Registry No.—**2,** 58240-96-3; **3,** 58240-97-4; **4,** 58240-98-5; **5,** 58240-99-6; **6,** 58241-00-2; **7,** 58267-55-3; **8,** 58241-01-3; **9,** 58341-82-5; **10,** 58249-35-7; **11,** 58241-02-4; **12,** 58241-03-5; **13,** 58241-04-6; **14,** 58241-05-7; **15,** 58241-06-8; *p*-chlorobenzyl chloride, 104-83-6; dimedone methyl ether, 4683-45-8; isophorone, 78-59-1; methyl bromide, 74-83-9.

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Zero Bridge Cleavage and a Neighboring Hydroxyl Group Effect in the Oxymercuration of Bicyclo[3.1.0]hexanes

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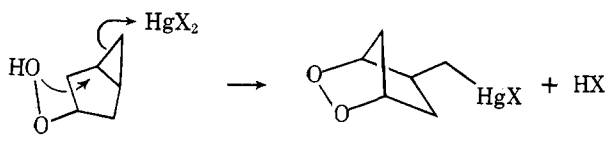
Cleavage of the zero bridge is a major pathway in the oxymercuration of all bicyclo[3.1.0]hexanes examined. Though a 3-acetoxy substituent has no effect on the competition between peripheral and bridge C–C bond cleavage, a cis or trans 3-hydroxyl group markedly promotes the latter. Thus, oxymercuration–acetylation–demercuration of *cis*-3-hydroxybicyclo[3.1.0]hexane (**3b**) gives mainly *cis*-1,3-diacetoxycyclohexane (83%). The intermediate mercurial from zero bridge cleavage of **3b** gives *cis*-1,3-diacetoxy-*cis*-5-chlorocyclohexane upon reaction with chlorine in pyridine. Hence, the electrophilic addition leading to zero bridge cleavage involves inversion of stereochemistry at the center of electrophilic attack as well as at the center of nucleophilic attack.

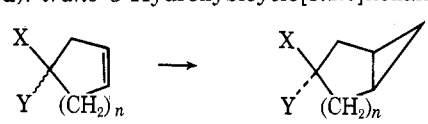
This study of the oxymercuration of bicyclic cyclopropanes is part of our general examination of the utility of oxymercuration reactions for the total synthesis of prostaglandin endoperoxides.[1] These biological precursors of prostaglandins are base-sensitive derivatives of 2,3-dioxabicyclo[2.2.1]heptane. Peroxymercuration of olefins[2] or cyclopropanes[3] which can be performed under neutral or mildly acidic conditions is especially attractive for the synthesis of base-sensitive secondary alkyl peroxides. Since inversion of configuration at the site of nucleophilic attack is strongly favored for oxymercuration of cyclopropanes,[18] intramolecular peroxymercuration of **1** is expected to lead to **2** by cleavage of a peripheral C–C bond of the three-membered ring. Moreover, oxymercuration of bicyclo[3.1.0]hexane is reported to result in the desired cleavage of a peripheral rather than bridge C–C bond of the three-membered ring.[4] However, we now report that cleavage of the bridge bond is a major pathway for oxymercuration of bicyclo[3.1.0]hexanes. We have also uncovered a novel neighboring group effect on the electrophilic cleavage of a cyclopropane. Thus, some substituents promote almost exclusive cleavage of the zero bridge in bicyclo[3.1.0]hexanes. Moreover, these bridge cleaving oxymercurations are stereospecific and provide an effective new route for the stereospecific synthesis of polysubstituted cyclohexanes.



1 2

Results

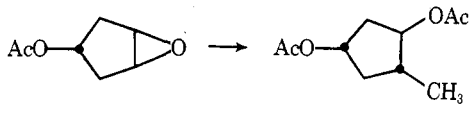
A. Syntheses of Oxymercuration Substrates and Products. Bicyclo[3.1.0]hexane (**3a**),[5] *cis*-3-hydroxybicyclo[3.1.0]hexane (**3b**),[6] and *cis*-3-hydroxybicyclo[4.1.0]heptane (**3c**)[7] were prepared by Simmons–Smith methylenation of the corresponding olefins. Acetylation of **3b** gave the acetate (**3d**). *trans*-3-Hydroxybicyclo[3.1.0]hexane (**3f**)[6] was



X=H or OH
n=1 or 2

3a, X = Y = H; n = 1
b, X = OH; Y = H; n = 1
c, X = OH; Y = H; n = 2
d, X = OAc; Y = H; n = 1
e, X, Y = O; n = 1
f, X = H; Y = OH; n = 1

obtained from the cis epimer (**3b**) by oxidation to the ketone (**3e**) with chromium trioxide–pyridine complex in methylene chloride followed by reduction with aluminum isopropoxide in 2-propanol. *cis*-1,3-Diacetoxycyclohexane (**4b**) and *trans*-1,3-diacetoxycyclohexane (**4c**) were prepared by acetylation of the commercially available diols. 1,3-Diacetoxy-4-methylcyclopentane (**5b**) was prepared by



6 5b

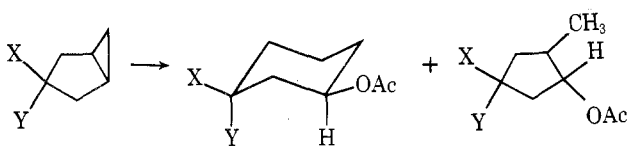
Table I. Product Distributions from Oxymercuration–Acetylation–Demercuration of Bicyclo[3.1.0]hexanes

	Product yields, %				
	Relative				
Reactant	4a[b]	4b[b]	4c[b]	5	Overall
3a (H,H)[a]	63			37 (a)[b]	95
3b (OH,H)		92	1[c]	8 (b)[b]	91
3d (OAc,H)		59	2[c]	39 (b)[b]	68
3f (H,OH)		5[c]	88	7 (c)[b]	58

[a] (X,Y). [b] a(H,H), b(OAc,H), c(H,OAc). [c] Maximum yield estimated by GC analysis of acetate mixture; not isolated.

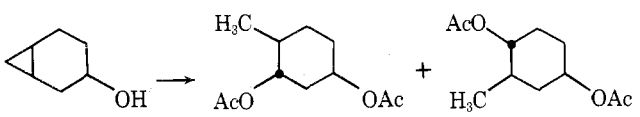
reaction of lithium dimethylcuprate with *trans*-1-acetoxy-3,4-epoxycyclopentane (**6**)[8] followed by acetylation of the product hydroxy acetate.

B. Oxymercuration Reactions. Oxymercuration–Acetylation–Demercuration. Levina et al.[4] reported that oxymercuration of bicyclo[3.1.0]hexane (**3a**) with aqueous mercuric acetate gives, after treatment with KBr, a single crystalline product (60%) with an elemental composition $C_6H_{11}OBrHg$ which was assumed to be 1-bromomercurimethyl-2-hydroxycyclopentane. However, the moderate material balance vitiates the conclusion that electrophilic cleavage of the three-membered ring occurs regiospecifically at the peripheral rather than bridge C–C bond. We now report that acetylation of the crude oxymercurial from **3a** with acetic anhydride in pyridine followed by demercuration with aqueous sodium borohydride gives a mixture of two acetates in 95% overall yield. These are cyclohexyl acetate (**4a**) and 2-methylcyclopentyl acetate (**5a**). The relative yields of these products as well as those from similar treatment of the substituted bicyclic cyclopropanes **3b, 3d,** and **3f** are given in Table I. Similar treatment of *cis*-3-hydroxybicyclo[4.1.0]heptane (**3c**) gives a 4:6 mixture of two



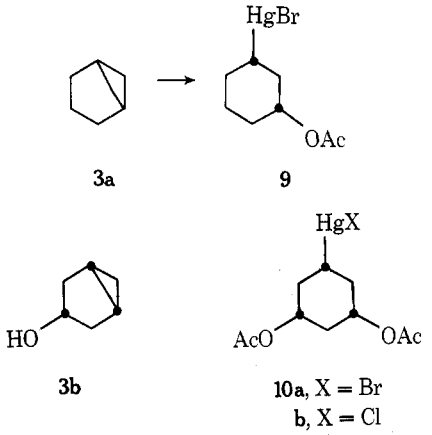
3 4 5

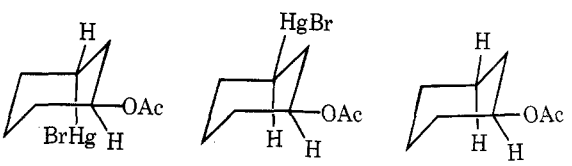
diacetates **7** and **8** in 98% yield. The structures indicated for these diacetates are assumed since a trans relationship between the methyl and vicinal acetate groups is expected from the proclivity for inversion of configuration at the site of nucleophilic attack in oxymercuration of cyclopropanes.[2c] The remaining acetate is assumed to be cis to the methyl group since the progenitors of these groups, the methylene of the cyclopropyl ring and the original hydroxyl group, were cis.

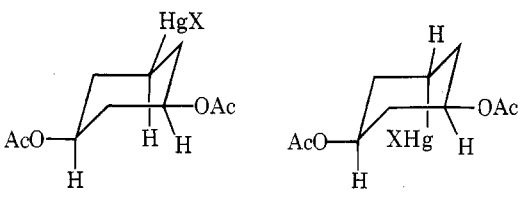


3c 7 8

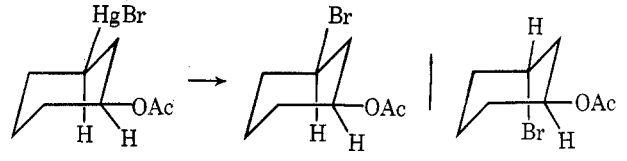
Isolation of Cyclohexyl Mercurials from 3a and 3b. In order to provide further evidence for bridge cleavage in the oxymercuration of bicyclo[3.1.0]hexanes, mercurials from zero bridge cleavage of bicyclo[3.1.0]hexane (**3a**) and *cis*-3-hydroxybicyclo[3.1.0]hexane (**3b**) were isolated. The crude organomercuric acetate product mixtures were converted into the respective organomercuric halides by reaction with potassium halide. Crystallization of the organomercuric halide mixtures from chloroform–ether gave isomerically pure samples of *cis*-1-acetoxy-3-chloromercuricyclohexane (**9**) and *cis*-1,3-diacetoxy-*cis*-5-halomercuricyclohexanes (**10**) from **3a** and **3b,** respectively. These structural assignments are based on an analysis of the ^1H NMR spectra of the halides obtained by reaction of the mercurials with halogen under conditions favoring complete retention of configuration.[9] Thus, *trans*-3-bromomercuricyclohexyl acetate (**9t**) will favor a conformation with an axial bromomercuri group and an equatorial acetoxy group since the *A* values for these groups are *A* = 0[10] and 0.7,[11] respectively. The C-1 proton resonance of the trans isomer will be shifted downfield from the chemical shift observed for the corresponding proton in the cis isomer (**9c**) owing to deshielding by the axial bromomercuri group.[12] Since only a single resonance is observed for this proton in the oxymercuration product, it follows that this product is only a single isomer. The similarity of the chemical shift for this proton (δ4.90) to that of the corresponding proton in cyclohexyl acetate (δ 4.80) suggests structure **9c** for the oxymercuration product. This assignment is confirmed below. Similarly, *trans*-5-halomercuricyclohexyl *cis*-1,3-diacetate (**11**) will favor a conformation with an axial halomercuri group and equatorial acetoxy groups. Again only a single resonance is found for the protons at C-1 and C-3. This suggests that the oxymercuration products are isomerically pure. The choice of structure **10** rather than **11** for the oxymercuration product is supported by further transformations outlined below.







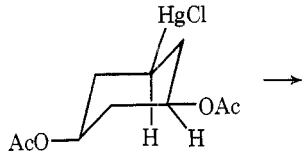
Reaction of **9c** with bromine in pyridine gives *cis*-3-bromocyclohexyl acetate (**12c**) with retention of the configuration at C-3.[9] The chemical shift of the C-1 proton resonance is δ 4.66 compared to δ 4.80 for cyclohexyl acetate. The corresponding proton in *trans*-3-bromocyclohexyl acetate (**12t**) is expected to absorb at considerably lower field



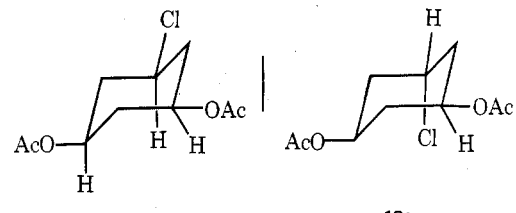
9c 12c 12t

owing to deshielding of the bromo group[13] for which A = 0.4.[11]

Reaction of *cis*-5-chloromercuri-*cis*-1,3-cyclohexyl diacetate (**10b**) with chlorine in pyridine gives *cis*-5-chloro-*cis*-1,3-cyclohexyl diacetate (**13c**) with retention of the configuration at C-5.[9] The chemical shift of the C-1 and C-3 pro-



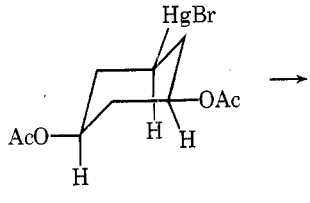
10b



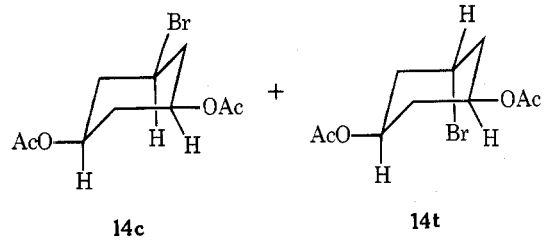
13c 13t

ton resonance is δ 4.75 compared to δ 4.70 in *cis*-1,3-cyclohexyl diacetate, and δ 4.80 for cyclohexyl acetate. The corresponding protons in *trans*-5-chloro-1,3-cyclohexyl diacetate are expected to absorb at considerably lower field owing to deshielding by the chloro group.[13]

Unexpectedly, reaction of *cis*-5-bromomercuricyclohexyl diacetate (**10a**) with bromine in pyridine gives an equal mixture of *cis*- and *trans*-5-bromo-1,3-cyclohexyl diacetates (**14c** and **14t**) with loss of configurational integrity at



10a

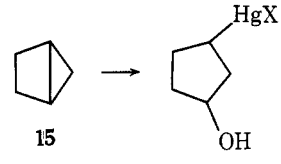


14c 14t

C-5. We have no explanation for this lack of stereospecificity. Though nonstereospecific reactions of mercurials with halogen are common, such reactions with pyridine as solvent generally are stereospecific.[9] The chemical shifts of the C-1, C-3, and C-5 ^{1}H NMR absorptions in **14c** and **14t** are clearly discernible from the spectrum of the mixture. The C-1 and C-3 proton resonances in **14c** occur at δ 4.4–5.0 compared to δ 4.75 in **13c**, δ 4.70 in *cis*-1,3-cyclohexyl diacetate, and δ 4.80 for the C-1 proton resonance in cyclohexyl acetate while the corresponding proton resonance for **14t** is at considerably lower field (δ5.24) owing to deshielding by the neighboring bromo group. Furthermore, the C-5 proton absorption in **14t** occurs at δ 4.4–5.0 which is considerably downfield from the corresponding absorption (δ 3.93) in **14c** in accord with the fact that equatorial proton resonances are about 0.45 ppm downfield from the corresponding axial proton resonances for cyclohexyl derivatives.[14]

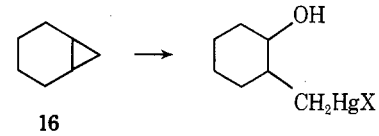
Discussion

A. Regioselectivity of Cyclopropane Cleavage in Bicyclo[3.1.0]hexanes. *Electrophilic cleavage of the cyclopropane ring of bicyclo[3.1.0]hexane* (**3a**) *is not regiospecific.* Thus, Markownikoff addition with cleavage of a peripheral cyclopropyl C–C bond of **3a** accounts for only 37% of the oxymercuration products. The major product (**4a**) arises by anti-Markownikoff oxymercuration with cleavage of the zero bridge bond of the cyclopropyl ring. While this behavior is unusual for oxymercuration of cyclopropanes in general,[15] it is precedented for reactive cyclopropanes in strained systems. Thus, bicyclo[2.1.0]pentane (**15**) undergoes exclusively anti-Markownikoff oxymercuration with rupture of the highly reactive zero bridge bond of the three-membered ring.[4] In contrast, oxymercuration of bicy-



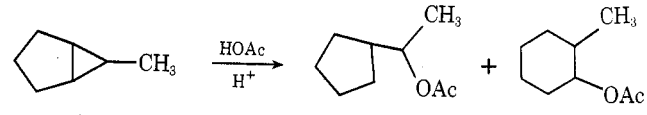
15

clo[4.1.0]heptane (**16**) results in exclusive Markownikoff addition with rupture of the peripheral C–C bond of the three membered ring.[4] Clearly, the extent of zero bridge



16

cleavage in oxymercuration of bicyclic cyclopropanes parallels the degree of ring strain in these molecules. The nonregiospecific, borderline behavior of bicyclo[3.1.0]hexane (**3a**) observed in the present study is consistent with the behavior of the derivatives of **3a** in other electrophilic addition reactions. Acid-promoted acetolysis of 6-methylbicyclo[3.1.0]hexanes (**17**) is nonregiospecific involving cleavage of both bridge and peripheral C–C bonds of the three-membered ring in similar yields.[16] Lead tetraacetate[17] and thal-



17

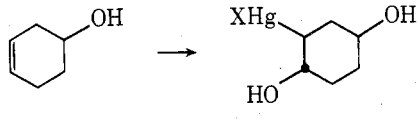
lium triacetate[17b] cleave the three-membered ring of bicyclo[3.1.0]hexane (**3a**) nonregiospecifically while they regiospecifically cleave the zero bridge of bicyclo[2.1.0]pentane (**15**).

B. Stereoselectivity of Electrophilic Addition to the Zero Bridge in Bicyclo[3.1.0]hexanes. The carbon center undergoing nucleophilic attack generally undergoes inversion of stereochemistry during oxymercuration of cyclopropanes.[18] The data in Table I show that nucleophilic attack during zero bridge cleavage of **3b**, **3d**, and **3f** involves almost exclusive inversion stereochemistry.

Cyclopropanes can undergo attack by electrophiles with either inversion or retention of configuration at the carbon to which the electrophile becomes attached.[18] The differ-

ence in energy for retention vs. inversion is small. In the present work, the mercurials **9** and **10** resulting from zero bridge cleavage in **3a** and **3b** were isolated in good yields by crystallization from the reaction product mixtures. The mercurials are each a single isomer. The formation of minor amounts of isomeric mercurials cannot be ruled out since the material balance is not quantitative. Nevertheless the addition of the electrophile involves predominant, if not exclusive, inversion of configuration at the carbon undergoing electrophilic attack. In the case of **3a,** we assume that addition of the nucleophile involves inversion of configuration at carbon. The cis relationship of the mercuribromide and acetate substituents in the bridge cleaved product (**9**) establishes an inversion pathway for attack by the electrophile.

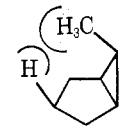
C. Neighboring Group Effect in Electrophilic Cleavage of Cyclopropanes. The influence of substituents in determining the stereochemistry of electrophilic addition during oxymercuration of *olefins* is well known.[19] Thus, cyclohexenes with polar (Lewis base) substituents in the 4 position undergo stereospecific and position specific oxymercuration.[19a] The mercuric group always adds to the 2 position from the same side of the ring as the original substituent while the nucleophile adds to the 1 position trans to the mercury. The stereoselectivity observed was attrib-



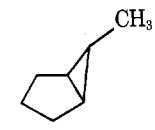
uted to a combination of two factors: preferential diaxial opening of an initial mercurinium ion through a chairlike transition state and preferential formation of a cis mercurinium ion owing to coordinative stabilization by the polar substituent. The position specificity is generally held to result from an inductive effect of the substituent. A similar, though less pronounced,[19c] substituent effect was reported for the oxymercuration of cyclohexenes with polar substituents in the 3 position.[19b] The importance of a coordinative interaction between polar substituent and mercury in directing mercuration has been questioned.[19f,g] Such an interaction in the oxymercuration of cyclohex-2-enols is either very small or nonexistent and the directing effect of hydroxyl substituents in these systems can be accounted for by their effect on conformational equilibria. This conclusion cannot be extrapolated to all unsaturated alcohols. In particular the operation of a product-determining coordinative interaction between substituents and mercury in oxymercuration of cyclohex-3-en-1-ols is not doubted.

In the present study a novel effect of a neighboring hydroxyl group was uncovered in which the substituent moderates the reaction pathway in oxymercuration of cyclopropanes. Thus, cleavage of the three-membered ring during oxymercuration of bicyclo[3.1.0]hexane (**3a**) occurs nonregiospecifically. Rupture of the zero bridge is slightly favored over rupture of a peripheral C–C bond. The reaction pathway is *not* changed by an acetate substituent in the 3 position (i.e., **3d**). In contrast, a hydroxyl group in the 3 position profoundly alters the reaction pathway. Both *cis*- and *trans*-bicyclo[3.1.0]hexan-3-ol (**3b** and **3f**) exhibit an unusually high proclivity toward anti-Markownikoff electrophilic addition resulting in selective cleavage of the zero bridge bond of the bicyclic cyclopropanes during oxymercuration.

The endo methyl substituent in **17n** increases the ring strain in this bicyclic cyclopropane relative to **17x,** which has an exo methyl substituent. The direct relationship between the extent of zero bridge cleavage and ring strain was invoked to account for the greater proportion of zero bridge cleavage during acid-promoted acetolysis of **17n** relative to that found for **17x.**[16]



17n



17x

The cis 3-hydroxyl group in **3b** might cause an increase in ring strain compared to **3a.** However, such increased ring strain cannot account for the greater proportion of zero bridge cleavage during oxymercuration observed for **3b** relative to **3a.** A similar increase in ring strain should result from the cis 3-acetoxy group in **3d.** However, no increase in the extent of zero bridge cleavage is observed for oxymercuration of **3d** compared with **3a.** Furthermore, the trans 3-hydroxyl group in **3f** also promotes zero bridge cleavage relative to **3a.** However, no increase in ring strain is expected in **3f** compared to **3a.**

The hydroxyl group in **3b** and **3f** may exert its influence on the reaction pathway through coordination with the electrophile as postulated for the influence of the hydroxyl group in oxymercuration of cyclohex-3-en-1-ols. Or the hydroxyl group may interact with the attacking nucleophile by hydrogen bonding. It is not clear why such interactions with *either* a cis or trans hydroxyl group would promote zero bridge cleavage. A satisfactory explanation of the mechanistic basis of this novel neighboring hydroxyl group effect must await further study.

Conclusion

Oxymercuration–acetylation of hydroxylated bicyclic cyclopropanes gives good to excellent yields of diacetoxy mercurials. Cleavage of the zero bridge is a major pathway for all of the bicyclo[3.1.0]hexyl compounds examined. An acetoxy substituent in the 3 position has little effect on the competition between cleavage of the zero bridge and the peripheral cyclopropyl C–C bonds. In sharp contrast, a 3-hydroxy substituent promotes almost exclusive cleavage of the zero bridge, and the electrophilic addition involves predominant double inversion. Oxymercuration of bicyclo[3.1.0]hexanes is thus a useful reaction for the stereospecific synthesis of polysubstituted cyclohexanes. The effect of a neighboring hydroxyl group does not extend to the next larger homologue. A 3-hydroxy substituent does not lead to zero bridge cleavage of bicyclo[4.1.0]heptane.

Experimental Section

General. Analytical gas–liquid phase chromatography was performed with a Varian Model 1400 flame ionization detector chromatograph utilizing a 15 ft × 0.125 in. column containing 15% FFAP (Free Fatty Acid Phase) on Chromosorb P at 190° (column 1). Preparative GLC was performed with a Varian Model 202B instrument utilizing a 10 ft × 0.25 in. column containing 10% DEGS (diethylene glycol succinate) on 60/80 Chromosorb P at 180 °C (column 2) or a 10 ft × 0.25 in. column containing 10% FFAP on 60/80 Chromosorb P at 180 °C (column 3). Proton magnetic resonance spectra were recorded with a Varian A-60A or HA-100 FT spectrometer with tetramethylsilane as internal standard (except for mercurials) and $CDCl_3$ as solvent unless indicated otherwise. Mass spectra were determined with a Du Pont Model 21-094 GC–MS with computer analysis. Boiling points are uncorrected. Melting points were measured with a Thomas-Hoover capillary melting point apparatus. Microanalyses were performed by Chemalytics, Inc., Tempe, Ariz.

Materials. Bicyclo[3.1.0]hexane (**3a**),[5] *cis*-3-hydroxybicyclo[3.1.0]hexane (**3b**),[6] *trans*-3-hydroxybicyclo[3.1.0]hexane (**3f**),[6] *cis*-3-hydroxybicyclo[4.1.0]heptane (**3c**),[7] and *trans*-6-oxabicyclo[3.1.0]hexan-3-ol acetate (**6**)[8] were prepared by reported procedures.

***cis*-3-Acetoxybicyclo[3.1.0]hexane (3d).** The cis alcohol **3b**[6]

(1.2 g, 12.2 mmol) was treated with acetic anhydride (3.68 g, 720 mmol) and pyridine (2 ml). The resulting solution was heated at 60 °C for 6 h and then stirred overnight at room temperature. The mixture was diluted with ether (50 ml) and washed with cold saturated aqueous $NaHCO_3$ and cold 10% HCl. The ether solution was dried ($MgSO_4$), filtered, and concentrated by rotary evaporation to give a colorless oil (1.7 g, 98%): ^1H NMR δ 0.40 (m, 2 H), 1.30 (m, 2 H), 2.00 (s, 3 H), 1.80–2.50 (m, 4 H), 5.20 (t, 1 H, J = 6.5 Hz); mass spectrum (70 eV) m/e (rel intensity) 43 (74), 79 (57), 80 (100), 81 (97), 140 (22).

***cis*-1,3-Diacetoxycyclohexane (4b).** A commercial mixture of isomeric 1,3-cyclohexanediols (Aldrich) was acetylated as for **3d** above. A sample of the pure cis isomer was obtained from the resulting mixture of acetates by preparative GLC (column 3): ^1H NMR δ 2.0 (s, 6 H, OAc), 1.10–2.40 (m, 8 H, C-2, 4, 5, 6), 4.70 (m, 2 H, C-1, 3). Relative retention times of the cis and trans isomers are 1.2 and 1.0, respectively. Reduction of this diacetate with lithium aluminum hydride in ether afforded a diol which was identical (^1H NMR) with authentic *cis*-1,3-cyclohexanediol.[20]

***trans*-1,3-Diacetoxycyclohexane (4c).** This was also isolated from the above mixture: ^1H NMR δ 1.5–2.9 (m, 8 H, C-2, 4, 5, 6), 2.0 (s, 6 H, OAc), 5.10 (m, 2 H, C-1, 3).

Oxymercuration–Acetylation–Demercuration of Bicyclo[3.1.0]hexane (3a). To mercuric acetate (2.39 g, 7.50 mmol) was added **3a** (600 mg, 7.31 mmol) and water (7 ml). The mixture was magnetically vigorously stirred in a stoppered flask for 24 h at room temperature. The water was removed in vacuo (2.5 mm) and the residual colorless oily solid was acetylated with an excess of acetic anhydride in pyridine (10:1 anhydride:mercurial) at ambient temperature over 24 h. Volatiles were removed in vacuo (2 mm) and the residual oil was reduced with $NaBH_4$ (1 g) in water (10 ml) over 24 h. The product was extracted into ether (3 × 17 ml). The extract was washed with cold 10% HCl followed by saturated aqueous $NaHCO_3$, dried ($MgSO_4$), and filtered. Solvent was removed by distillation leaving a mixture of acetates (0.97 g, 98%). Analysis of the mixture by GLC (column 1) revealed two components in a ratio of 37:63 with relative retention times 1.00 and 1.36, respectively. The products were separated by preparative GLC (column 2). The component of longer retention time was identified as cyclohexyl acetate by NMR spectrum and GLC retention time: ^1H NMR δ 2.0 (s, 3 H, OAc), 1.1–2.35 (10 H), 4.80 (m, 1 H, C-1). The minor component, **2-methylcyclopentyl acetate (5a),** was characterized as follows: ^1H NMR δ 0.90 (d, 3 H, J = 6.5 Hz, methyl), 2.0 (s, 3 H, OAc), 1.30–2.20 (7 H), 4.65 (m, 1 H, C-1).

Anal. Calcd for $C_8H_{14}O_2$: C, 67.61; H, 9.86. Found for **5a:** C, 67.77; H, 10.16.

Oxymercuration–Acetylation–Demercuration of *cis*-Bicyclo[3.1.0]hexan-3-ol (3b). A mixture of mercuric acetate (1.69 g, 5.30 mmol) and **3b**[6] (500 mg, 5.10 mmol) in water (3 ml) was vigorously magnetically stirred at room temperature for 3 h. Water was then removed in vacuo (1 mm) to give 2.24 g of crude oily mercurial. This product was acetylated with acetic anhydride (1.1 ml, 50 mmol) and pyridine (4 ml, 50 mmol) by stirring at room temperature for 2 days. Volatile components of the resulting mixture were removed in vacuo (1 mm) and the residual oil was reduced with sodium borohydride (1.5 g) in water by stirring for 3 h at room temperature. The products were extracted into ether (3 × 20 ml). The combined extracts were washed with aqueous 10% HCl and then saturated aqueous $NaHCO_3$, dried ($MgSO_4$), and filtered, and solvents were removed by rotary evaporation to give a mixture of acetates (0.92 g, 90%); GLC analysis (column 1) indicated three components with relative retention times 1.00, 1.27, and 1.55 in a ratio of 7.6:1.4:91.0, respectively. The two major components were isolated by preparative GLC (column 3) and identified as **4b** (91% component) and **5b** (8% component): ^1H NMR δ 1.10 (d, 3 H, J = 6.4 Hz, methyl), 1.2–2.5 (5 H), 2.03 (s, 6 H, OAc), 4.84 (m, 1 H), 5.20 (m, 1 H). The minor component, which has a GLC retention time (column 1) identical with that of an authentic sample of **4c,** was not isolated.

Oxymercuration–Acetylation–Demercuration of *cis*-Bicyclo[3.1.0]hexan-3-ol Acetate (3d). A mixture of mercuric acetate (2.58 g, 8.0 mmol) and **3d** (1.10 g, 7.85 mmol) in water (3 ml) was vigorously stirred at room temperature for 20 h. Volatile components of the mixture were then removed in vacuo (2 mm). The residue was acetylated and demercurated as for **3b** above to give a mixture of acetates (1.1 g, 68%) consisting of three components (GLC analysis on column 1) in a ratio of 39:2:59. The two major components were isolated by preparative GLC (column 3) and identified as **4b** (59% component) and **5b** (39% component). The minor component, which has a GLC retention time (column 1) identical with that of an authentic sample of **4c,** was not isolated.

Oxymercuration–Acetylation–Demercuration of *trans*-Bicyclo[3.1.0]hexan-3-ol (3f). A mixture of mercuric acetate (488 mg, 1.55 mmol) and **3f**[6] (147 mg, 1.50 mmol) in water (2 ml) was vigorously magnetically stirred at room temperature for 20 h. The water was removed in vacuo (2 mm) and the residue acetylated and demercurated as for **3b** above to give a mixture of acetates (175 mg, 58%) consisting of three components in a ratio of 7:88:5. The minor component, which has a GLC retention time (column 3) identical with that of **4b,** was not isolated. The other two components were isolated by preparative GLC (column 3) and identified by ^1H NMR comparison with authentic samples. The major product (88% component) is **4c** and the third product (7% component) is **5c.**

***cis*-4-Methyl-*trans*-1,3-cyclopentyl Diacetate (5b).** Methyllithium (75 mmol) in ether (51 ml) was added dropwise under nitrogen at 0 °C to a mechanically stirred suspension of CuI (7 g, 37 mmol) in ether (340 ml). After stirring for 0.5 h, a clear gray solution was obtained. *trans*-6-Oxabicyclo[3.1.0]hexan-3-ol acetate (**6**,[8] 2.6 g, 18.7 mmol) was added in one portion. The resulting mixture was stirred at 0 °C for 12 h. Ice-cold aqueous 10% HCl was then added dropwise. The organic phase was separated, washed with saturated aqueous sodium bicarbonate and then saturated aqueous sodium chloride, dried ($MgSO_4$), filtered, and concentrated by rotary evaporation. The residue was acetylated with acetic anhydride in pyridine to give crude **5b** (1.2 g) as a yellow oil. Pure **5b** was obtained by preparative GLC (column 2): ^1H NMR δ 1.10 (d, 3 H, J = 6.5 Hz, methyl), 1.2–2.5 (5 H), 2.03 (s, 6 H, OAc), 4.85 (m, 1 H), 5.20 (m, 1 H); mass spectrum (70 eV) m/e (rel intensity) 43 (100), 80 (66), 81 (25), 140 (36), 200 (1).

Oxymercuration–Acetylation–Demercuration of *cis*-Bicyclo[4.1.0]heptan-3-ol (3c). A mixture of mercuric acetate (1.47 g, 4.60 mmol) and **3c**[7] (500 mg, 4.47 mmol) in water (3 ml) was vigorously stirred magnetically. After 2 min the reaction mixture had become homogeneous and the mixture was stirred for an additional 1.5 h at room temperature. Volatile components of the reaction mixture were removed in vacuo (1 mm) and the residue was acetylated and demercurated as for **3b** above to give a mixture of acetates (0.94 g, 98%) consisting of two components in a ratio of 59:41 with relative GLC retention times of 1.00 and 1.24, respectively (column 2). Pure samples were obtained by preparative GLC (column 2, 185 °C) of diacetate I (59% component) and diacetate II (41% component). Diacetate I: ^1H NMR δ 0.94 (d, 3 H, J = 5 Hz, methyl), 1.3–2.5 (7 H), 2.07 (2 s, 6 H, acetate methyls), 4.80 (m, 1 H, α to OAc), 5.17 (m, 1 H, α to OAc).

Anal. Calcd for $C_{11}H_{18}O_4$: C, 61.68; H, 8.41. Found for I: C, 61.52; H, 8.57. Diacetate II: ^1H NMR δ 0.94 (d, 3 H, J = 5 Hz, methyl), 1.0–2.2 (7 H), 2.00 (s, 3 H, OAc), 2.05 (s, 3 H, OAc), 4.1–5.0 (2 H, α to OAc).

Anal. Calcd for $C_{11}H_{18}O_4$: C, 61.68; H, 8.41. Found for II: C, 61.57; H, 8.62.

***cis*-3-Bromomercuricyclohexyl Acetate (9).** Acetylated mercurial was prepared from bicyclo[3.1.0]hexane (**3a,** 17.3 mmol) as described above. Chromatography of this product on 80–200 mesh silica gel (40 g) afforded a light yellow oil which was treated with a twofold excess of KBr in water. The reaction mixture was extracted with ether and the extract dried ($MgSO_4$) and filtered, and solvent was removed by rotary evaporation. The oily, semisolid residue was triturated with cold ether (10 ml) to leave white, crystalline **9** (42%): mp 120.5–123.5 °C; ^1H NMR δ (CH_2Cl_2 as internal standard) 1.5–2.3 (8 H, C-2, 4, 5, 6), 2.10 (s, 3 H, OAc), 2.85 (m, 1 H, C-3), 4.90 (m, 1 H, C-1).

Anal. Calcd for $C_8H_{13}O_2HgBr$: C, 22.79, H, 3.11. Found for **9:** C, 22.88; H, 3.08.

Reduction of the oily residue, obtained from concentration of the ether extract from the above trituration, with aqueous sodium borohydride gave mainly 2-methylcyclopentyl acetate (**5a,** 32%).

***cis*-5-Bromomercuri-*cis*-1,3-cyclohexyl Diacetate (10a).** Acetylated mercurial was prepared from *cis*-bicyclo[3.1.0]hexan-3-ol (**3b,** 5.1 mmol) as described above. Treatment with a twofold excess of KBr in water gave a white, crystalline precipitate which was collected by filtration with suction. The solid was dissolved in chloroform. The solution was dried ($MgSO_4$), filtered, and concentrated. Crystallization of the residue from chloroform–ether gave **10a** as white needles: mp 141–142 °C (56%); ^1H NMR δ (CH_2Cl_2 as internal standard) 1.84–2.25 (6 H, C-2, 4, 6), 2.10 (s, 6 H, OAc), 2.64 (q, 1 H, J = 4 Hz, C-5), 5.00 (quintet, 2 H, J = 4 Hz, C-1, 3).

Anal. Calcd for $C_{10}H_{15}O_4HgBr$:C, 25.04; H, 3.13. Found for **10a:** C, 25.16; H, 2.83.

***cis*-5-Chloromercuri-*cis*-1,3-cyclohexyl Diacetate (10b).**

Acetylated mercurial from **3b** was treated with a twofold excess of NaCl in water in analogy with the preparation of **10a** above. It was characterized by the near identity of its NMR spectrum with that of **10a:** ^{1}H NMR δ ($CHCl_3$ as internal standard) 1.50–2.27 (5 H, C-2, 4, 6), 2.12 (s, 6 H, OAc), 2.60 (q, 1 H, J = 4.5 Hz, C-5), 5.06 (quintet, 2 H, J = 3.7 Hz, C-1, 3).

3-Bromocyclohexyl Acetate (12). A solution of 3-bromomercuricyclohexyl acetate (**9,** 1.0 g, 2.38 mmol) in anhydrous pyridine (4 ml) was treated dropwise with a solution of bromine (0.64 g, 4 mmol) in pyridine (2 ml) at −40 °C. After the resulting mixture was stirred for 10 min, it was allowed to warm to 25 °C and then stirred for 1.5 h. Pyridine was removed by rotary evaporation and the oily solid residue was taken up in ether (50 ml). The solution was washed with saturated aqueous $NaHCO_3$ and then with saturated aqueous $CuSO_4$, dried ($MgSO_4$), and concentrated by rotary evaporation. The NMR spectrum of this crude material indicated almost pure **12.** A pure sample was obtained by preparative GLC (column 2): 100 MHz ^{1}H NMR δ 1.0–2.4 (8 H, C-2, 4, 5, 6), 2.03 (s, 3 H, OAc), 3.95 (tt, 1 H, J = 4, 14 Hz, C-3), 4.66 (tt, 1 H, J = 4, 11 Hz, C-1); mass spectrum (70 eV) m/e (rel intensity) 43 (92), 61 (11), 81 (100), 162 (7), 221 (63), 223 (58).

***cis*-5-Chloro-*cis*-1,3-cyclohexyl Diacetate (13c).** A solution of chlorine (1.5 ml of 1.75 M) in CCl_4 was added dropwise to a solution of *cis*-5-chloromercuri-*cis*-1,3-cyclohexyl diacetate (**10b,** 385 mg, 0.89 mmol) in pyridine (8 ml) at −40 °C under nitrogen. The resulting mixture was stirred at −40 °C for 1 h, then allowed to warm to room temperature and stirred for an additional 1 h. Solvents were removed by rotary evaporation and the residue was taken up in ether (50 ml). The solution was washed with saturated aqueous $NaHCO_3$ and then with saturated aqueous $CuSO_4$, dried ($MgSO_4$), filtered, and concentrated by rotary evaporation to give **13c** (121 mg, 58%): ^{1}H NMR δ 1.45 (d, 2 H, J = 11.5 Hz, C-4, 6), 1.85 (d, 2 H, J = 11.5 Hz, C-4, 6), 2.05 (s, 6 H, OAc), 2.1–2.8 (m, 2 H, C-2), 3.84 (tt, 1 H, J = 4, 12 Hz, C-5), 4.75 (tt, 2 H, J = 4.3, 12 Hz, C-1, 3); mass spectrum (70 eV) m/e (rel intensity) 43 (100), 79 (40), 96 (49), 97 (23), 114 (13), 138 (13), 139 (21), 174 (17), 234 (12), 236 (4).

Bromination of *cis*-5-Bromomercuri-*cis*-1,3-cyclohexyl Diacetate (10a). A solution of bromine (0.64 g, 4 mmol) in pyridine (2 ml) was added to a solution of **10a** (1.5 g, 3.14 mmol) in pyridine (6 ml) at −40 °C under an atmosphere of dry nitrogen. After completion of the addition the solution was warmed to room temperature and stirred for 2.5 h. Pyridine and other volatiles were removed in vacuo (4 mm) and the oily residue was taken up in ether (100 ml). The solution was washed with saturated aqueous $NaHCO_3$ and then saturated aqueous $CuSO_4$, dried ($MgSO_4$), filtered, and concentrated by rotary evaporation. This material was passed through a column of 80–200 mesh silica gel (10 g) with chloroform as eluting solvent. Removal of solvent by rotary evaporation gave a mixture of isomeric 5-bromo-*cis*-1,3-cyclohexyl diacetates (68%): ^{1}H NMR δ 1.3–2.8 (6 H, C-2, 4, 6), 2.00 (s, 6 H, OAc), 3.93 (tt, 0.5 H, J = 4, 12 Hz, C-5 in *cis*-5-bromo), 4.4–5.0 (1.5 H, C-1, 3 in *cis*-5-bromo and C-5 in *trans*-5-bromo), 5.24 (tt, 1 H, J = 4.5, 7.5 Hz, C-1, 3 in *trans*-5-bromo); mass spectrum (70 eV) m/e (rel intensity) 41 (28), 43 (100), 61 (36), 67 (23), 69 (31), 79 (58), 83 (39), 176 (31), 178 (29), 218 (30), 220 (31), 279 (25), 281 (25).

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Registry No.—**3a,** 285-58-5; **3b,** 694-43-9; **3c,** 40213-64-7; **3d,** 58268-46-5; **3f,** 694-44-0; **4b,** 832-09-7; **4c,** 26688-53-9; **5a,** 40991-94-4; **5b,** 58268-47-6; **5c,** 58311-28-7; **6,** 25494-20-6; **7,** 58268-48-7; **8,** 58268-49-8; **9c,** 58268-50-1; **10a,** 58268-51-2; **10b,** 58268-52-3; **12c,** 58268-53-4; **13c,** 58268-54-5; **14c,** 58268-55-6; **14t,** 58268-56-7; acetic anhydride, 108-24-7; *cis*-1,3-cyclohexanediol, 823-18-7; *trans*-1,3-cyclohexanediol, 5515-64-0; mercuric acetate, 1600-27-7; cyclohexyl acetate, 622-45-7.

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Stereochemistry of Reactions of Silacyclobutanes

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Preparations and separations of geometric isomers and structural assignments based on NMR spectra are described for a number of 1-substituted 1,2-dimethylsilacyclobutanes. The stereochemical course for a number of reactions of these derivatives has been determined. There is a decided bias toward retention in the strained ring system even for reactions that are inversions in unstrained organosilanes; nevertheless, inversion can be observed to occur. Mechanistic possibilities are discussed, and an unusual temperature dependence of stereochemical outcome for Br_2 cleavage of an aryl–silicon bond is described.

In recent years considerable attention has been devoted to stereochemical studies of reactions at nonmetal atoms incorporated in strained cyclic systems. Such studies have been particularly important in development of a comprehensive rationalization of the relations between stereochemistry and mechanism in substitution reactions at four-coordinate phosphorus,[1] and recently unusual stereochemical outcomes for reactions at carbon atoms in small rings