Anal. Calcd for $C_{17}H_{17}NO_2$: C, 76.38; H, 6.41; N, 5.23. Found: C, 76.22; H, 6.41; N, 5.20.

Spectroscopic Detection of the Iminium Ions. NMR Spectra. A solution of the α-oxo amide (**1**) (5 mg) in 0.5 mL of CD_3OD containing D_2SO_4 (5%) was irradiated in an NMR tube with a 300-W high-pressure mercury lamp at -78 °C for 10-20 min. The NMR spectra were measurd at -50 °C immediately after the irradiation.

Visible Spectra. A solution of **1** (2-3 mg) in 3 mL of CH_3OH containing H_2SO_4 (5%) was irradiated in a cell for UV spectroscopy at -78 °C for 10-20 min. The visible spectra were recorded immediately after the irradiation.

Photolysis of Cyclohexyl Benzoylformate (12) in the Presence of Imines. The ester (200 mg) and an equimolar amount of the imine (**6**) were dissolved in dry benzene (10 mL). The solution was placed in a Pyrex tube and 1.5 g of molecular sieves (4 Å) was added. The tube was sealed, allowed to stand overnight, and then irradiated with a 1000-W high-pressure mercury lamp at 80 °C. After removal of the solvent, the product was isolated by flash chromatography on silica gel.

Acknowledgment. We thank Associate Professor O. Kikuchi for his helpful suggestions and discussions on the problems of diradicals and zwitterions. This research was supported by a Grant-in-Aid from the Ministry of Education, Science and Culture, Japan (No. 464160).

Registry No. 1b, 22381-21-1; **1c**, 64201-02-1; **1d**, 64201-00-9; **1e**, 84731-08-8; **1f**, 84731-09-9; **1g**, 84711-82-0; **1h**, 51804-83-2; **1i**, 40991-79-5; **1j**, 64201-19-0; **1k**, 84711-83-1; **2b**, 64201-17-8; **2d**, 64201-13-4; **2e**, 84711-90-0; **2f**, 84711-84-2; **2g**, 84711-91-1; **2h**, 64201-09-8; **2l**, 84711-85-3; **2j**, 64201-08-7; **2k**, 84711-86-4; **3d**, 64201-07-6; **3e**, 84711-87-5; **3f**, 84711-88-6; **3i**, 64201-01-0; **3j**, 64200-99-3; **3k**, 84711-89-7; **7b**, 84711-92-2; **7g**, 84711-93-3; **12**, 61598-01-4.

Alkoxides as Nucleophiles in (π-Allyl)palladium Chemistry. Synthetic and Mechanistic Studies

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Abstract: A new methodology for the use of alkoxides as nucleophiles in (π-allyl)palladium chemistry has been developed. In this process an allylic alcohol serves as the precursor to the π-allyl complex and a triethylsilyl (TES) ether as precursor to the alkoxide nucleophile. By using $Pd(PPh_3)_4$ in CCl_4, $PPh_3Cl^+CCl_3^-$ is generated transposing the ROH into an oxyphosphonium group, $R-O-P^+Ph_3$, and liberating Cl^-. The Cl deprotects the TES ether, providing the nucleophile in situ. Application of this reaction to the preparation of a variety of furans is discussed. This process was determined to proceed with overall predominant retention of configuration. Mechanistic studies suggest a small energy difference between attack by alkoxide on the allyl ligand of the intermediate complex and attack on the metal, followed by reductive elimination.

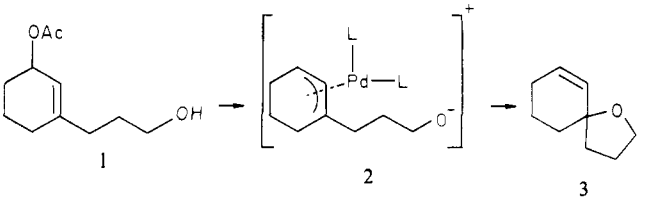
Introduction

Alkoxides have been of only limited utility as nucleophiles in (π-allyl)palladium chemistry. To date, only sodium salts of methanol, benzyl alcohol, and phenol have been successfully employed in transetherification reactions in synthetically useful yields.[1] As constituted, this process requires large amounts of palladium catalyst (2 equiv) and relatively high temperatures (60-85 °C).[1] In addition, the stereochemistry of this reaction has not been investigated further stifling its exploitation as a synthetic methodology.

Our efforts in the use of alkoxides in (π-allyl)palladium chemistry have resulted in the elucidation, including overall stereochemistry, of a process that occurs at modest temperatures, involves significantly smaller amounts of catalyst, and originates from a functionally simplified precursor. In addition, our studies of the mechanism and stereochemistry of this reaction suggest that alkoxides may exhibit a relatively small energy difference between the usual attack by nucleophiles on the allyl ligand and attack at the metal center followed by reductive elimination.

Results and Discussion

Preliminary Studies. Initial efforts centered on the preparation of the allylic acetate **1**, as a precursor to the required π-allyl complex **2**. Cyclization of **2** was expected to provide the spirofuran **3** in strict analogy with results obtained with carbon[2] and amine[3] nucleophiles. The synthesis of **1** was accomplished as outlined in Scheme I. The sequence was initiated by the reaction of the Normant Grignard[4] reagent derived from 3-chloropropanol with the vinylogous ester 3-ethoxy-2-cyclohexen-1-one. The resulting keto-alcohol **4** was converted to its triethylsilyl ether ((TES)Cl, NEt_3, THF, room temperature) and then reduced to the allylic alcohol **5** (DIBAL-H, $PhCH_3$, -40 °C). Acetylation (Ac_2O, NEt_3, DIMAP,[5] CH_2Cl_2, 0 °C) and desilation (NEt_3-HF, CH_3CN, 60 °C) provide **1** in 64% yield from the vinylogous ester. Treatment of **1** with any one of a variety of hydride bases (Li, Na, K) followed by 5-7 mol % of $Pd(DIPHOS)_2$ or $Pd(PPh_3)_4$ in refluxing THF resulted in destruction of catalyst and only poor yields of spirofuran **3**. Optimal yields (30%) were obtained by



1 2 3

(1) Takahashi, K.; Miyake, A.; Hata, G. *Bull. Chem. Soc. Jpn.* **1972**, *45*, 230.

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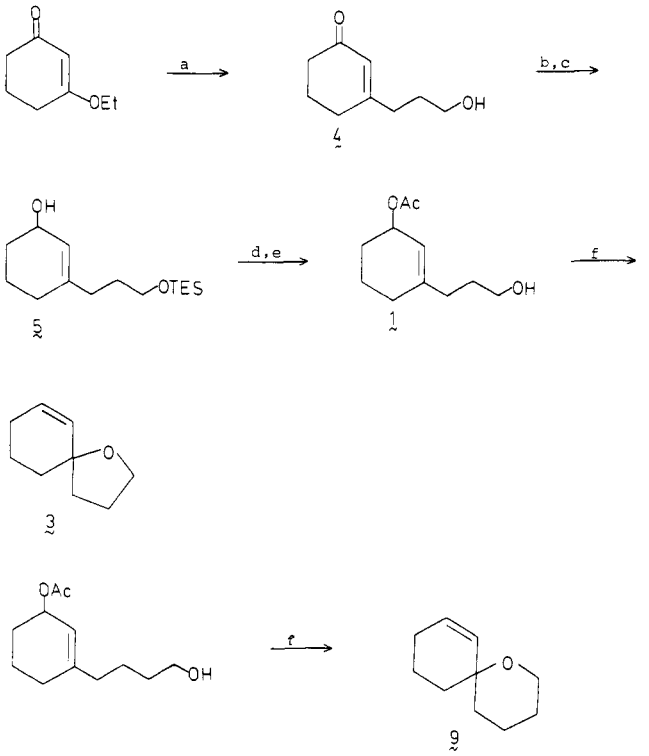
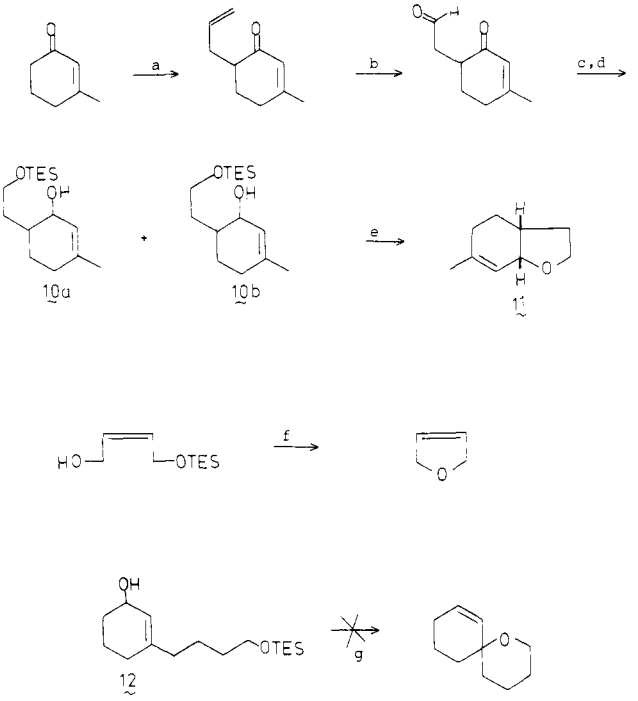
Scheme I



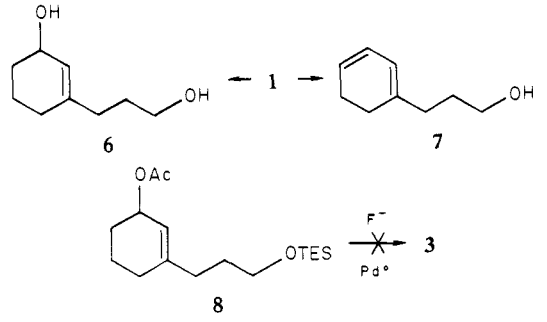
a, $ClMgCH_2CH_2CH_2OMgCl$, THF; b, (TES)Cl, NEt_3, THF, room temperature; c, DIBAL-H, $PhCH_3$, −40 °C; d, Ac_2O, NEt_3, DIMAP, CH_2Cl_2, 0 °C; e, NEt_3-HF, CH_3CN, 60 °C; f, *n*-BuLi, THF, HMPA, −78 °C, then $Pd(DIPHOS)_2$, 70 °C

Scheme II



a, (1) LDA, THF, −78 °C, (2) allyl bromide, 55% yield; b, (1) O_3, pyridine, (2) Zn, HOAc, 99% yield; c, $LiAlH_4$, Et_2O, 69% yield; d, (TES)Cl, Et_3N, THF, 87% yield; e, 0.1 equiv of $Pd(PPh_3)_4$, CCl_4, room temperature, 95% yield; f, 0.5 equiv of $Pd(PPh_3)_4$, CCl_4, 70 °C, 48 h, 95% yield; g, 0.5 equiv of $Pd(PPh_3)_4$, 1.5 equiv of PPh_3, CCl_4, 50 °C, 6 h.

treatment of **1** with an equivalent of *n*-BuLi at −78 °C in THF containing HMPA (1 equiv) followed by addition of $Pd(DIPHOS)_2$ (10% excess DIPHOS to stabilize the Pd(0) catalyst)[6] and slow warming to reflux. The major side products from these reactions were typically the diol **6**, formed by either base-promoted ketene elimination from the acetate **4** or saponification, and the diene **7**. Attempts to circumvent ketene elimination (saponification) either by use of a pivalate or benzoate ester or by direct treatment of the acetoxy triethylsilyl ether **8** with fluoride ion failed to provide any **3**. Comparable results were obtained in the homologous series that led to the production of the spiropyran **9**.



These preliminary experiments suggested that a substrate possessing an allylic-X moiety that could be transformed into a good leaving group only under the reaction conditions and, in addition, an alkoxide nucleophile present in a masked form that could be released under nonbasic reaction conditions might significantly curtail the production of the unwanted side products **6** and **7** and allow efficient cyclization.

(Triphenylphosphine)palladium(0)–CCl_4 Reaction. As a result, subsequent efforts centered on the simplified precursor **5** (prepared as indicated in Scheme I). In this regard, it was reasoned that if CCl_4 were used as solvent in the $Pd(PPh_3)_4$ reaction, the following sequence would ensue. PPh_3 liberated from the complex would react with the CCl_4 to form the known $PPh_3Cl^+CCl_3^-$ salt.[7] Trapping of this intermediate by the allylic alcohol in **5** would provide an oxyphosphonium ion and $HCCl_3$. On the basis of results recently reported,[8] reaction of this oxyphosphonium ion with external nucleophiles (i.e., other than Cl^-) can be realized. If palladium served this role, the required π-allyl complex would result. Then the Cl^- generated in situ would unmask the alkoxide nucleophile to facilitate cyclization to the oxaspirocycle. In the event, admixture of **5** with 0.1 equiv of $Pd(PPh_3)_4$ in CCl_4 at room temperature provided the spirofuran **3** in 86% yield in 12 h. Performance of the necessary control reactions (5 equiv of PPh_3, CCl_4, **5**) showed no formation of spirocycle after 24 h at room temperature. When the control reaction mixture was heated to 70 °C, spirofuran **3** was formed albeit in somewhat smaller yield (50%).[9]

Additional examples of this reaction were also investigated. The allylic alcohol precursors **10a,b** were prepared as outlined in Scheme II by alkylation of the kinetic enolate of 3-methyl-2-cyclohexen-1-one with allyl bromide followed by specific ozonolysis of the terminal olefin, $LiAlH_4$ reduction, and selective silylation of the resulting primary alcohol.

Treatment of the allylic alcohol **10a** or **10b** with 0.1 equiv of $Pd(PPh_3)_4$ in CCl_4 for 2.5 h at room temperature resulted in a quantitative yield of the cis-fused 3-methyl-9-oxabicyclo[4.3.0]-non-2-ene (**11**). No reaction was found to occur at room tem-

(6) Use of excess phosphine in this reaction did prevent precipitation of the catalyst as palladium black but also significantly slowed the rate of reaction.

(7) For a review of the PPh_3–CCl_4 reaction see: Appel, R.; Halstenberg, M. in "Organophosphorus Reagents in Organic Synthesis"; Cadogan, J. I. G., Ed.; Academic Press, New York, 1979; pp 387–431.

(8) Slagle, J. D.; Huang, T. T.-S.; Franzus, B. *J. Org. Chem.* **1981**, *46*, 3526. Brett, D.; Downie, I. M.; Lee, J. B. **1967**, *32*, 855.

(9) Other products in this process were typically cyclohexadiene derivatives and chlorides derived from the primary O(TES) moiety.

(10) The larger amount of catalyst and higher temperatures were necessary to achieve a reasonable rate of reaction.

(11) Barry, C. N.; Evans, S. A., Jr. *J. Org. Chem.* **1981**, *46*, 3361.

perature by using PPh_3–CCl_4 and **10a,b**, but cyclization could be effected at 45 °C in 20 h. The stereochemical aspects of this reaction will be discussed subsequently.

Similarly, the monotriethylsilyl ether of *cis*-2-butene-1,4-diol could be cyclized by using 0.5 equiv of $Pd(PPh_3)_4$ in CCl_4 at 70 °C in 48 h (sealed tube) providing 2,5-dihydrofuran in 95% yield (Scheme II). The greater severity of conditions required in this cyclization may be due to difficulties in achieving the geometry necessary for closure. The control reaction (2 equiv of PPh_3, CCl_4, 70 °C, 48 h) in this case did show minor amounts of cyclization (15%).

Precursors that would provide pyrans, e.g., **12** (Scheme II), did not cyclize under these conditions but instead formed primary chloride derivatives. We attribute this result to the necessity of having a rapid ring closure by the deprotected TES ether. The slow rate (10 times slower than five-membered ring) of six-membered ring formation permits the competing trapping of the incipient alkoxide by Ph_3P^+Cl, eventually resulting in chloride formation. Precursors that would result in seven- or eight-membered ring ethers similarly failed to cyclize. The latter results were rationalized in like fashion.

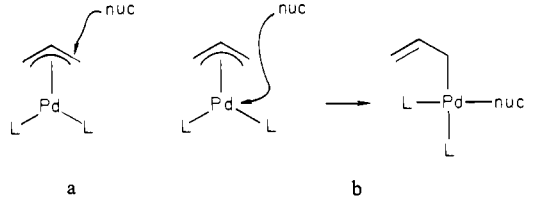
Symmetrical diols have been cyclized to ethers by using the PPh_3–CCl_4 reagents, but our results demonstrate the first use of an unsymmetrical diol selectively derivatized to control the regiochemistry of the cyclization.

Mechanistic and Stereochemical Studies. Leaving Group. Consistent with the proposed mechanism is the fact that in the control reactions described (**5**, **10a,b**), not only is the cyclization not observed but also no allylic chloride is produced. If the chloride were to be the π-allyl precursor, it should be formed at room temperature with PPh_3–CCl_4. In addition, although allylic alcohols themselves can be precursors to (π-allyl)palladium complexes[12] the observation that the diol **6** could not be converted to **3** on reaction with $Pd(PPh_3)_4$ in THF also suggests the intermediacy of the oxyphosphonium species.

The catalytic (0.1 equiv) use of $Pd(PPh_3)_4$ in the reaction, however, requires the process also be catalytic in PPh_3. The fate of PPh_3 as required by the suggested mechanism is conversion to $PPh_3{\rightarrow}O$. For the mechanism to remain viable, $PPh_3{\rightarrow}O$ must be reconverted to PPh_3 under the reaction conditions. Although silyl chlorides have been reported to effect this reduction,[13] reaction of (TES)Cl and $PPh_3{\rightarrow}O$ in CCl_4 at room temperature did not rapidly produce Ph_3P. ^1H NMR studies showed however that no free or Pd-complexed PPh_3 was present in the reaction at its conclusion suggesting its conversion to $PPh_3{\rightarrow}O$ or PPh_3Cl^+. Details of this reduction remain to be determined.

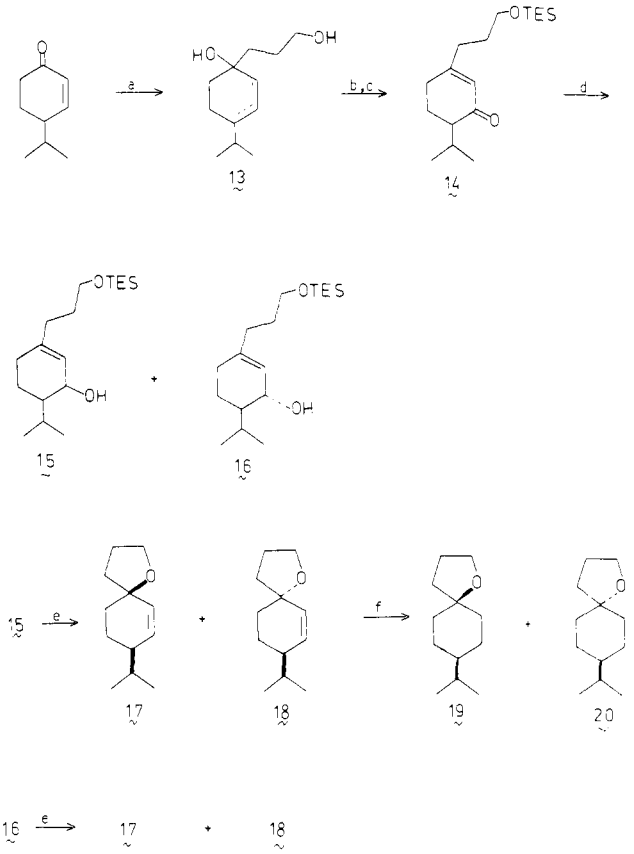
Nucleophile. Also consistent with the proposed mechanism is the fact that chloride ion was found to be capable of efficiently deprotecting trimethylsilyl ethers of primary alcohols (e.g., *n*-butyl alcohol) in CCl_4 at room temperature.

Stereochemistry. Although complete stereospecificity has been established in the addition of malonate type nucleophiles[14] to (π-allyl)palladium complexes via inversion at carbon in the oxidative addition and inversion by attack of nucleophile (nuc) exclusively on the allyl ligand (path a), recent results with hydride,[15] amine,[16] acetate,[16,17] and carbon nucleophiles[18] on these complexes have demonstrated the feasibility of attack directly on the metal (path b) followed by reductive elimination to give overall inversion of configuration at carbon. In light of these results and also to enhance synthetic applicability, the determination of the stereochemistry of the $Pd(PPh_3)_4$–CCl_4 process was desirable. This was accomplished by means of the sequence outlined in Scheme III.



a b

Scheme III



16 $\xrightarrow{e}$ 17 + 18

a, $ClMgCH_2CH_2CH_2OMgCl$, THF; b, (TES)Cl, DIMAP, THF, 0 °C → room temperature; c, CrO_3, py, CH_2Cl_2; d, DIBAL-H, $PhCH_3$, 0 °C; e, $Pd(PPh_3)_4$, CCl_4, room temperature; f, diimide.

The starting material 4-isopropyl-2-cyclohexen-1-one was prepared by the method of Stork.[19] Addition of the Normant Grignard reagent[4] derived from 3-chloropropanol to this enone provided the diols **13**.[20] Selective conversion of the primary alcohols **13** to their triethylsilyl ethers ((TES)Cl, DIMAP, THF, 0 °C → room temperature) and separation of the desired allylic alcohol derivatives were accomplished by MPLC (38% from the enone). Oxidation (CrO_3, py, CH_2Cl_2, 67%)[21] gave the transposed enone **14**. Reduction of **14** (DIBAL-H, $PhCH_3$, 0 °C) provided the allylic alcohols **15** and **16** in 46% and 39% yields, respectively. The allylic alcohols were separated by MPLC and identified as the cis and trans isomers, respectively, by ^1H NMR spectroscopy.[22]

(12) Atkins, K. E.; Walker, W. E.; Manyik, R. M. *Tetrahedron Lett.* **1970**, 3821. Moreno-Manas, M.; Trius, A. *Ibid.* **1981**, 3109. Verhoeven, T. R.; Trost, B. M. *J. Am. Chem. Soc.* **1980**, *102*, 4730.

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(18) Schwartz, J.; Temple, J. S.; Riediker, M. *J. Am. Chem. Soc.* **1982**, *104*, 1310. Matsushita, H.; Negishi, E. *J. Chem. Soc., Chem. Commun.* **1982**, 160.

(19) Stork, G.; Brizzolara, A.; Landesman, H.; Szmuszkovicz, J.; Terrell, R. *J. Am. Chem. Soc.* **1963**, *85*, 207.

(20) Some isomerization to the homoallylic alcohol was observed on workup of the Grignard.

(21) Only modified Collins reagent (Ratcliffe, R.; Rodehorst, R. *J. Org. Chem.* **1970**, *35*, 4000) allowed the allylic transposition to occur in the presence of the acid-sensitive TES ether. Pyridinium dichromate and chlorochromate reagents did not achieve this reaction: cf. Dauben, W. G.; Michno, D. M. *J. Org. Chem.* **1977**, *42*, 682.

Reaction of **15** with 0.1 equiv of $Pd(PPh_3)_4$ in CCl_4 at room temperature resulted in a 20:1 mixture of spirofurans **17** and **18**, respectively, while **16** gave a 1:5 mixture of **17** and **18** (90% yield in each case). The control reaction, PPh_3–CCl_4 (no Pd) and 70 °C, failed to produce **17** or **18**, so the stereochemistry of the non-metal-catalyzed cyclization could not be determined.[23] The stereochemistry of the isopropyl spirofurans was established after their MPLC separation by diimide hydrogenation to give the known saturated spirofurans **19** and **20**.[24] This established that the $Pd(PPh_3)_4$–CCl_4 process proceeded with predominant retention of configuration. To determine if there was a stereochemical bias inherent in the cyclization reaction, **15** was treated with a catalytic amount of concentrated aqueous HCl in THF. This resulted in cyclization but produced a 1:1 mixture of **17** and **18**.

The lower stereochemical integrity observed in the trans case **16** is due to the ready isomerization of **18** to **17** under the reaction conditions. Interestingly, the isomerization of **17** to **18** is considerably slower under these conditions.

The small loss of stereochemical integrity in the cis case may be due to (1) allyl chloride formation with inversion of configuration followed by the usual π-allyl alkylation process, although no chloride could be detected in the room-temperature control experiment, (2) ionization of a fraction of the oxyphosphonium intermediate to an allyl cation followed by trapping by palladium or alkoxide,[25] and (3) a mixed mechanism involving a partitioning of the attack by the alkoxide nucleophile at the metal center and attack directly on the allyl ligand.

The viability of (3) seems especially likely on the basis of the ready isomerization of **18** that must involve attack at Pd by some nucleophile in order to accomplish the conversion to **17** and the observation that the cis and trans allylic alcohols **10a,b** *both* formed exclusively the cis-fused bicyclic system.[26] Initial formation of trans product and its rapid isomerization to **11** under the reaction conditions was demonstrated for **10b**.

The ease of isomerization of these systems suggests the existence of only a small energy difference between attack by alkoxides on the ligand and the metal center.

Additional experiments are currently in progress to further illuminate this mechanism and to establish the scope and limitations of this new reaction.

Experimental Section

General Data. Infrared spectra were determined on a Perkin-Elmer PE 467 spectrophotometer and are reported in inverse centimeters. ^1H NMR spectra were recorded on a JEOLCO MH-100 (100 MHz), a Bruker WH-400 (400 MHz), or a Varian EM 390 (90 MHz) spectrometer. Chemical shifts are reported in δ units and coupling constants in hertz; splitting patterns are designated as follows: s, singlet; d, doublet; t, triplet; q, quartet; m, multiplet, b, broad. Mass spectra were recorded on a Du Pont 21-490B spectrometer at an ionizing voltage of 70 eV. Precise masses were obtained on a VG 7035 instrument. Melting points were determined on a Mel-Temp apparatus and are uncorrected. Microanalyses were performed by Galbraith Laboratories, Knoxville, Tenn. Medium-pressure liquid chromatography (MPLC) was run by using Woelm silica gel (32–63 μm) in the indicated solvent. Et_2O, DME, and THF were distilled immediately before use from benzophenone ketyl. Pyridine, hexane, CH_2Cl_2, and NEt_3 were distilled from CaH_2.

3-(3-Hydroxypropyl)-2-cyclohexenone, 4. Methyl magnesium chloride (2.9 M solution in tetrahydrofuran) was added dropwise to a solution of 3-chloropropanol (1.88 mL, 22.5 mmol) in tetrahydrofuran (23 mL) cooled to −20 °C. The mixture was permitted to warm to room temperature, and then magnesium turnings (0.684 g, 28.2 mmol) were added. Dibromoethane (four drops) was then added, and the solution was refluxed for 12 h. The reaction was cooled to −15 °C, and 3-ethoxy-2-cyclohexenone (2.2 mL, 15 mmol) was added. The solution was stirred for 2 h at −15 °C and warmed to 0 °C, and a solution of saturated aqueous ammonium chloride was added dropwise to destroy excess Grignard reagent. Aqueous hydrochloric acid (3 N, 15 mL) was then added to the mixture, and the aqueous layer was immediately extracted with ethyl acetate (3 × 50 mL). The combined organic extracts were washed with saturated aqueous sodium chloride solution (20 mL), dried with anhydrous sodium sulfate, and filtered, and the solvent was removed under reduced pressure to yield **4** as a viscous yellow oil (2.86 g, 82% yield). This material was used without further purification: ^1H NMR (100 MHz, $CDCl_3$) δ 5.86 (s, 1 H), 3.62 (t, J = 5.7 Hz, 2 H), 3.05 (s, 1 H), 2.50–1.10 (m, 10 H); IR (CCl_4) 3450, 2945, 2875, 1660, 1630, 1532, 1250, 1192, 1054, 814, 738 cm^{-1}.

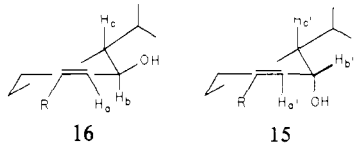
3-(3-((Triethylsilyl)oxy)propyl)-2-cyclohexenone. Chlorotriethylsilane (3.4 g, 22.6 mmol) was added to a solution of **4** (2.86 g, 18.6 mmol) and triethylamine (5.6 g, 55.8 mmol) in tetrahydrofuran (15 mL) cooled to 0 °C. The resulting mixture was permitted to warm to room temperature and stirred for 3 h. The solution was diluted with hexane (120 mL) and was washed with water (2 × 30 mL) and saturated aqueous sodium bicarbonate solution (2 × 30 mL). The organic layer was dried over anhydrous sodium sulfate and filtered and the solvent removed under reduced pressure to give a quantitative yield of 3-(3-((triethylsilyl)-oxy)propyl)-2-cyclohexenone (4.9 g). The material was used without further purification: ^1H NMR (100 MHz, $CDCl_3$) δ 5.82 (s, 1 H), 3.58 (t, J = 7 Hz, 2 H), 2.44–1.40 (m, 10 H), 0.98 (t, J = 8 Hz, 9 H), 0.64 (q, J = 8 Hz, 6 H); IR (CCl_4) 2940, 2890, 1666, 1622, 1452, 1408, 1232, 1100, 1010, 948, 704 cm^{-1}; mass spectrum, m/e 268 (M^+).

3-(3-((Triethylsilyl)oxy)propyl)-2-cyclohexenol, 5. Diisobutylaluminum hydride (9.3 mL of a 2.02 M solution in toluene) was added to a solution of 3-(3-((triethylsilyl)oxy)propyl)-2-cyclohexenone (4.6 g, 17.2 mmol) in toluene (60 mL) cooled to −40 °C. The reaction mixture was stirred for 7 h at −40 °C, and then it was quenched with a saturated aqueous sodium sulfate solution (10 mL). Celite was added to the reaction until it became viscous, and the solution was allowed to warm to 0 °C. The resulting mixture was stirred 1 h and then filtered and the solvent removed under reduced pressure to give **5** (4.6 g, 100% yield). This material was used without further purification. The sample for elemental analysis was prepared by MPLC using ether/hexane (1:1) as eluant: ^1H NMR (100 MHz, $CDCl_3$) δ 5.48 (s, 1 H), 4.12 (br s, 1 H), 3.58 (t, J = 7 Hz, 2 H), 3.40 (s, 1 H), 2.20–1.24 (m, 10 H), 1.00 (t, J = 8 Hz, 9 H), 0.66 (q, J = 8 Hz, 6 H); IR (CCl_4) 3690, 2960, 2880, 1540, 1245, 1080, 1010, 910, 745 cm^{-1}; mass spectrum, m/e 270 (M^+). Anal. Calcd for $C_{15}H_{30}O_2Si$: C, 66.61; H, 11.18. C, 66.61; H, 11.18. Found: C, 66.62; H, 11.30.

3-Acetoxy-1-(3-((triethylsilyl)oxy)propyl)cyclohexene. To a solution of **5** (0.08 g, 0.30 mmol), triethylamine (0.06 g, 0.6 mmol), and 4-(dimethylamino)pyridine (0.007 g, 0.06 mmol) in dichloromethane (2 mL) cooled to 0 °C was added acetic anhydride (0.034 g, 0.30 mmol). The reaction was stirred at 0 °C for 2 h, and then it was quenched with water (1 mL) and diluted with diethyl ether (15 mL). The layers were separated, and the organic phase was washed with saturated aqueous sodium bicarbonate solution (5 mL), brine (2 × 5 mL), and water (5 mL). The organic layer was dried over anhydrous magnesium sulfate and filtered, and the solvent was removed under reduced pressure. The oil was purified by MPLC eluting with diethyl ether/hexane (1:10) to afford 3-acetoxy-1-(3-((triethylsilyl)oxy)propyl)cyclohexene (0.077 g, 82% yield), which was immediately carried on to the next reaction: ^1H NMR (100 MHz, $CDCl_3$) δ 5.44 (s, 1 H), 3.58 (5, J = 7 Hz, 2 H), 2.20–1.30 (m, 13 H), 0.96 (t, J = 8 Hz, 9 H), 0.60 (q, J = 8 Hz, 6 H); IR (CCl_4) 2970, 2890, 1745, 1380, 1250, 1090, 1020, 920, 790, 730 cm^{-1}; mass spectrum, m/e 312 (M^+).

3-Acetoxy-1-(3-hydroxypropyl)cyclohexene, 1. Triethylammonium fluoride (4 mL, 16 mmol, 4 M solution in acetonitrile) was added to 3-acetoxy-1-(3-((triethylsilyl)oxy)propyl)cyclohexene (3.1 g, 9.94 mmol) in acetonitrile (20 mL). The resulting mixture was heated at 60 °C for 12 h. The reaction was cooled to room temperature and quenched with water (10 mL), and the solution was extracted with ethyl acetate (5 × 10 mL). The organic phase was filtered through anhydrous magnesium

(22) The 400-MHz ^1H NMR results in $D_2O/CDCl_3$ used to assign these structures were as follows: **16**, 5.38 (b s, $J_{H_aH_b} \leq 2$ Hz, H_a), 4.01 ppm (d, $J_{H_bH_c}$ = 7.5 Hz, H_b); **15**, 5.61 (d, $J_{H_{a'}H_{b'}}$ = 5.8 Hz, $H_{a'}$), 4.12 ppm (pseudo t, $J_{H_bH_{c'}}$ = 4.0 Hz, $H_{b'}$).



16 15

(23) This is in contrast to the simple spirofuran cyclization.

(24) Speziale, V.; Lattes, A. *J. Heterocycl. Chem.* **1979**, *16*, 465. Moulines, J.; Lalande, R. *Bull. Chem. Soc. Fr.* **1971**, *2*, 1075.

(25) Significant racemization of optically active 2-octanol in its conversion to the chloride has been reported in ref 11.

(26) The cis-fused ring system is assumed to be thermodynamically more stable, but we are unable to conclude whether the exclusive formation of cis isomer represents a kinetic or thermodynamic result. Trans isomer was prepared by using the PPh_3–CCl_4 reaction. Assignment of stereochemistry in **10a,b** was made by ^1H NMR spectroscopy in strict analogy to **15** and **16**. Stereo assignment in the products was based on analogy to model fused bicyclic systems: Doutheau, A.; Gore, J. *Bull. Chem. Soc. Fr.* **1976**, 2047.

sulfate and the solvent removed under reduced pressure. Chromatography of the oil with diethyl ether/hexane (1:2) as eluant using MPLC resulted in pure **1** (1.90 g, 96% yield): ^{1}H NMR (90 MHz, $CDCl_3$) δ 5.43 (s, 1 H), 5.20 (s, 1 H), 3.60 (t, J = 7 Hz, 2 H), 2.30–1.40 (m, 14 H); IR (CCl_4) 3620, 3460, 2920, 2870, 1738, 1454, 1430, 1372, 1210, 1015, 905 cm^{-1}; mass spectrum, m/e 198 (M^+). Anal. Calcd for $C_{11}H_{18}O_3$: C, 66.64; H, 9.15; O, 24.21. Found: C, 66.47; H, 9.27; O, 24.16.

Formation of 7-Oxaspiro[5.4]dec-2-ene, 3, from the Allylic Acetate 1. To **1** (0.986 g, 4.98 mmol) in tetrahydrofuran (50 mL) cooled to −78 °C was added *n*-butyllithium (3.36 mL, 4.98 mmol, 1.48 M). The reaction was stirred 30 min, and then hexamethylphosphoramide (0.87 mL, 41.98 mmol) and a solution of DIPHOS (0.04 g, 0.100 mmol) and Pd(DIPHOS)$_2$ (0.45 g, 0.498 mmol) in tetrahydrofuran (2 mL) were added. The solution was slowly warmed to reflux and was kept at this temperature for 48 h. The reaction was cooled to room temperature and was quenched with saturated aqueous ammonium chloride solution (2.5 mL). The resulting mixture was extracted with pentane/ether (1:1, 5 × 30 mL), and the combined organic layer was filtered through anhydrous magnesium sulfate. The solvent was removed under reduced pressure at 0 °C. The resulting yellow oil was purified by MPLC, eluting with diethyl ether/pentane (1:15) to give a clear oil (0.200 g, 30% yield): ^{1}H NMR (400 MHz, $CDCl_3$) δ 5.70 (dt, J = 10.0, 3.6 Hz, 1 H), 5.51 (d, J = 10 Hz, 1 H), 3.79 (t, J = 7.0 Hz, 2 H), 1.99–1.45 (m, 10 H); IR (CCl_4) 3020, 2930, 2860, 1540, 1438, 1252, 1206, 1044, 992, 888 cm^{-1}; mass spectrum, m/e 138 (M^+). Anal. Calcd for $C_9H_{14}O$: C, 78.21; H, 10.21. Found: C, 78.65; H, 10.14.

Formation of 7-Oxaspiro[5.4]dec-2-ene, 3, from 5. To palladium tetrakis(triphenylphosphine) (0.015 g, 0.0133 mmol, 0.1 equiv) was added a solution of **5** (0.036 g, 0.133 mmol) in carbon tetrachloride (0.4 mL). The mixture was stirred at room temperature for 12 h. The reaction was then diluted with pentane (10 mL), filtered through Celite, and concentrated under reduced pressure at 0 °C. The yellow oil was purified by silica gel preparative layer chromatography using diethyl ether/hexane (1:4) as the eluting solvent to give **3** (0.016 g, 86% yield) in all respects identical with that prepared from **1**.

3-Methyl-6-(2-propenyl)-2-cyclohexenone. To diisopropylamine (6.6 mL, 46.8 mmol) in tetrahydrofuran (46.8 mL) at 0 °C was added *n*-butyllithium (22.8 mL, 34.3 mmol, 1.5 M). The solution was stirred 15 min at 0 °C and cooled to −78 °C, and 3-methyl-2-cyclohexen-1-one (3.6 mL, 31.2 mmol) was added. The reaction mixture was stirred at −78 °C for 2 h, and allyl bromide (3.0 mL, 34.3 mmol) was added. The solution was allowed to warm to −20 °C and stored at −20 °C overnight. The reaction was quenched with water (15 mL) and extracted with diethyl ether (3 × 20 mL). The ethereal extracts were combined, washed with water (15 mL) and saturated aqueous sodium chloride solution (15 mL), filtered through anhydrous magnesium sulfate, and concentrated. The crude product was purified by MPLC using diethyl ether/hexane (1:2) as the eluant to give 3-methyl-6-(2-propenyl)-2-cyclohexenone (2.59 g, 55% yield), which was immediately carried on to the next reaction: ^{1}H NMR (90 MHz, $CDCl_3$) δ 6.03–5.50 (m, 2 H), 5.16–4.80 (m, 2 H), 2.87–1.33 (m, 10 H); IR (CCl_4) 2980, 2920, 2860, 1680, 1640, 1546, 1250, 1220, 1000, 980, 912, 810, 745 cm^{-1}; mass spectrum, m/e 150 (M^+).

2-(4-Methyl-2-oxo-3-cyclohexenyl)acetaldehyde. A stream of ozone was bubbled into a cooled solution (−78 °C) containing 3-methyl-6-(2-propenyl)-2-cyclohexenone (2.088 g, 14.0 mmol) and pyridine (1.26 mL, 15.7 mmol) in methylene chloride (250 mL; Sudan Red 7B was employed as an indicator). Ozone was bubbled into the reaction for 0.5 h after the red color of the indicator had disappeared. The solution was then poured into a flask containing zinc dust (7.14 g). Acetic acid (14.0 mL) was added, and the flask was placed immediately into a room temperature water bath and stirred for 2 h. The mixture was filtered through Celite and washed with water (3 × 50 mL), 5% aqueous potassium hydroxide (3 × 75 mL), and water (3 × 70 mL) until neutral to litmus. The solution was filtered through anhydrous magnesium sulfate and concentrated under reduced pressure to obtain a yellow oil, which was used without further purification (2.19 g, 99% yield): ^{1}H NMR (90 MHz, $CDCl_3$) δ 9.80 (s, 1 H), 5.87 (s, 1 H), 3.23–1.36 (m, 10 H); IR (CCl_4) 3920, 1730, 1680, 1540, 1080, 1015, 770 cm^{-1}; mass spectrum, m/e 152 (M^+).

6-(2-Hydroxyethyl)-3-methyl-2-cyclohexenol. 2-(4-Methyl-2-oxo-3-cyclohexenyl)acetaldehyde (0.85 g, 5.6 mmol) was dissolved in diethyl ether (10 mL) and added dropwise to a solution containing lithium aluminum hydride (0.159 g, 4.2 mmol) in diethyl ether (2 mL) cooled to 0 °C. The reaction was stirred at 0 °C for 1 h and quenched with water (5 mL). Diethyl ether (20 mL) was added, and the solution was stirred at room temperature for 1 h, filtered through Celite/anhydrous magnesium sulfate, and concentrated. The resulting oil was purified by MPLC, eluting with diethyl ether/hexane (1:1) to give a mixture of cis and trans diols (0.60 g, 69% yield). This mixture was used without further purification.

3-Methyl-6-(2-((triethylsilyl)oxy)ethyl)-2-cyclohexenol, 10a,b. To a mixture of the 6-(2-hydroxyethyl)-3-methyl-2-cyclohexenols (0.527 g, 3.4 mmol) in triethylamine (1 mL, 6.8 mmol) and tetrahydrofuran (20 mL) cooled to −20 °C was added chlorotriethylsilane (0.510 g, 3.4 mmol). The solution was stirred 3 h at −20 °C, and then it was quenched with water (10 mL) and diluted with hexane (30 mL). The organic phase was separated, washed with water (10 mL), saturated aqueous sodium bicarbonate solution (10 mL), and brine (10 mL), and filtered through anhydrous magnesium sulfate. The solution was concentrated and purified by MPLC using diethyl ether/hexane (1:1) as the eluant to give 3-methyl-6-(2-((triethylsilyl)oxy)ethyl)-2-cyclohexenol (0.801 g, 87% yield) in a ratio of 2:3 cis:trans which was immediately used in the next reaction. The spectral data were as follows: cis: ^{1}H NMR (400 MHz, $CDCl_3$) δ 5.53 (s, 1 H), 4.08 (b s, 1 H), 3.85 (br s, 1 H), 3.77 (ddd, J = 15, 10, 4.7 Hz, 1 H), 3.67 (dt, J = 10, 4 Hz, 1 H), 2.10–1.25 (m, 10 H), 0.95 (t, J = 4 Hz, 9 H), 0.60 (q, J = 4 Hz, 6 H); IR (CCl_4) 3430, 2960, 1550, 1460, 1440, 1380, 1240, 1080, 1010, 750 cm^{-1}; mass spectrum, m/e 270 (M^+). Trans: ^{1}H NMR (400 MHz, $CDCl_3$) δ 5.32 (s, 1 H), 4.05 (b s, 1 H), 3.85 (m, 1 H), 3.77 (dt, J = 5.5, 3 Hz, 1 H), 3.67 (dt, J = 6.8, 3 Hz, 1 H), 2.08–1.27 (m, 10 H), 0.94 (t, J = 4 Hz, 9 H), 0.60 (8, J = 4 Hz, 6 H); IR (CCl_4) 3450, 2960, 2880, 1490, 1460, 1440, 1380, 1250, 1210, 1085, 1008, 820 cm^{-1}; mass spectrum, m/e 270 (M^+).

Cis-Fused 3-Methyl-9-oxabicyclo[4.3.0]non-2-ene, 11. Palladium tetrakis(triphenylphosphine) (0.027 g, 0.023 mmol, 0.08 equiv) was added to a solution containing *trans*-3-methyl-6-(2-((trimethylsilyl)-oxy)ethyl)-2-cyclohexenol (0.075 g, 0.28 mmol) and carbon tetrachloride (0.9 mL) under nitrogen at room temperature. The solution was stirred overnight at room temperature, diluted with pentane (20 mL), filtered through Celite, and concentrated. ^{1}H NMR indicates quantitative conversion to the cis-fused product **11**. The oil was purified on an alumina prep plate using diethyl ether/hexane (1:4) as an eluant (R_f 0.6) giving pure **11** (0.038 g, 95% yield): ^{1}H NMR (400 MHz, $CDCl_3$) δ 5.50 (s, 1 H), 3.99 (s, 1 H), 3.87 (dd, J = 14, 8.4 Hz, 1 H), 3.67 (dd, J = 14.0, 8.4 Hz, 1 H), 2.05 (m, 2 H), 1.87 (m, 2 H), 1.65 (s, 3 H), 1.60–1.32 (m, 3 H); IR (CCl_4) 2960, 2940, 2860, 1550, 1260, 1075, 1005, 980, 820, 770, cm^{-1}; high-resolution mass spectrum calculated for $C_9H_{14}O$ 138.1043, found 138.1008.

cis-3-Methyl-6-(2-((trimethylsilyl)oxy)ethyl)-2-cyclohexenol (0.030 g, 0.11 mmol) was reacted with palladium tetrakis(triphenylphosphine) (0.012 g, 0.010 mmol) and carbon tetrachloride (0.35 mL) in strict analogy to the conditions above, giving only **11** as product.

1-((Triethylsilyl)oxy)-*cis*-2-buten-4-ol. To *cis*-2-butene-1,4-diol (1.5 g, 17.05 mmol) and triethylamine (4.74 mL, 34.1 mmol) in tetrahydrofuran (70 mL) cooled to −20 °C was added chlorotriethylsilane (2.85 g, 17.05 mmol). The solution was stirred 3 h at −20 °C, then quenched with water (30 mL) and diluted with hexane (150 mL). The organic phase was separated, washed with water (50 mL), saturated aqueous sodium bicarbonate (50 mL), and brine (50 mL), and filtered through anhydrous magnesium sulfate. The solution was concentrated and purified by MPLC using diethyl ether/hexane (1:1) as an eluant to give 1-((triethylsilyl)oxy)-*cis*-2-buten-4-ol (2.07 g, 60% yield): ^{1}H NMR (90 MHz, $CDCl_3$) δ 5.52 (m, 2 H), 4.20–3.86 (m, 4 H), 3.72 (m, 1 H), 1.03–0.26 (m, 15 H); IR (CCl_4) 3480, 2964, 2920, 2882, 1458, 1414, 1070, 1024, 730 cm^{-1}; mass spectrum, m/e 202 (M^+).

2,5-Dihydrofuran. Palladium tetrakis(triphenylphosphine) (0.135 g, 0.12 mmol, 0.5 equiv), 4-((triethylsilyl)oxy)-*cis*-2-butenol (0.48 g, 0.24 mmol, 1.0 equiv) and carbon tetrachloride (0.9 mL) were sealed in a thick-walled tube in vacuo and heated to 70 °C for 48 h. The solution was cooled, the tube was opened, and the contents were spectrally analyzed. ^{1}H NMR and GC analyses inicate 95% conversion to 2,5-dihydrofuran, found to be in all respects identical with an authentic sample. The spectral data were as follows: ^{1}H NMR (90 MHz, $CDCl_3$) δ 5.78 (s, 2 H), 4.43 (s, 4 H).

4-Isopropyl-1-(3-hydroxypropyl)-2-cyclohexenol, 13. Methylmagnesium chloride (13.2 mL, 37 mmol, 2.8 M in THF) was added to 3-chloropropanol (3.1 mL, 37 mmol) in tetrahydrofuran (40 mL) cooled to −20 °C. The solution was permitted to warm to room temperature, and magnesium turnings (1.04 g, 43.5 mmol) were added. The mixture was refluxed for 12 h, then the solution was cooled to −20 °C, and 4-isopropyl-2-cyclohexenone (3.11 g, 22.5 mmol) in tetrahydrofuran (3 mL) was added dropwise. The reaction was stirred for 1 h and then quenched with saturated aqueous sodium sulfate (50 mL) and water (50 mL). The aqueous layer was extracted with ethyl acetate (3 × 100 mL). The combined organic layers were filtered through anhydrous magnesium sulfate, and the solvent was removed under reduced pressure to afford a yellow oil (4.5 g, 100%), which was used without further purification: ^{1}H NMR (90 MHz, $CDCl_3$) δ 5.56 (b s, 2 H), 3.56 (m, 2 H), 2.86 (br s, 2 H), 2.50–1.14 (m, 10 H), 1.10–0.60 (m, 6 H); IR (CCl_4) 3340, 2970,

2950, 2880, 1720, 1470, 1390, 1370, 1055, 1020, 970, 730 cm^{-1}; mass spectrum, *m/e* 198 (M^+).

4-Isopropyl-1-(3-((triethylsilyl)oxy)propyl)-2-cyclohexenol. To a mixture of the crude diols (4.5 g, 22.5 mmol) and 4-(dimethylamino)-pyridine (3.2 g, 26 mmol) in tetrahydrofuran (50 mL) at 0 °C was added chlorotriethylsilane (4.3 mL, 26 mmol). The solution was permitted to warm to room temperature and was stirred for 2 h. The reaction was quenched with water (25 mL) and diluted with hexane (100 mL). The layers were separated, and the organic phase was extracted with saturated aqueous sodium bicarbonate solution (25 mL) and brine (25 mL), filtered through anhydrous magnesium sulfate, and concentrated. The resulting yellow oil was purified by MPLC using diethyl ether/hexane (1:15) as the eluant to give a mixture of 4-isopropyl-1-(3-((triethylsilyl)oxy)-propyl)-2-cyclohexenols (2.67 g, 38% yield): ^1H NMR (100 MHz, $CDCl_3$) δ 5.56 (s, 2 H), 3.58 (t, *J* = 6 Hz, 2 H), 2.52 (s, 1 H), 2.04–1.16 (m, 10 H), 0.90 (m, 15 H), 0.60 (m, 6 H); IR (CCl_4) 3620, 3440, 2960, 2910, 2870, 1470, 1415, 1385, 1240, 1100, 1015, 910, 815, 620 cm^{-1}; mass spectrum *m/e* 312 (M^+).

6-Isopropyl-3-(3-((triethylsilyl)oxy)propyl)-2-cyclohexen-1-one, 14. Chromium trioxide (4.0 g, 40 mmol) was added to pyridine (8.0 mL, 80 mmol) and dichloromethane (80 mL). The resulting brick-red solution was stirred 20 min, and then the 4-isopropyl-1-(3-((triethylsilyl)oxy)-propyl)-2-cyclohexenols (2.07 g, 6.63 mmol) dissolved in dichloromethane (2 mL) were added dropwise. The solution was stirred 20 min and then filtered through a bed of alumina. The residue was extracted with dichloromethane (2 × 50 mL), and the combined washings were filtered through alumina. The solvent was removed under reduced pressure, then diethyl ether (150 mL) was added to the residue, and the resulting mixture was filtered through anhydrous magnesium sulfate. The solvent was removed under reduced pressure, and the resulting yellow oil was purified by MPLC using diethyl ether/hexane (1:25) as the eluant to give **14** (1.42 g, 67% yield): ^1H NMR (100 MHz, $CDCl_3$) δ 5.80 (s, 1 H), 3.60 (t, *J* = 6 Hz, 2 H), 2.50–1.40 (m, 10 H), 0.88 (m, 15 H), 0.60 (m, 6 H); IR (CCl_4) 2990, 2980, 2950, 2880, 1745, 1680, 1635, 1460, 1380, 1370, 1245, 1210, 1100, 1015, 1010, 965, 910, 755, 740 cm^{-1}; mass spectrum, *m/e* 310 (M^+). Anal. Calcd for $C_{18}H_{34}O_2Si$: C, 69.61: H, 11.03. Found: C, 69.88; H, 11.00.

6-Isopropyl-3-(3-((triethylsilyl)oxy)propyl)-2-cyclohexenol, 15 and 16. To 6-isopropyl-3-(3-((triethylsilyl)oxy)propyl)-2-cyclohexenone, **14** (1.174 g, 3.87 mmol), in toluene (15.5 mL) at 0 °C was added a solution of diisobutylaluminum hydride (2.9 mL, 2.0 M). The solution was stirred 30 min, and then it was quenched with saturated aqueous sodium sulfate (10 mL). Celite was added until the solution became viscous, and then it was stirred for 45 min. The mixture was filtered and the solvent removed under reduced pressure. The resulting yellow oil was purified by MPLC with diethyl ether/hexane (1:25) as the eluant to give *cis*-6-isopropyl-3-(3-((triethylsilyl)oxy)propyl)-2-cyclohexenol, **15** (555 mg, 46% yield), and *trans*-6-isopropyl-3-(3-((triethylsilyl)oxy)propyl)-2-cyclohexenol, **16** (470 mg, 39% yield). The spectral data were as follows. Cis: ^1H NMR (400 MHz, $CDCl_3$) δ 5.61 (d, *J* = 5.8 Hz, 1 H), 4.12 (br s, 1 H), 3.56 (t, *J* = 7.3 Hz, 2 H), 2.00 (m, 4 H), 1.76–1.56 (m, 5 H), 1.26 (dq, *J* = 9.5 Hz, 1 H), 1.06 (b s, 1 H), 0.92 (m, 15 H), 0.64 (q, *J* = 7.8 Hz, 6 H); IR (CCl_4) 3625, 2960, 2920, 2880, 1460, 1390, 1240, 1120, 1105, 1095, 1080, 1015, 960, 900, 800, 790, 750, 735 cm^{-1}; mass spectrum, *m/e* 312 (M^+). Anal. Calcd for $C_{18}H_{36}O_2Si$: C, 69.17; H, 11.61. Found: C, 69.53; H, 11.55. Trans: ^1H NMR (400 MHz, $CDCl_3$) 5.38 (b s, 1 H), 4.01 (vb s, 1 H), 3.56 (t, *J* = 6.5 Hz, 2 H), 1.99 (m, 4 H), 1.65 (m, 4 H), 1.23 (m, 3 H), 0.88 (m, 15 H), 0.57 (q, *J* = 7.8 Hz, 6 H); IR (CCl_4) 3620, 2980, 2950, 2930, 2890, 1750, 1550, 1460, 1390, 1375, 1245, 1100, 1085, 1010, 800, 750; mass spectrtum, *m/e* 312 (M^+). High-resolution mass spectrum calculated for $C_{18}H_{34}OSi$ 312.2484, found 312.2483.

Reaction of 15 To Form 4-Isopropyl-7-oxaspiro[5.4]dec-2-ene, 17 and 18. To palladium tetrakis(triphenylphosphine) (0.009 g, 0.008 mmol, 0.1 equiv) was added **15** (0.025 g, 0.08 mmol) in carbon tetrachloride (0.3 mL). The solution was stirred overnight at room temperature, diluted with pentane (20 mL), filtered through Celite and anhydrous magnesium sulfate, and concentrated. The 400-MHz ^1H NMR spectrum indicates 90% conversion to the cyclized products in a 20:1 ratio of cis:trans. The spectral data were as follows. Cis: ^1H NMR (400 MHz, $CDCl_3$) δ 5.71 (dd, *J* = 10.2, 2 Hz, 1 H), 5.56 (dd, *J* = 10.2, 2 Hz, 1 H), 3.87 (dd, *J* = 15.2, 6.8 Hz, 1 H), 3.75 (dd, *J* = 15.2, 6.8 Hz, 1 H), 1.93–1.41 (m, 10 H), 0.87 (dd, *J* = 8.8, 6.8 Hz, 6 H); IR (CCl_4) 3200, 2990, 2980, 2890, 1465, 1450, 1390, 1375, 1165, 1120, 1105, 1050, 1040, 945, 925, 855, 740, 730 cm^{-1}; mass spectrum, *m/e* 180 (M^+). Anal. Calcd for $C_{12}H_{20}O$: C, 79.94; H, 11.18. Found: C, 79.76; H, 11.35. Trans: ^1H NMR (400 MHz, $CDCl_3$) δ 5.59 (s, 2 H), 3.89–3.78 (m, 2 H), 1.91–1.26 (m, 10 H), 0.85 (dd, *J* = 10.8, 6.89 Hz, 6 H); IR (CCl_4) 3030, 2980, 2940, 2880, 1465, 1450, 1385, 1110, 1075, 1050, 1040, 935, 735 cm^{-1}; mass spectrum, *m/e* 180 (M^+). Anal. Calcd for $C_{12}H_{20}O$: C, 79.94; H, 11.18. Found: C, 79.76; H, 11.35.

Reaction of 16 To Form 4-Isopropyl-7-oxaspiro[5.4]dec-2-ene, 17 and 18. *cis*-6-Isopropyl-3-(3-((triethylsilyl)oxy)propyl)-2-cyclohexenol (0.010 g, 0.032 mmol) in carbon tetrachloride (0.12 mL) was added to palladium tetrakis(triphenylphosphine) (0.004 g, 0.0032 mmol, 0.1 equiv). The reaction was stirred for 25 min at room temperature. The solution was diluted with pentane (10 mL), filtered through celite and anhydrous magnesium sulfate, and concentrated. The 400-MHz ^1H NMR spectrum indicates a 90% conversion to the cyclized products in a 1:4.6 ratio of cis:trans. Spectral analyses found these products to be in all respects identical with the isomers formed from **15**.

***cis*-4-Isopropyl-7-oxaspiro[5.4]decane, 19.**[26] Hydrazine (0.75 mL, 0.023 mmol) was added to *cis*-4-isopropyl-7-oxaspiro[5.4]dec-2-ene, **17** (0.050 g, 0.28 mmol), in absolute ethanol (1 mL). The solution was refluxed for 60 h, cooled, and extracted with diethyl ether (3 × 15 mL). The combined ethereal extracts were washed with water (10 mL), filtered through a bed of anhydrous magnesium sulfate, and concentrated. The oil was purified by MPLC using diethyl ether/hexane (1:4) as an eluant to give **19** (0.036 g, 71% yield): ^1H NMR (400 MHz, $CDCl_3$) δ 3.79 (t, *J* = 6.8 Hz, 2 H), 1.86–1.00 (m, 14 H), 0.84 (d, *J* = 6.8 Hz, 6 H); IR (CCl_4) 2960, 2930, 2860, 1535, 1460, 1440, 1040, 920, 725 cm^{-1}; mass spectrum, *m/e* 82 (M^+).

***trans*-4-Isopropyl-7-oxaspiro[5.4]decane, 20.**[26] To *trans*-4-isopropyl-7-oxaspiro[5.4]dec-2-ene, **18** (0.050 g, 0.28 mmol), in absolute ethanol (1 mL) was added hydrazine (0.75 mL, 0.023 mol). The solution was refluxed for 36 h, cooled, and extracted with diethyl ether (3 × 15 mL). The combined ethereal extracts were washed with water (10 mL), filtered through a bed of anhydrous magnesium sulfate, and concentrated. The oil was purified by MPLC using diethyl ether/hexane (1:4) as an eluant to give **20** (0.048 g, 94% yield): ^1H NMR (400 MHz, $CDCl_3$) δ 3.79 (t, *J* = 6.8 Hz, 2 H), 1.91–1.84 (m, 2 H), 1.71–1.43 (m, 9 H), 1.01–0.99 (m, 3 H), 0.83 (d, *J* = 6.8 Hz, 6 H); IR (CCl_4) 2980, 2950, 2890, 2880, 1540, 1460, 1090, 1075, 740 cm^{-1}; mass spectrum, *m/e* 182 (M^+).

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Registry No. 1, 84695-63-6; **3**, 7129-25-1; **4**, 61589-86-4; **5**, 84695-61-4; **10a**, 84695-68-1; **10b**, 84695-69-2; **11**, 84695-70-5; **13**, 84695-59-0; **14**, 84695-73-8; **15**, 84695-74-9; **17**, 84695-76-1; **18**, 84695-77-2; **19**, 32405-41-7; **20**, 32405-42-8; 3-chloropropanol, 627-30-5; 3-ethoxy-2-cyclohexenone, 5323-87-5; 3-(3-((triethylsilyl)oxy)propyl)-2-cyclohexenone, 84695-60-3; chlorotriethylsilane, 994-30-9; 3-acetoxy-1-(3-((triethylsilyl)oxy)propyl)cyclohexene, 84695-62-5; 3-methyl-6-(2-propenyl)-2-cyclohexenone, 84695-64-7; 3-methyl-2-cyclohexen-1-one, 1193-18-6; allyl bromide, 106-95-6; 2-(4-methyl-2-oxo-3-cyclohexenyl)-acetaldehyde, 84695-65-8; *cis*-6-(2-hydroxyethyl)-3-methyl-2-cyclohexenol, 84695-66-9; *trans*-6-(2-hydroxyethyl)-3-methyl-2-cyclohexenol, 84695-67-0; 1-((triethylsilyl)oxy)-*cis*-2-buten-4-ol, 84695-71-6; *cis*-2-butene-1,4-diol, 6117-80-2; 2,5-dihydrofuran, 1708-29-8; palladium tetrakis(triphenylphosphine), 14221-01-3; 4-isopropyl-2-cyclohexenone, 500-02-7; 4-isopropyl-1-(3-((triethylsilyl)oxy)propyl)-2-cyclohexenol, 84695-72-7; hydrazine, 302-01-2; **16**, 84695-75-0.