layer was extracted with ether (1 × 50 mL). The combined organic layers were washed successively with saturated $NaHCO_3$ and brine and dried over Na_2SO_4, and the solvent was removed in vacuo. The residue was distilled in vacuo to give 502 mg (50%) of **22**, bp 30 °C (0.25 mmHg), which by ^1H NMR spectroscopy contained several aldehydic impurities. The material was sufficiently pure for conversion to *exo*-methyl ether **20**.

2-*endo*-Methoxy-6-methylenebicyclo[3.1.0]hex-3-ene (*endo*-Methyl Ether 19). In a 15-mL round-bottomed flask equipped with a stir bar was placed 400 mg (8.33 mmol) of a 50% sodium hydride dispersion. This was washed successively with dry pentane (3 × 5 mL) and THF (1 × 5 mL). About 3 mL of THF was added, and the flask was fitted with a serum cap/N_2 inlet. The mixture was stirred and cooled to −15 °C with an ice/salt/water bath. Freshly distilled **21** (Method A, 600 mg, 5.56 mmol) in THF (2 mL) was added slowly to the flask via syringe over a 10-min period. After H_2 evolution ceased, the rusty brown suspension was stirred an additional 15 min. Freshly distilled iodomethane (7.9 g, 56 mmol) was then added gradually via syringe over a 20-min period. The mixture was stirred an additional 15 min at −15 °C and then filtered through a coarse sintered-glass funnel. The solution was refiltered, if necessary, and the solvent was removed in vacuo. The dark residual oil was passed through a short silica gel column (CH_2Cl_2 eluant) to remove colored impurities. Removal of the solvent in vacuo gave 624 mg (92%) of **19**. As needed for characterization and pyrolyses, this material was further purified by GC on column C (45, 70, 70, 8.6).

^1H NMR (250 MHz, $CDCl_3$): δ 5.98 (ddd, 1 H, C-4 proton), 5.38 (m, 2 H, C-3 and C-7 protons), 5.29 (s, 1 H, C-7 proton), 5.04 (d, 1 H, $J_{1,2}$ = 6.8 Hz, C-2 proton), 3.43 (s, 3 H, CH_3), 2.43 (m, 1 H, C-5 proton), 2.22 (m, 1 H, $J_{1,2} = J_{1,5}$ = 6.8 Hz, C-1 proton). ^1H NMR (500 MHz, C_6D_6): 5.68 (ddd, 1 H, C-4 proton), 5.35 (m, 3 H, C-3 and C-7 protons), 4.84 (d, 1 H, C-2 proton), 3.18 (s, 3 H, CH_3), 2.16 (m, 1 H, C-5 proton), 1.93 (m, 1 H, C-1 proton).

^{13}C NMR (62.9 MHz, $CDCl_3$): δ 139.0 (s, C-6), 135.1 (d, C-3 or C-4), 129.7 (d, C-4 or C-3), 101.1 (t, C-7), 89.3 (d, C-2), 57.8 (q, CH_3), 28.2 (d, C-1 or C-5), 19.7 (d, C-5 or C-1).

GC/MS (60, 1, 15, 200, 1.7): *m/e* 122 (47%, M), 121 (61%, −H), 107 (15%, $-CH_3$), 92 (19%, $-CH_2O$), 91 (86%, $-CH_3O$), 79 (42%, $-C_2H_3O$), 78 (21%, $-C_2H_4O$), 77 (100%, $-C_2H_5O$).

Anal. Calcd for $C_8H_{10}O$: C, 78.65; H, 8.25. Found: C, 78.50; H, 8.24.

2-*exo*-Methoxy-6-methylenebicyclo[3.1.0]hex-3-ene (*exo*-Methyl Ether 20). This compound was prepared with the procedure described for **19** except that exo alcohol **22** was used in lieu of **21**; yield 404 mg (60%). As needed for characterization and pyrolyses, this material was further purified by GC on column C (45, 60, 60, 8.6); this procedure gave **20** mixed with 10–20% rearrangement products **28** + **29**.

^1H NMR (250 MHz, $CDCl_3$): δ 6.21 (m, 1 H, C-4 proton), 5.62 (m, 1 H, C-3 proton), 4.22 (unresolved m, 1 H, $J_{1,2}$ = 2.0 Hz, C-2 proton), 3.37 (s, 3 H, CH_3), 2.55 (m, 1 H, C-5 proton), 2.33 (m, 1 H, C-1 proton). ^1H NMR (500 MHz, benzene-d_6): δ 5.93 (m, 1 H, C-4 proton), 5.53 (m, 1 H, C-3 proton), 5.09 (d, 1 H, C-7 proton), 5.03 (t, 1 H, C-7 proton), 4.20 (unresolved m, 1 H, C-2 proton), 3.13 (s, 3 H, CH_3), 2.29 (unresolved m, 2 H, C-1 and C-5 protons).

^{13}C NMR (62.9 MHz, $CDCl_3$): δ 138.9 (s, C-6), 137.0 (d, C-3 or C-4), 128.1 (d, C-4 or C-3), 98.9 (t, C-7), 86.3 (d, C-2), 54.8 (q, CH_3), 27.5 (d, C-1 or C-5), 26.7 (d, C-5 or C-1).

GC/MS (50, 1, 15, 200, 1.40): identical with GC/MS of **19**.

Anal. Calcd for $C_8H_{10}O$: C, 78.65; H, 8.25. Found: C, 78.42; H, 7.80.

2-*exo*-Methyl-2-*endo*-hydroxy-6-methylenebicyclo[3.1.0]hex-3-ene (Tertiary Alcohol 33). Enone **27** (2.00 g, 18.9 mmol) and absolute ether (100 mL) were placed in a 250-mL round-bottomed flask equipped with a stir bar, pressure-equalized addition funnel, and N_2 inlet. The solution was stirred and cooled to −78 °C with a dry ice/acetone bath. Methyllithium (1.7 M, 17.0 mL, 28.9 mmol) in ether was added dropwise via the addition funnel while the temperature was maintained at −78 °C. A pink solid formed during the addition. After addition was complete (20 min), the mixture was stirred for 15 min at 0 °C and then carefully quenched with H_2O. The purple mixture was filtered to remove solids. The liquid phases were separated, and the aqueous layer was extracted with ether (1 × 50 mL). The combined organic layers were washed with H_2O (1 × 25 mL) and brine (1 × 25 mL). The ethereal solution was dried over Na_2SO_4, and the solvent was removed in vacuo. The residue was distilled in vacuo to give 820 mg (36%) of **33**, bp 30–35 °C (0.2 mmHg).

^1H NMR (250 MHz, $CDCl_3$): δ 5.81 (dd, 1 H, J = 5.3, 2.3 Hz, C-4 proton), 5.29 (m, 3 H, C-3 and C-7 protons), 2.38 (m, 1 H, C-5 proton), 2.08 (m, 1 H, C-1 proton), 1.73 (s, 1 H, hydroxyl proton), 1.47 (s, 3 H, CH_3).

^{13}C NMR (62.9 MHz, $CDCl_3$): δ 141.2 (s, C-6), 136.6 (d, C-3 or C-4), 132.2 (d, C-4 or C-3), 100.6 (t, C-7), 86.3 (s, C-2), 28.2 (d, C-1 or C-5), 27.5 (d, C-5 or C-1), 27.5 (q, CH_3).

GC/MS (60, 1, 15, 200, 0.63): *m/e* 122 (21%, M), 107 (17%, $-CH_3$), 79 (52%, $-C_2H_3O$), 77 (52%, $-C_2H_5O$), 43 (100%, $-C_6H_7$).

IR (neat): 3480 cm^{-1}.

Attempted Epimerization of 33. Following the general procedure for the preparation of **22**, 100 mg of **33**, 10 mL of ether, and 10 mL of 5% H_2SO_4 were stirred for 15 min, and the reaction mixture was worked up in the usual way. The only product observed by ^1H NMR was 2-methyl-4-*exo*-hydroxy-6-methylenebicyclo[3.1.0]hex-2-ene (**35**).

^1H NMR (500 MHz, $CDCl_3$): δ 5.24 (s, 1 H), 5.23 (s, 1 H), 5.07 (s, 1 H), 4.45 (unresolved m, 1 H, C-4 proton), 2.40 (m, 1 H, bridgehead proton), 2.28 (m, 1 H, bridgehead proton), 1.88 (s, 3 H, CH_3), 1.65 (br s, 1 H, hydroxyl proton).

GC/MS (50, 1, 15, 200, 1.43): *m/e* 136 (53%, M), 135 (37%, −H), 121 (85g, $-CH_3$), 105 (42%, $-CH_3O$), 91 (69%, $-C_2H_5O$), 79 (28%,

$-C_3H_5O$), 78 (72%, $-C_3H_6O$), 77 (100%, $-C_3H_7O$).

Exact mass calcd for $C_9H_{12}O$: 136.0889. Found: 136.0882.

2-*exo*-Methyl-2-*endo*-methoxy-6-methylenebicyclo[3.1.0]hex-2-ene (25). Synthesis from **33** and workup as described for **19** gave 550 mg (82%) of **25**. As needed for characterization and pyrolyses, this material was further purified by GC on column C (50, 60, 60, 15.6).

^{1}H NMR (250 MHz, $CDCl_3$): δ 5.86 (dd, 1 H, J = 5.5, 2.2 Hz, C-4 proton), 5.35 (m, 2 H, C-3 and C-7 protons), 5.26 (t, 1 H, C-7 proton), 3.34 (s, 3 H, OCH_3), 2.44 (m, 1 H, C-5 proton), 1.44 (s, 3 H, CH_3). ^{1}H NMR (500 MHz, benzene-d_6): δ 5.59 (dd, 1 H, C-4 proton), 5.33 (m, 2 H, C-3 and C-7 protons), 5.25 (t, 1 H, C-7 proton), 3.23 (s, 3 H, OCH_3), 2.15 (m, 1 H, C-5 proton), 1.69 (m, 1 H, C-1 proton), 1.36 (s, 3 H, CH_3).

^{13}C NMR (62.9 MHz, $CDCl_3$): δ 139.6 (s, C-6), 134.7 (d, C-3 or C-4), 131.8 (d, C-4 or C-3), 100.9 (t, C-7), 91.4 (s, C-2), 52.8 (q, OCH_3), 27.5 (d, C-1 or C-5), 25.3 (q, CH_3), 24.9 (d, C-5 or C-1).

6-Methyl-6-chlorobicyclo[3.1.0]hexan-2-one (50). A mixture of the corresponding ethylene ketal[18,19] (26.0 g, 138 mmol), diethyl ether (400 mL), and 5% H_2SO_4 (180 mL) was vigorously stirred overnight at room temperature. The organic layer was washed succesively with saturated $NaHCO_3$ and brine and dried over Na_2SO_4, and the solvent was removed in vacuo. The residue was distilled in vacuo with a 6-in. Vigreux column; after a small forerun, 17.0 g (85%) of **50**, bp 48 °C (0.5mmHg), was collected as a colorless oil, which solidified at 0 °C to a white crystalline mass. The presence of two epimers (10:1 ratio) was evident from the ^{13}C NMR spectrum.

^{1}H NMR (90 MHz, $CDCl_3$): δ 2.3–1.7 (m, 6 H), 1.60 (s, 3 H, CH_3).

^{13}C NMR (22.5 MHz, $CDCl_3$): (Major diastereomer) δ 211.5 (s, C-2), 50.4 (s, C-6), 41.3 (d, C-1), 36.5 (t, C-3), 35.5 (d, C-5), 28.2 (q, CH_3), 20.9 (t, C-4); (Minor diastereomer) 42.2, 36.3, 33.7, 29.1, 19.7 (quaternary carbons were not observed).

GC/MS (80, 1, 15, 200, 1.33): m/e 146 (2%, M + 2), 144 (7% M), 118 (4%, –CO or C_2H_4), 116 (13%, –CO or C_2H_4), 109 (6%, –Cl), 104 (32%, $-C_2H_2O$), 102 (100%, $-C_2H_2O$), 81 (31%, –COCl or C_2H_4Cl), 79 (24%, $-CH_2OCl$ or C_2H_6Cl).

This procedure was successfully scaled up 2-fold.

2,2-Dimethoxy-3-bromo-6-methyl-6-chlorobicyclo[3.1.0]hexane. This compound was prepared by the general procedure of Garbisch.[26] Ketone **50** (10.0 g, 69.2 mmol) and absolute methanol (125 mL) were placed in a 250-mL three-necked round-bottomed flask equipped with a stir bar, thermometer, pressure-equalized addition funnel, and N_2 inlet. The mixture was stirred and cooled to 15 °C. Bromine (3.7 mL, 11.1 g, 69.4 mmol) was placed in the addition funnel, and one drop was added to the methanolic solution. After several minutes the solution decolorized. The solution was then cooled to 13 °C, and the remainder of the bromine was added dropwise at such a rate so as to maintain a faint coloration of bromine at all times. During addition the temperature was gradually lowered to 8 °C. After the addition was complete, the solution was cooled to 0 °C and K_2CO_3 (40 g) was added. After it was stirred for 1 h, the mixture was poured into 150 mL of ice water and 100 mL of pentane. The layers were separated, and the aqueous layer was extracted with pentane (1 × 100 mL). The combined pentane extracts were dried over Na_2SO_4, and the solvent was removed in vacuo to give 14.9 g (80%) of product as a nearly colorless unstable oil, which contained several impurities by ^{1}H NMR. The material was used immediately for conversion to **18**.

^{1}H NMR (250 MHz, $CDCl_3$): δ 4.37 (dd, 1 H, CHBr), 3.44 (s, 3 H, OCH_3), 3.40 (s, 3 H, OCH_3), 2.7–2.1 (m, 4 H), 1.59 (s, 3 H, CH_3). Extraneous signals were observed at δ 2.92, 2.20, and 1.70.

2,2-Dimethoxy-6-methylenebicyclo[3.1.0]hex-3-ene (18). A solution of potassium *tert*-butoxide (Aldrich, used without further purification, 28.0 g, 250 mmol) in 250 mL of dry DMSO was prepared in a 500-mL round-bottomed flask equipped with a stir bar and N_2 inlet. With stirring, a solution of the halogenated ketal (14.9 g, 55.3 mmol) in 50 mL of dry DMSO was slowly added to the *tert*-butoxide/DMSO solution. The resulting black mixture was stirred and heated to 65 °C for 2 h under N_2. (To avoid the vinyl cyclopropane rearrangement, one should not allow the temperature to exceed 65 °C.) The reaction mixture was cooled to room temperature and quenched with 500 mL of ice water. The mixture was continuously extracted with pentane for 48 h. The pentane extract was washed with H_2O (1 × 100 mL) and brine (1 × 100 mL) and dried over Na_2SO_4, and the solvent was removed in vacuo. The residue was distilled in vacuo to give 2.70 g (26% from **50** of **18** bp 36 °C (0.3 mmHg). As needed for characterization and pyrolyses, this material was further purified by GC on column A (60, 120, 120, 8.0) and then column F (70, 120, 120, 52.7).

^{1}H NMR (250 MHz, $CDCl_3$): δ 6.14 (ds, 1 H, J = 5.2, 2.2 Hz, C-4 proton), 5.58 (d, 1 H, J = 5.2 Hz, C-3 proton), 5.32 (dd, 1 H, C-7 proton), 5.27 (t, 1 H, C-7 proton), 3.42 (s, 3 H, OCH_3), 3.33 (s, 3 H, OCH_3), 2.53 (m, 1 H, C-5 proton), 2.25 (m, 1 H, C-1 proton). ^{1}H NMR (500 MHz, C_6D_6): δ 5.78 (dd, 1 H, C-4 proton), 5.55 (d, 1 H, C-3 proton), 5.23 (dd, 1 H, C-7 proton), 5.21 (t, 1 H, C-7 proton), 3.32 (s, 3 H, OCH_3), 3.20 (s, 3 H, OCH_3), 2.23 (m, 2 H, C-1 and C-5 protons).

^{13}C NMR (62.9 MHz, $CDCl_3$): δ 138.8 (s, C-6), 136.2 (d, C-3 or C-4), 128.5 (d, C-4 or C-3), 115.0 (s, C-2), 100.9 (t, C-7), 52.1 (q, OCH_3), 49.5 (q, OCH_3), 26.3 (d, C-1 or C-5), 24.8 (d, C-5 or C-1).

GC/MS (70, 1, 15, 200, 1.58): m/e 152 (35%, M), 151 (19%, –H), 137 (36%, $-CH_3$), 122 (14%, $-CH_2O$), 121 (49%, $-CH_3O$), 109 (26%, $-C_2H_3O$), 105 (27%, $-CH_3O_2$ or C_2H_7O), 91 (68%, $-C_2H_5O_2$), 79 (21%, $-C_3H_5O_2$), 78 (67%, $-C_3H_6O_2$), 77 (100%, $-C_3H_7O_2$).

Anal. Calcd for $C_9H_{12}O_2$: C, 71.03; H, 7.95. Found: C, 70.77; H, 8.00.

(1*R*,2*S*,5*R*,*SS*)- and (1*S*,2*R*,*SS*)-*N*-Methyl-*S*-(*endo*-hydroxy-6-methyl-6-chlorobicyclo[3.1.0]hexyl-2-methyl)-*S*-phenylsulfoximine (51). A solution of (+)-(*S*)-*N*,*S*-dimethyl-*S*-phenylsulfoximine, $[\alpha]_D$ = +167° (acetone), was prepared in a 2-L round-bottomed flask equipped with a stir bar, pressure-equalized addition funnel, and N_2 inlet. A small quantity of triphenylmethane (0.1 g) was added as an indicator, and the solution was stirred and cooled to 0 °C. *n*-Butyllithium, 2.3 M in hexanes, was added dropwise via the addition funnel to an orange-red endpoint; about 100 mL was required. The solution was stirred an additional 15 min at 0 °C and then cooled to –78 °C. A solution of ketone **50** (32.0 g, 221 mmol) in dry THF (150 mL) was added dropwise via the addition funnel over a 1-h period. The deep yellow solution was stirred an additional 2 h at –78 °C and then poured into an equal volume of ice-cold 10% aqueousNH_4Cl. The mixture was extracted with ether (2 × 1 L), and the combined organic extracts were washed with H_2O (1 × 500 mL) and brine (1 × 500 mL). The ethereal layer was dried over Na_2SO_4, and the solvent was removed in vacuo to give a dark oil containing some suspended solids. Analysis of this material by ^{1}H NMR revealed a 1:1 ratio of two isomers. The mixture was subjected to gravity or flash column chromatography on silica gel (2:1 ethyl acetate/hexane solvent system). The faster moving diastereomer (R_f = 0.38, fraction A), rapidly solidified to a yellow crystalline mass; yield 34.0 g. The slower moving diastereomer (R_f = 0.28, fraction B, was obtained as an oil, which slowly solidified; yield 31.1 g. (The adducts from the minor C-6 diastereomer of **50** eluted more rapidly than these two and were generally not collected.) The combined yield of chromatographed isomers **51** was therefore 65.1 g (quantitative). These compounds were slightly cross-contaminated but sufficiently pure for conversion to optically active **50**. For spectral and analytical purposes, samples of **51** could be recrystallized from ether with final cooling to –20 °C.

^{1}H NMR (250 MHz, $CDCl_3$): (fraction A) δ 7.87 (dd, 2 H, *o*-C_6H_5), 7.58 (m, 3 H, *m*- and *p*-C_6H_5), 6.93 (s, 1 H, OH), 3.40 (d, 1 H, AA′ pattern, J = 13.7 Hz, diastereotopic SCH), 3.13 (d, 1 H, AA′ pattern, J = 13.7 Hz, diastereotopic SCH), 2.63 (s, 3 H, NCH_3), 2.49 (d, 1 H, $J_{1,5}$ = 6.9 Hz, C-1 proton), 2.26 (m, 1 H), 1.90 (m, 2 H), 1.66 (s, 3 H, CH_3), 1.55 (m, 2 H); (fraction B) δ 7.86 (dd, 2 H, *o*-C_6H_5), 7.58 (m, 3 H, *m*- and *p*-C_6H_5), 6.37 (s, 1 H, OH), 3.47 (dd, 1 H, AA′X pattern, J = 13.8, 1.3 Hz, diastereotopic SCH), 3.21 (d, 1 H, AA′ pattern, J = 13.8 Hz, diastereotopic SCH), 2.60 (s, 3 H, NCH_3), 2.55 (partially obscured m, 1 H), 2.20 (m, 1 H), 2.03 (m, 2 H), 1.54 (s, 3 H, CH_3), 1.42 (m, 2 H).

^{13}C NMR (62.9 MHz, $CDCl_3$): (fraction A) δ 139.2 (s, *ipso*-C_6H_5 carbon), 133.4 (s, *p*-C_6H_5 carbon), 129.8 (d, *o*- or *m*-C_6H_5 carbons), 129.2 (d, *m*- or *o*-C_6H_5 carbons), 83.0 (s, C-2), 65.2 (t, SCH_2 carbon), 51.5 (s, C-6), 38.8 (t, C-3 or C-4), 37.9 (d, C-1 or C-5), 32.6 (d, C-5 or C-1), 29.9 (q, NCH_3 or cyclopropyl CH_3 carbon), 29.0 (q, cyclopropyl CH_3 or NCH_3 carbon), 23.7 (t, C-4 or C-3); (fraction B) δ 139.5 (s, *ipso*-C_6H_5 carbon), 133.2 (d, *p*-C_6H_5 carbon), 129.6 (d, *o*- or *m*-C_6H_5 carbons), 129.1 (d, *m*- or *o*-C_6H_5 carbons), 82.7 (s, C-2), 64.4 (t, SCH_2 carbon), 50.8 (s, C-6), 41.0 (d, C-1 or C5), 35.6 (t, C-3 or C-4), 31.7 (d, C-5 or C-1), 29.8 (q, NCH_3 or cyclopropyl CH_3 carbon), 29.0 (q, cyclopropyl CH_3 or NCH_3 carbon), 25.0 (t, C-4 or C-3).

IR (neat): (fraction A or B) 3600–3200 (OH), 1270–1190 cm^{-1}.

Anal. Calcd for $C_{15}H_{20}O_2NSCl$: C, 57.41; H, 6.42; N, 4.46; S, 10.22; Cl, 11.30. Found: (fraction A) C, 57.29; H, 6.49; N, 4.29; S, 10.09; Cl, 11.15; (fraction B) C, 57.48; H, 6.50; N, 4.43; S, 10.13; Cl, 11.22.

(–)- and (+)-6-Methyl-6-chlorobicyclo[3.1.0]hexan-2-one (50). Fraction A of **51**, 20.2 g (64.4 mmol), was pyrolyzed in a Kugelrohr distillation apparatus at 80–120 °C (0.2 mmHg), and the distillate was collected in a receiver at –78 °C. The resulting yellow oil was dissolved in ether (200 mL) and extracted with 10% H_2SO_4 (3 × 300 mL). The combined acidic aqueous extracts were set aside and worked up as described below. The organic layer was washed with saturated $NaHCO_3$ (100 mL) and brine (100 mL). The ethereal layer was dried over Na_2SO_4, and the solvent was removed in vacuo to give 7.01 g (75%) of (–)-**50**, $[\alpha]^{22}_D$ = –35.6° (–35.6° (c = 0.949, acetone). Repetition of this procedure with fraction B of **51** (14.7 g, 46.9 mmol) gave 4.20 g (62%) of (+)-**50**, $[\alpha]^{22}_D$ = +38.4° (c = 0.954, acetone).

The combined acidic extracts from pyrolysis of fractions A and B were brought to pH 8–9 with 20% NaOH and extracted with $CHCl_3$ (3 × 100 mL). The combined organic extracts were dried over Na_2SO_4, and the solvent was removed in vacuo. Vacuum distillation of the residue gave 9.5 g (50% recovery) of the (+)-sulfoximine reagent with essentially unchanged optical activity.

(−)- and (+)-Spiro[6-methylenebicyclo[3.1.0^{1,5}]hex-3-ene-2,2′-[1′,3′]-dioxolane], (−)- and (+)-17a. In a 250-mL round-bottomed flask equipped with a stir bar, thermometer, and pressure-equalized dropping funnel, (−)-**50** (7.00 g, 48.4 mmol) was dissolved in ethylene glycol (70 mL). The solution was stirred and heated to 30 °C in a warm-water bath. Bromine (2.59 mL, 7.77 g, 48.6 mmol) was placed in the addition funnel, and 1 drop was added to the flask. After the red color had dissipated (5–10 min), the remainder of the bromine was added dropwise at a rate to maintain a faint red color at all times. After the addition was complete, the reaction mixture was poured into a vigorously stirred mixture of sodium carbonate (30 g) and pentane (100 mL). The mixture was stirred for 30 min, and then water (100 mL) was slowly added. The layers were separated, and the aqueous layer was extracted with pentane (2 × 100 mL). The combined organic layers were dried over Na_2SO_4, and the solvent was removed in vacuo to give 10.9 g (85%) of optically active bromo chloride as colorless needles. Analysis by ^{1}H NMR showed a 10:1 ratio of C-3 diastereomers. This material was immediately dissolved in dry DMSO (20 mL) and added to a stirred solution of potassium *tert*-butoxide (18.2 g) in dry DMSO (150 mL). The black mixture was stirred for 90 min at 70 °C. Workup of the reaction as described[18] for the racemic series gave 2.78 g (46% from (−)-**50**, 54% from the bromo chloride) of (−)-**17a**). From optically active (−)-**50** was obtained (−)-**17a**, $[\alpha]^{23}_D = -313°$, $[\alpha]_{365} = -1176°$ (c = 0.9205, $CHCl_3$). Repetition of this procedure with (+)-**50** (4.20 g, 29.1 mmol) gave an 88% yield of bromo chloride and then 1.92 g of (+)-**17a**, $[\alpha]_D = +377°$, $[\alpha]^{23}_{365} = 1436°$ (c = 0.9179, $CHCl_3$).

Racemic and (−)-(*R*)-7-Methyl-1,4-dioxaspiro[4.5]decane (3-Methylcyclohexanone Ethylene Ketal, 58). In a 350-mL round-bottomed flask equipped with a stir bar, a Dean–Stark trap, and a reflux condenser were placed racemic 3-methylcyclohexanone (10 g, 89.3 mmol), ethylene glycol (20 g, 323 mmol), and benzene (100 mL). A few crystals of *p*-toluenesulfonic acid were added, and the two-phase mixture was stirred and heated at reflux for 90 min until the theoretical amount of water had been collected. The mixture was cooled to room temperature, stirred with Na_2CO_3 (2 g) for 1 h, and poured into 200 mL of water. The layers were separated, the aqueous layer was extracted with pentane (2 × 50 mL), and the organic layer was washed with 20 mL of water. After having been dried over Na_2SO_4, the solvent was evaporated and, the residue was distilled to give 12.8 g (92%) of **58**, bp 48 °C (0.5 mmHg). Samples for spectroscopy were further purified by GC on column A (60, 100, 100, 13.5).

^{1}H NMR (270 MHz, $CDCl_3$): δ 3.91 (s, 4 H, C-2 and C-3 protons), 1.64 (m, 5 H), 1.43 (m, 2 H), 1.13 (t, 1 H), 0.89 (d, 3 H, CH_3), 0.83 (partially obscured, 1 H).

^{13}C NMR (62.9 MHz, $CDCl_3$): δ 109.1 (s, C-5), 64.1 (t, C-2 or C-3), 63.9 (t, C-3 or C-2), 43.5 (t), 34.4 (t), 33.8 (t), 30.3 (d, C-7), 23.1 (q, CH_3), 22.1 (t).

GC/MS (60, 1, 15, 200, 2.32): *m/e* 156 (8%, M), 141 (7%, $-CH_3$), 113 (100%, $-C_2H_3O$ or C_3H_7), 99 (66%, $-C_3H_5O$ or C_4H_9), 86 (28%, $-C_4H_7O$).

Repetition of this procedure with (+)-(*R*)-3-methylcyclohexanone (10.0 g, $[\alpha]^{23}_D = +13.4°$ (neat); lit.[27] $[\alpha]^{25}_D = +13.5°$ (neat)) gave 12.8 g (92%) of (−)-**58**, $[\alpha]^{23}_D = -9.39°$, $[\alpha]^{23}_{365} = -30.4°$ (c = 0.4152, $CHCl_3$).

Racemic and (−)-(3*R*)-7-Methyl-6,10-dibromo-1,4-dioxaspiro[4.5]decane (3-Methyl-2,6-dibromocyclohexanone Ethylene Ketal, 59). Racemic **58** (8.00 g, 51.3 mmol) and dry ether (100 mL) were placed in a 250-mL three-necked round-bottomed flask equipped with a stir bar, pressure-equalized addition funnel, and condenser. Bromine (5.60 mL, 16.8 g, 105 mmol) was added dropwise with stirring at a rate to maintain gentle reflux of the ether. The solution was stirred an additional 1 h, and then a cooled solution of sodium ethylene glycolate (prepared from 2.4 g of Na/65 mL of ethylene glycol) was slowly added over 15 min. The mixture was poured into ice water (200 mL) containing $NaHCO_3$ (5 g). The layers were separated, and the aqueous layer was extracted with ether (2 × 50 mL). The combined ether extracts were washed with H_2O (20 mL) and brine (20 mL). The organic layer was dried over Na_2SO_4, and the solvent was removed in vacuo. The residual oil (16.1 g) was dissolved in methanol (15 mL) and cooled overnight in a refrigerator to give 6.39 g (40%) of **59** as colorless needles. An analytical sample could be obtained by recrystallization from methanol (1 mL/g of **59**); mp 96.2–98 °C. The ^{1}H and ^{13}C NMR spectra showed the presence of only one diastereoisomer (relative configuration unknown).

^{1}H NMR (270 MHz, $CDCl_3$): δ 4.24 (m, 5 H, C-2, C-3, and C-6 protons), 4.05 (dd, 1 H, J = 12.4, 4.4 Hz, C-10 proton), 2.26 (m, 2 H), 2.08 (m, 1 H), 1.66 (m, 2 H), 1.20 (d, 3 H, CH_3).

^{13}C NMR (62.9 MHz, $CDCl_3$): δ 108.9 (s, C-5), 69.2 (t, C-2 or C-3), 66.9 (t, C-3 or C-2), 61.0 (d, C-6 or C-10), 56.7 (d, C-10 or C-6), 36.8 (d, C-7), 32.1 (t, C-8 or C-9), 30.6 (t, C-9 or C-8), 15.1 (q, CH_3).

GC/MS (100, 1, 15, 200, 4.63): *m/e* 316 (4%, M + 4), 314 (8%, M + 2), 312 (4%, M), 235 (43%, −Br), 233 (49%, −Br), 193 (89%, complex fragmentation), 191 (78%, complex fragmentation), 179 (87%, complex fragmentation), 166 (27%, complex fragmentation), 164 (27%, complex fragmentation), 153 (28%, $-HBr_2$).

Anal. Calcd for $C_9H_{14}O_2Br_2$: C, 34.45; H, 4.50; Br, 50.86. Found: C, 34.60; H, 4.51; Br, 50.60.

Repetition of this procedure with (−)-**58** (8.00 g) gave 16.1 g of an oil, which would not crystallize. This material was eluted from a silica gel column with 2:1 hexane/ethyl acetate solvent system containing 0.01% triethylamine. The fraction with R_f = 0.63 (5.47 g) crystallized upon standing. The crystals were washed with ice-cold methanol and then recrystallized twice from methanol to give 1.17 g (7%) of (−)-**59**, mp 87.0–88.5 °C, with softening at 50 °C, $[\alpha]^{23}_D = -28.9°$, $[\alpha]^{23}_{365} = -87.7°$ (c = 1.310, $CHCl_3$). The ^{1}H and ^{13}C NMR spectra of this material were identical with those of racemic **59**.

Racemic and (+)-(1*R*,2*R*,6*S*)-2-*endo*-Methylspiro[bicyclo[3.1.0^{1,5}]-hexane-6,2′-[1′,3′]dioxolane] (2-*endo*-Methylbicyclo[3.1.0]hexan-6-one Ethylene Ketal, 55). Finely divided magnesium turnings (335 mg, 24.0 mol) were placed in a 15-mL three-necked round-bottomed flask equipped with a stir bar, a pressure-equalized addition funnel, a condenser, and an inlet for N_2 gas. The system was flame-dried and cooled under N_2. Dry THF (2 mL) and a small crystal of iodine were added to the flask, and the mixture was stirred vigorously at 40 °C. A solution of racemic **59** (4.00 g, 12.7 mmol) in dry THF (5 mL) was placed in the addition funnel and a few drops were added to the flask. After 5–10 min, a vigorous reaction set in, and the mixture turned cloudy and gray. After the reaction had subsided, the mixture was cooled to room temperature. The remainder of the **59**/THF solution was added dropwise at a rate to maintain gentle reflux. The mixture was heated at reflux an additional 2 h, cooled to room temperature, poured into ice water (200 mL), and extracted with ether (4 × 50 mL). The combined organic extracts were washed with water (20 mL) and brine (20 mL). The ethereal layer was dried over Na_2SO_4, and the solvent was removed in vacuo. The residue was distilled in vacuo to give 1.47 g (75%) of **55** as a colorless liquid, bp 50 °C (0.5 mmHg). This material was further purified by GC on column A (60, 100, 100, 13.0) and/or column E (65, 110, 110, 46.8).

^{1}H NMR (500 MHz, $CDCl_3$): δ 3.98 (m, 2 H, C-4′ or C-5′ protons), 3.88 (m, 2 H, C-5′ or C-4′ protons), 2.35 (m, 1 H, C-2 proton), 1.87 (m, 2 H), 1.67 (m, 1 H), 1.52 (m, 1 H), 1.45 (m, 1 H), 1.32 (m, 1 H), 1.04 (d, 3 H, CH_3).

^{13}C NMR (62.9 MHz, $CDCl_3$): δ 99.8 (s, C-6 or C-2′), 65.6 (t, C-4′ or C-5′), 64.0 (t, C-5′ or C-4′), 36.0 (d), 31.6 (d), 31.3 (t, C-3 or C-4), 26.6 (t, C-4 or C-3), 26.1 (d), 18.1 (q, CH_3).

GC/MS (80, 1, 15, 200, 1.08): *m/e* 154 (9%, M), 153 (4%, −H), 139 (49%, $-CH_3$), 126 (18%, $-C_2H_4$), 112 (100%, $-C_3H_6$).

Anal. Calcd for $C_9H_{14}O_2$: C, 70.10; H, 9.15. Found: C, 70.22; H, 9.16.

During the GC purification of **55**, a minor (~10%) fraction with retention times of 14.2 and 57.5 min on columns A and F, respectively, was collected and tentatively identified as a 1:1 mixture of dioxolanes. No attempt to separate these was made.

^{1}H NMR (270 MHz, $CDCl_3$): (first isomer) δ 5.10 (unresolved m, 1 H), 4.1–3.6 (m, 5 H), 2.3–1.2 (m, 5 H), 1.03 (d, 3 H, CH_3); (second isomer) δ 4.96 (unresolved m, 1 H), 4.1–3.6 (m, 5 H), 2.3–1.2 (m, 5 H), 0.92 (d, 3 H, CH_3).

Repetition of this procedure with (−)-**59** (1.00 g) gave 410 mg (84%) of (+)-**55**, $[\alpha]^{23}_D = +68.6°$, $[\alpha]^{23}_{365} = +219°$ (c = 0.8075, $CHCl_3$).

General Procedures for Solution-Phase Pyrolyses. Analytical Runs. In a typical experiment, the appropriate bicyclohexene (5–10 mg) was purified by GC and dissolved in 0.5 mL of a suitable solvent in an NMR tube. The sample was degassed by three freeze–pump–thaw cycles and sealed in vacuo at 0.1 mm. Pyrolysis was carried out by completely submerging the tube in a well-stirred oil bath preset at a desired temperature. The tube was removed at a predetermined time, cooled in an ice bath, and analyzed by NMR, analytical GC, or GC/MS.

Preparative Runs. A suitable quantity of the GC-purified bicyclohexene was made up as a benzene solution (0.05–0.15 M). The sample was placed in a thick-walled tube, subjected to three freeze–pump–thaw cycles, and sealed in vacuo. Thermolysis was carried out as for the analytical runs. The solvent was removed in vacuo, and the products were purified by GC.

(27) Dauben, W. G.; Wipke, W. T. *J. Org. Chem.* **1967**, *32*, 2976.

Pyrolysis of *endo*-Methyl Ether 19. After having been heated 72 h at 54 °C in benzene-d_6, **19** gave a reaction mixture containing two products (analysis by 500-MHz ^{1}H NMR): 2-methylene-6-*endo*-methoxybicyclo[3.1.0]hex-3-ene (**28**) and the corresponding 6-*exo*-methoxy isomer (**29**). Integration of the exocyclic methylene signals gave a product distribution of 97% **28** and 3% **29**. Analysis by GC on column G (70, 110, 120) showed 97.6% **28** (retention time 15.63 min) and 2.4% **29** (retention time 9.70 min). Pyrolysis of **19** at 70 °C for 3 h and at 140 °C for 3 min gave **28**/**29** ratios of 97:3 and 95:5, respectively, by ^{1}H NMR. The diastereomers from a preparative scale run with 300 mg of **19** in 25 mL of benzene heated 3 min at 140 °C could be separated on column F (80, 100, 100): retention times 8.3 min (**29**) and 13.5 min (**28**).

^{1}H NMR (250 MHz, $CDCl_3$): (major isomer (**28**)) δ 6.03 (d, 1 H, C-3 proton), 5.94 (m, 1 H, C-4 proton), 5.11 (s, 1 H, C-2 exocyclic methylene proton), 5.08 (s, 1 H, C-2 exocyclic methylene proton), 3.39 (pseudo t, 1 H, $J_{6,1} = J_{6,5} = 6.5$ Hz, C_6 proton), 3.25 (s, 3 H, CH_3), 2.32 (m, 2 H, C-1 and C-5 protons).

^{1}H NMR (500 MHz, benzene-d_6): (major isomer (**28**)) δ 5.99 (d, 1 H, C-3 proton), 5.74 (m, 1 H, C-4 proton), 5.08 and 5.05 (two s, 1 H each, C-2 exocyclic methylene protons), 3.01 (s, 3 H, CH_3), 3.00 (partially obscured pseudo t, 1 H, $J_{6,1} = J_{6,5} = 6.5$ Hz, C-6 proton), 2.00 (pseudo t with fine structure, 1 H, $J_{1,5} = J_{1,6} = 6.5$ Hz, C-1 proton), 1.94 (d of pseudo t, 1 H, $J_{5,1} = J_{5,6} = 6.5$ Hz, $J_{5,4} = 2.5$ Hz, C-5 proton).

^{1}H NMR (250 MHz, $CDCl_3$): (minor isomer (**29**)) δ 6.09 (m, 1 H, C-4 proton), 5.88 (d, 1 H, C-3 proton), 4.97 and 4.89 (two s, 1 H each, C-2 exocyclic methylene protons), 3.36 (s, 3 H, CH_3), 2.72 (s, 1 H, C-6 proton), 2.30 (m, 2 H, C-1 and C-5 protons).

^{1}H NMR (500 MHz, benzene-d_6): (minor isomer (**29**)) δ 5.81 (m, 1 H, C-4 proton), 5.73 (d, 1 H, C-3 proton), 4.97 and 4.89 (two s, 1 H each, C-2 exocyclic methylene protons), 3.02 (s, 3 H, CH_3), 2.70 (s, 1 H, C-6 proton), 2.32 (d with fine structure, 1 H, $J_{1,5} = 6.2$ Hz, C-1 proton), 2.25 (dd, 1 H, $J_{5,1} = 6.2$ Hz, $J_{5,4} = 2.3$ Hz, C-5 proton).

^{13}C NMR (62.9 MHz, $CDCl_3$): (major isomer (**28**)) δ 150.0 (s, C-2), 133.4 (d, C-3 or C-4), 131.4 (d, C-4 or C-3), 108.7 (t, C-2 exocyclic methylene carbon), 66.5 (d, C-2), 5.85 (q, CH_3), 31.6 (d, C-1 or C-5), 28.7 (d, C-5 or C-1). The minor isomer was not obtained in sufficient quantity for ^{13}C NMR spectroscopy.

GC/MS (60, 1, 15, 100, 1.22): (major isomer **28**) *m/e* 122 (56%, M), 121 (78%, –H), 107 (18%, $-CH_3$), 92 (25%, $-CH_2O$), 91 (88%, $-CH_3O$), 79 (45%, $-C_2H_3O$), 78 (21%, $-C_2H_4O$), 77 (100%, $-C_2H_5O$).

GC/MS (60, 1, 15, 100, 0.77): (minor isomer **29**) *m/e* 122 (26%, M), 121 (28%, –H), 107 (9%, $-CH_3$), 92 (14%, $-CH_2O$), 91 (47%, $-CH_3O$), 79 (40%, $-C_2H_3O$), 78 (25%, $-C_2H_4O$), 77 (100%, $-C_2H_5O$).

Exact mass calcd for $C_8H_{10}O$: 122.0732. Found: (**28**) 122.0735; (**29**) 122.0732.

Exhaustive pyrolysis of **19** in CD_3OH (80 °C, 2 h) afforded **28** and **29** with no CD_3O incorporation (GC/MS).

Individual Pyrolyses of *endo*- and *exo*-Methoxyhomofulvenes 28 and 29. Samples of **28** and **29** prepared as described above and free of cross-contamination were pyrolyzed at 100 °C for 2 h and at 140 °C for 3 min. This produced no observable changes in the ^{1}H 500-MHz NMR spectrum.

Pyrolysis of *exo*-Methyl Ether 20. A GC-purified sample of **20** in benzene-d_6 was analyzed by 500-MHz ^{1}H NMR and found to contain 19% of the homofulvene rearrangement products **28** and **29**. The ratio of **28**/**29** was 91:9. (This ratio did not reflect the true pyrolysis product ratio **28**/**29** because, in the GC purification process, it was possible to separate partially **20** from **28** but not from **29**. Consequently, samples of **20** obtained by preparative GC were enriched in **29**.) Exhaustive pyrolysis of this mixture at 54 °C for 3 h gave an NMR distribution of 95% **28** and 5% **29**. When corrected for the initial 91:9 ratio of **28**/**29**, the actual product distribution from **20** was 96% **28** and 4% **29**. A duplicate run gave results indistinguishable from these.

Exhaustive pyrolysis of **20** in CD_3OH at 60 °C for 1 h gave **28** and **29** with no incorporation of CD_3O (GC/MS analysis).

Pyrolysis of Tertiary Methyl Ether 25. After having been heated for 17 h at 59 °C, a sample of **25** was completely consumed. Analysis by 500-MHz ^{1}H NMR spectroscopy showed the presence of two products whose proportions could be determined by integration of the upfield methyl signals: 2-methylene-6-methyl-6-*endo*-methoxybicyclo[3.1.0]-hex-3-ene (**36**, 97%) and the corresponding 6-*exo*-methoxy isomer (**37**, 3%). A similar pyrolysis of **25** at 125 °C gave a product distribution of 96% **36** and 4% **37**. No attempt was made to separate the isomers.

^{1}H NMR (500 MHz, benzene-d_6): (**36**) δ 6.01 (d, 1 H, C-3 proton), 5.81 (m, 1 H, C-4 proton), 5.08 and 5.04 (two s, 1 H each, C-2 exocyclic methylene protons), 3.00 (s, 3 H, OCH_3), 1.95 (d, 1 H, $J_{1,5} = 5.6$ Hz, C-1 proton), 1.88 (dd, 1 H, $J_{5,1} = 5.6$ Hz, $J_{5,4} = 2.5$ Hz, C-5 proton), 1.07 (s, 3 H, CH_3); (**37**) (partial spectrum) δ 4.98 (s, 1 H, C-2 exocyclic methylene proton), 3.03, (s, 3 H, OCH_3), 2.38 (m, 2 H, C-1 and C-5 protons), 1.18 (s, 3 H, CH_3).

^{13}C NMR (62.9 MHz, $CDCl_3$): (**36**) δ 150.9 (s, C-2), 133.7 (d, C-3 or C-4), 132.5 (d, C-4 or C-3), 107.9 (t, C-2 exocyclic methylene carbon), 69.7 (s, C-6), 55.1 (q, OCH_3), 39.4 (d, C-1 or C-5), 37.1 (d, C-5 or C-1), 20.2 (q, CH_3). An insufficient quantity of **37** was present for ^{13}C NMR spectroscopy.

GC/MS (50, 1, 15, 200, 1.80): (**36** and **37**) *m/e* 136 (71%, M), 135 (48%, –H), 121 (92%, $-CH_3$), 105 (43%, $-CH_3O$), 91 (75%, $-C_2H_5O$), 79 (27%, $-C_3H_5O$), 78 ($-C_3H_6O$), 77 (100%, $-C_3H_7O$).

Exact mass (**36** and **37**) calcd for $C_9H_{12}O$: 136.0889. Found: 136.0885.

Exhaustive pyrolysis of **25** in CD_3OH (70 °C, 3 h) gave **36** and **37** with no incorporation of CD_3O (GC/MS analysis).

Pyrolysis of Dimethyl Ketal 18. A sample of **18** in benzene-d_6 was 90% consumed after 8 h at 100 °C. The only product observed by ^{1}H NMR was 2-methylene-6,6-dimethoxybicyclo[3.1.0]hex-3-ene (**48**). This substance was unstable in the absence of solvent. A ^{13}C NMR sample could be prepared by rapid evaporation of the benzene with an air current followed by immediate addition of $CDCl_3$.

^{1}H NMR (500 MHz, benzene-d_6): δ 5.95 (d, 1 H, C-3 proton), 5.78 (m, 1 H, C-4 proton), 5.04 and 5.01 (two s, 1 H each, C-2 exocyclic methylene proton), 3.18 (s, 3 H, CH_3), 3.17 (s, 3 H, CH_3), 2.46 (s, 2 H, C-1 and C-5 protons). ^{1}H NMR (250 MHz, $CDCl_3$): δ 6.03 (m, 2 H, C-3 and C-4 protons), 5.11 and 5.07 (two s, 1 H each, C-2 exocyclic methylene protons), 3.37 (s, 3 H, CH_3), 3.29 (s, 3 H, CH_3), 2.56 (dd, 1 H, C-5 proton), 2.48 (d, 1 H, C-1 proton).

^{13}C NMR (62.9 MHz, $CDCl_3$): δ 150.6 (s, C-2), 135.1 (d, C-3 or C-4), 132.5 (d, C-4 or C-3), 107.9 (t, C-2 exocyclic methylene carbon), 97.4 (s, C-6), 54.2 (q, CH_3), 53.0 (q, CH_3), 38.4 (d, C-1 or C-5), 35.4 (d, C-5 or C-1).

GC/MS (70, 1, 15, 200, 1.35): *m/e* 152 (35%, M), 151 (26%, –H), 137 (32%, $-CH_3$), 121 (14%, $-CH_3O$), 109 (16%, $-C_2H_3O$), 105 (30%), 91 (58%, $-C_2H_5O_2$), 79 (14%, $-C_3H_5O_2$), 78 (61%, $-C_3H_6O_2$), 77 (100%, $-C_3H_7O_2$).

Exact mass calcd for $C_9H_{12}O_2$: 152.0838. Found: 152.0835.

Partial pyrolysis of **18** in CD_3OH (88 °C, 8 h, 60–65% conversion) gave 2% incorporation of one CD_3O in **48** and 7% incorporation of one CD_3O in **18** (GC/MS analysis, electron impact, or chemical ionization and observation of M or M + 1 ions). Double incorporation of OCH_3 into either **18** or **48** was not observed. These results varied slightly from run to run. Ketal exchange could not be entirely suppressed even when 1% pyridine was added to the reaction mixture before pyrolysis.

Pyrolysis of **18** in EtOH (100 °C, 8 h) gave **48** with no EtO incorporation (GC/MS or ^{1}H NMR analysis).

Pyrolysis of Butanediol Ketals 17b and 17c. Analysis of a sample of a mixture of **17b** and **17c** in benzene-d_6 was achieved by 500-MHz ^{1}H NMR spectroscopy. Double irradiation of the C-4 proton resonances at δ 5.86 led to collapse of the two doublets (C-3 protons) at δ 5.48 and 5.44. The two resulting singlets were integrated to give the ratio of **17b**/**17c**. The sample was then heated at 108 °C for 3 h (75–80% conversion). Two products were observed by 500-MHz ^{1}H NMR: (1*R*,5*S*,4′*R*,5′*R*)- and (1*S*,5*R*,4′*R*,5′*R*)-2-methylene-4′,5′-dimethylspiro[bicyclo[3.1.0^{1,5}]-hex-3-ene-6,2′-[1′,3′]dioxolane] (**40** and **41**).

^{1}H NMR (500-MHz, benzene-d_6) **40** and **41**: δ 6.01 (m, combined, 1 H, C-3 or C-4 protons), 5.88 (m, combined, 1 H, C-4 or C-3 protons), 5.07 and 5.01 (two s, combined 1 H each, C-2 exocyclic methylene protons), 3.52 (m, combined 2 H, C-4′ and C-5′ protons), 2.59 (m, combined 2 H, C-1 and C-5 protons), 0.94 (four overlapping d, combined 6 H, CH_3).

Double irradiation of the ketal methine region, centered at δ 3.52 of **40** and **41** led to collapse of the methyl doublets to four singlets at δ 0.96, 0.95, 0.94, and 0.91. The ratios were determined by integration or, more accurately, by cutting and weighing each peak in duplicate. This entire procedure was repeated with **17b**-enriched and **17c**-enriched samples. The resulted are given in Table III.

It was not readily apparent whether interconversion of **17b** and **17c** was occurring during pyrolysis because of the possibility that these two isomers rearranged at different rates.

Pyrolysis of Racemic Ethylene Ketal 17a. A sample of **17a** in benzene-d_6 was heated at 100 °C for 18 h. The only product observed by ^{1}H NMR spectroscopy was 2-methylenespiro[bicyclo[3.1.0^{1,5}]hex-3-ene-6,2′-[1′,3′]dioxolane] **43a**–**43a**′.[18,19] Prolonged pyrolysis, higher temperatures, or removal of solvent led to polymerization.

^{1}H NMR (250 MHz, benzene-d_6): δ 6.01 (d, 1 H, C-3 proton), 5.88 (m, 1 H, C-4 proton), 5.06 and 5.00 (two s, 1 H each, exocyclic methylene protons), 3.44 (m, 4 H, C-4′ and C-5′ protons), 2.60 (d, 1 H, AA′ pattern, C-1 proton), 2.55 (dd, 1 H, AA′X pattern, C-5 proton).

Partial pyrolysis of **17a** in $CDCl_3$ (100 °C, 8 h, 70% conversion) gave **43a**–**43a**′ along with 15–20% unidentified products. Several attempts to achieve GC separation (OV-101 and Carbowax 20M columns) gave only one polymeric fraction.

Table III. ^{1}H NMR Data for the Rearrangement of the Butanediol Ketals **17b** and **17c** to **40** and **41**

sample	**17b** + **17c**: C-3 proton ratio[d]	**40** + **41**: CH_3 ratios[d] integration	weighing[e]
A[a]	1.04:1.00	0.91:1.00:1.06:1.00	0.99:1.03:1.03:1.00
B[b]	0.56:1.00	0.96:0.93:0.98:1.00	1.03:0.98:1.01:1.00
C[c]	7.33:1.00	0.95:0.98:0.98:1.00	1.05:1.00:1.05:1.00

[a] Prepared from non-GC-resolved 6-methyl-6-chlorobicyclo[3.1.0]-hexan-2-one 2,3-butanediol ketal.[18] [b] Prepared from first GC fraction of methyl chloro ketal. [c] Prepared from second GC fraction of methyl chloro ketal. [d] Ratios of downfield to upfield signals. [e] Average of two runs.

^{1}H NMR (270 MHz, $CDCl_3$) **43a–43a′**: δ 6.05 (m, 2 H, C-3 and C-4 protons), 5.09 and 5.03 (two s, 1 H each, C-2 exocyclic methylene protons), 4.00 (m, 4 H, C-4′ and C-5′ protons), 2.58 (m, 2 H, C-1 and C-5 protons). Extraneous signals were observed at δ 6.20, 6.07, 5.53, 4.58, and 2.20–1.60.

Pyrolysis of (−)-17a. A sample of (−)-**17a**, 66 ± 2% ee (700 mg, 4.7 mmol) in benzene-d_6 (100 mL), and a sample of racemic **17a** (5 mg) in benzene-d_6 (0.5 mL) were heated simultaneously at 88.1 ± 0.1 °C in a doubly thermostated oil bath. After 1460 min, both tubes were simultaneously removed and plunged into ice water. Analysis by ^{1}H NMR using residual benzene as internal standard showed 78 ± 2% rearrangement. The pyrolysis solution from the optically active run was mixed with 1 L of 5:1 ethanol/THF in a 2-L round-bottomed flask equipped with a stir bar and pressure-equalized dropping funnel. The solution was stirred and cooled to 0 °C, and 95% hydrazine (90.0 g, 2.8 mol) was added gradually. This operation was followed by dropwise addition of 30% hydrogen peroxide (320 g, 2.8 mol) over a 2-h period. The solution was stirred overnight at 0 °C and then poured into a mixture of methylene chloride (2 L) and water (3 L). The layers were separated, and the aqueous layer was exhaustively extracted with more methylene chloride. The combined organic extracts were washed with water (2 × 500 mL) and brine (500 mL). The organic layer was dried over Na_2SO_4, and the solution was filtered and concentrated in vacuo at 10 °C to a volume of about 10 mL (higher temperatures or further concentration resulted in appreciable losses of the volatile products). The remaining solvent was removed by GC (300–500-μL injections) on column B (80, 120, 120); all fractions after the solvent were collected together. This material contained the desired products along with some aniline, which apparently is a minor impurity in commercial hydrazine. Most of the aniline was removed by GC (10-μL injections) on column A (70, 110, 110); all fractions after the aniline peak (retention time 1.8 min) were collected together. Finally, the products were separated by GC (10-μL injections) on column F (68, 90, 90). The products emerged in the following order: **55** (fraction A, retention time 96.2 min), **54** (fraction B, retention time 111.8 min), **53** (fraction C, retention time 122.2 min), **52** (fraction D, retention time 171.6 min). **56** (fraction E, retention time 210.6 min). These products were slightly cross-contaminated. Yields were not determined quantitatively but were low because of losses due to volatility during GC. The identity of each product was confirmed by ^{1}H NMR and MS data and by spectroscopic comparison with the products formed by individual diimide reductions of **17a** and **43a–43a′**. Further, the spectroscopic properties of **55** obtained by diimide reduction of **43a–43a′** and by reduction of **59** (see above) were identical.

^{1}H NMR (500 MHz, $CDCl_3$) fraction B (**54**): δ 3.95 (m, 2 H, C-4′ or C-5′ protons), 3.89 (m, 2 H, C-5′ or C-4′ protons), 2.20 (pseudo q, 1 H, $J_{2,1}$ = 0 Hz, C-2 proton), 1.87 (m, 2 H), 1.73 (m, 1 H), 1.60 (m, 1 H), 1.32 (d, 1 H, $J_{1,5}$ = 8.1 Hz, $J_{1,2}$ = 0 Hz, C-1 proton), 1.25 (m, 1 H), 0.95 (d, 3 H, CH_3).

GC/MS (80, 1,15, 200, 1.10): (fraction B (**54**)) *m/e* 154 (10%, M), 153 (4%, −H), 139 (41%, $-CH_3$), 126 (17%, $-C_2H_4$), 112 (100%, $-C_3H_6$ or C_2H_2O).

^{1}H NMR (500 MHz, $CDCl_3$): (fraction C (**53**)) δ 4.01 (m, 1 H, C-4′ or C-5′ proton), 3.95 (m, 3 H, C-5′ and C-4′ protons), 1.88 (m, 1 H), 1.74 (m, 1 H), 1.61 (m, 1 H), 1.43 (m, 1 H), 1.14 (m, 1 H), 1.08 (m, 1 H), 0.98 (d, 3 H, CH_3), 0.85 (m, 1 H, C-6 proton).

GC/MS (80, 1, 15, 200, 1.10): (fraction C (**53**)) *m/e* 154 (14%, M), 139 (100%, $-CH_3$), 125 (40%, $-C_2H_5$ or CHO), 113 (16%, $-C_3H_5$), 99 (15%, $-C_4H_7$), 86 (60%, $-C_5H_8$).

^{1}H NMR (270 MHz, $CDCl_3$): (fraction D (**52**)) δ 3.95 (m, 2 H, C-3′ or C-4′ protons), 3.87 (m, 2 H, C-4′ or C-3′ protons), 2.03 (m, 1 H), 1.89 (m, 1 H), 1.68 (m, 1 H), 1.54 (m, 1 H), 1.46 (m, 1 H), 1.36 (m, 1 H), 1.14 (d, 3 H, CH_3), 0.94 (m, 1 H, C-6 proton).

GC/MS (80, 1, 15, 200, 2.02): (fraction D (**52**)) *m/e* 154 (4%, M), 139 (100%, $-CH_3$), 125 (43%, $-C_2H_5$ or CHO), 113 (21%, $-C_3H_5$), 99 (16% $-C_4H_7$), 86 (63%, $-C_5H_8$).

Table IV. GC Analysis[a] of the Reduction Products from the Pyrolysis Mixture Obtained from (−)-**17a**

fraction	relative area, % **55**	**54**	**53**
A	94.4, 93.2 (93.8)	5.6, 6.8 (6.2)	0, 0 (0)
B	8.8, 8.4 (8.6)	87.5, 87.8 (87.7)	3.70, 3.77 (3.7)
C	0, 0 (0)	4.7, 3.9 (4.3)	95.3, 96.1 (95.7)

[a] Values in parentheses represent average of two runs. Retention time (min, column H): **55**, 85.96; **54**, 97.33; **53**, 111.22.

Table V. Optical Rotations of Fractions A–C at Various Wavelengths

λ, nm	$[\alpha]^{23}$, deg A[a]	B[b]	C[c]
589	0.000	+0.293	−17.5
578	0.000	+0.293	−18.4
546	0.000	+0.147	−20.9
436	0.000	−0.147	−35.2
365	0.000	−0.440	−53.2

[a] 13.09 mg/2.0 mL of $CHCl_3$ (*c* 0.6545). [b] 13.65 mg/2.0 mL of $CHCl_3$ (*c* 0.6825). [c] 5.60 mg/1.0 mL of $CHCl_3$ (*c* 0.560).

Table VI. Optical Rotations of Diimide Reduction Products **55**, **54**, and **53** at Various Wavelengths

λ, nm	$[\alpha]^{23}$, deg **55**[a,b]	**54**[a]	**53**[a,c]
589	−0.07 (+68.6)	+1.12	−18.3 (−20.9)
578	−0.08 (+71.5)	+1.17	−19.3 (−21.7)
546	−0.07 (+81.4)	+1.11	−21.9 (−24.8)
436	−0.09 (+139)	+1.41	−36.9 (−41.3)
365	−0.13 (+219)	+1.89	−55.7 (−62.8)

[a] Rotation errors were typically about 1°. [b] Values in parentheses represent the specific rotations of optically pure (+)-**55**. [c] Values in parentheses represent the optical rotation of (−)-**53** from the diimide reduction of (−)-**17a** before rearrangement.

^{1}H NMR (270 MHz, $CDCl_3$): (fraction E (**56**)) δ 4.89 and 4.81 (two s, 1 H each, C-2 exocyclic methylene protons), 3.90 (m, 4 H, C-4′ and C-5′ protons), 2.20–1.80 (m, 2 H), 1.55 (m, 2 H), 1.00 (m, 1 H).

GC/MS (80, 1, 15, 200, 1.75): (fraction E (**56**)) *m/e* 152 (42% M), 151 (14%, −H), 112 (20%, $-C_3H_4$), 107 (15%, $-C_2H_5O$), 80 (58%, $-C_3H_4O_2$), 79 (100%, $-C_3H_5O_2$).

Due to the presence of impurities, fractions D and E were not analyzed further. Fractions A–C were collected and analyzed in duplicate by GC on column H (110, 170, 180); the results are given in Table IV. The optical rotation of each fraction was measured at five wavelengths (Table V). From this data, the optical rotations of the individual components **55**, **54**, and **53** were determined by solution of three simultaneous equations expressing the three observed rotations as weighted averages of the components. The solutions are given in Table VI. In order to determine the retention of ee, a sample of (−)-**17a** (66 ± 2%) was subjected to diimide reduction, and the product **53** was isolated as described above. The rotations of this material are listed in Table VI also.

Enantiomeric Purity of 17a by ^{1}H NMR Analysis Using Lanthanide Shift Reagent. A 10-mg sample of (+)- or (−)-**17a** was dissolved in 0.5 mL of $CDCl_3$ in an NMR tube and the 500-MHz ^{1}H spectrum recorded. A saturated solution of tris[3-[(heptafluoropropyl)hydroxymethylene]-*d*-camphorato]europium (Eu(hfc)$_3$) in $CDCl_3$ (250 mg/mL) was added to the NMR sample in 5–10-mL increments, and the spectrum was recorded after each increment. The optimum enantiomeric shift differences were usually realized after addition of 25–35 mL of shift reagent; further addition led to severe line broadening and loss of resolution. Under favorable circumstances, every proton shift of the **17a** spectrum responded. However, the C-3 proton showed the greatest enantiomeric shift difference, that of the (+) isomer moving downfield faster. The C-4 proton signals at about δ 6 were doubly irradiated, which led to collapse of the two C-3 proton doublets to base-line-resolved singlets, integration of which gave the % ee. The results reported are the averages of several repeated runs. In benzene-d_6 or with Yb(hfc)$_3$ as shift reagent, similar but less pronounced shift differences were observed. These procedures failed to give useful shift differences for compounds **43a**, **54**, **55**, or **48**.

Nuclear Overhauser Experiments. In a typical experiment, 10–15 mg of the compound in 0.5 mL of $CDCl_3$ or benzene-d_6 contained in an NMR tube was subjected to four freeze–pump–thaw cycles and sealed in vacuo. Spectra of **28** required high-field conditions because of chem-

ical shift proximities and were taken at 500 MHz. Other experiments gave satisfactory results at 250 MHz. Gated decoupling used a 5-s saturating pulse. Following a 1-ms delay, a 6-ms rf pulse (55° tip angle) initiated the FID with an acquisition time of 1.7 s. A 10-s relaxation time followed before repetition of the pulse sequence. The data were processed by the method of spectral subtraction to enhance sensitivity. The results were obtained and are presented in the following form: proton saturated; proton signal(s) observed to be enhanced (% enhancement).

19: H_a; H_b (11), H_f (4), H_e (4). H_b; H_a (9), H_c (6). H_f; H_a (9), H_b (4), H_g (4).

20: H_a; H_b (4), H_f (17), H_e (7). H_b; H_a (3), H_f (7). H_f; H_a (11), H_b (10), H_e (2).

25: H_a; H_b (4), H_c (7), H_d (1), H_f (4). H_b; H_a (3), H_c (2), $H_f + H_h$ (2), H_g (2). H_c; H_a (3), H_b (3), H_d (4), $H_g + H_h$ (3).

28: H_a; $H_b + H_c$ (15) (possible enhancement of H_d not observed because of chemical shift proximity to H_a). $H_b + H_c$; H_a (13). H_d (500-MHz spectrum); H_a (11), H_h (3).

36: H_a; H_b (slight enhancement of ring proton signals). H_b; H_a (4), $H_c + H_d$ (11).

Pyrolysis of Chlorides 24 and 23. A sample of a **24/23** mixture (exo/endo = 8:1) in benzene-d_6 was heated at 55 °C for 3 h (100% conversion) and analyzed by 500-MHz ^{1}H NMR. The major product (>98%) was identified as benzyl chloride. At least 20 extraneous signals, corresponding to 1-2% of the total signal intensity, were present but not diagnostic. Further heating did not alter the spectrum. Identical results were obtained upon pyrolysis of a similar sample at lower temperature (35-50 °C) or upon partial pyrolysis in CD_3CN or in the gas phase.

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Stereoelectronic Effects in Sulfate Diesters and Sulfuric Acid

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Abstract: An X-ray crystallographic investigation of two 2,2-dioxo-1,3,2-dioxathianes has been undertaken, together with a comparative study of 1,1-dioxothiane, in a search for evidence of stereoelectronic effects in sulfate diesters. However, the differences between the axial and equatorial S=O bond lengths observed are so small that they cannot be detected by the X-ray experiment. Ab initio calculations on sulfuric acid and dimethyl sulfate showed that the sulfur-oxygen bond overlap populations, electron density at the sulfuryl oxygen atoms, and conformational energy were dependent on the S-OH(Me) torsion angle. These effects are interpreted in terms of stereoelectronic interactions between σ and π nonbonding electron pairs on divalent oxygen and the antibonding orbitals of sulfur-oxygen bonds. If an anomeric effect is defined simply as any $n \rightarrow \sigma^*$ orbital mixing interaction, this stereoelectronic effect must be viewed, at least in part, as anomeric. The stereoelectronic effect operating in H_2SO_4 and sulfate diesters may weaken S-O single bonds and influence overall charge distribution. Stereoelectronic effects in the chair conformation of six-membered cyclic sulfates result in the axial sulfuryl bond being longer than the equatorial. The bond length difference is such that it cannot be detected with confidence in the X-ray structure determinations presented, but it could account for the observed differences in the vibrational spectra of isotopically labeled sulfates.

The anomeric effect is widely recognized as having a major influence on the conformational preference of molecules containing geminal electronegative substituents.[1] Although this phenomenon was originally associated with sugars containing the RO-C-OH grouping it is not restricted to molecules with carbon as the central element, for example, 2-oxo-1,3,2-dioxathiane (**1**) adopts the chair conformation with the S=O axial.[2] If the underlying cause of the anomeric effect is stereoelectronic it would be expected that in 2,2-dioxo-1,3,2-dioxathiane (**2**) the axial S=O bond would be longer and the force constant weaker than that of the equatorial S=O bond. Indeed the differential isotope shift caused by heavy oxygen isotopes in the axial and equatorial S=O bonds of 2,2-dioxo-1,3,2-dioxathianes on the symmetric and antisymmetric SO_2 stretching frequencies provided support for this interpretation.[3]

We now report an X-ray crystallographic investigation of 2,2-dioxo-1,3,2-dioxathiane (**2**) and its 5-phenyl derivative (**3**) in order to explore the axial and equatorial S=O bond lengths. Since the equatorial S=O bond should not be susceptible to the generalized anomeric effect it should provide a valuable internal reference. A comparative X-ray crystallographic study of 1,1-dioxothiane (**4**) is also reported.

We have undertaken ab initio calculations with geometry optimization of a number of parameters simultaneously, including sulfur-oxygen bond lengths. This allows direct comparison with the crystal structures of **2** and **3**. In addition, conformation scans have been performed on H_2SO_4 corresponding to rotation about the S-O single bonds and bond angle changes at sulfur. All calculations include Mulliken population analysis. Bond overlap populations are the most widely used indicators for stereoelectronic effects (e.g., in calculations on P(V) species[4,5]) and provide an assessment of bond lengthening/shortening effects for conformers that are not fully geometry optimized. Calculations were also performed on rotamers of dimethyl sulfate.

In this study, the STO-3G* basis set is employed for conformational analysis and geometry optimization. Significant conformers are checked by geometry optimization and point calculations at the 3-21G(*) level. Limited calculations with a 4-31G

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