Tungsten-Promoted Intramolecular Alkoxycarbonylation for Synthesis of Complex Oxygenated Molecules

Chi-Chung Chen,[†] Jang-Shyang Fan,[†] Su-Ju Shieh,[†] Gene-Hsian Lee,[‡] Shie-Ming Peng,[‡] Sue-Lang Wang,[†] and Rai-Shung Liu*,[†]

Contribution from the Department of Chemistry, National Tsing Hua University, Hsinchu, 30043, Taiwan, Republic of China, and Department of Chemistry, National Taiwan University, Taipei, 10764, Taiwan, Republic of China

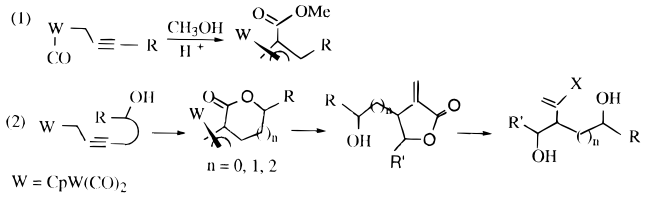
Received May 28, 1996[⊗]

Abstract: Intramolecular alkoxycarbonylation of tungsten−propargyl compounds proceeds with excellent diastereoselectivities to form η^3-δ- and -ϵ-lactones but for γ-lactones. With OSi(*t*-Bu)Me_2 substituted for an α-hydroxy group, η^3-γ-lactones are stereoselectively formed with *syn* stereoselection. An optically active tungsten η^3-γ-lactone is prepared from D-(+)-xylose to illustrate the stereochemical effect of OSi(*t*-Bu)Me_2. All these η^3-γ-, -δ-, and -ϵ-lactones are converted to allyl anions that react *in situ* with aldehydes and ketones to produce various β-(hydroxylalkyl)-α-methylene-γ-lactones with good diastereoselectivity. This reaction is also applied to the synthesis of chiral α-methylene butyrolactones. Organic carbonyls add to the π-allyl groups of η^3-γ- and -δ-lactones opposite the tungsten fragment, whereas additions occur from the metal side for η^3-ϵ-lactones. The stereochemical courses of these reactions are discussed in detail. These two tungsten-promoted reactions efficiently effect stereoselective transformation of chloroalkynols to complex α-methylene-γ-lactones, which are useful materials for syntheses of trisubstituted 1,3-, 1,4-, and 1-5-diols.

Introduction

Metal-mediated intramolecular alkoxycarbonylation is very useful for the syntheses of oxygenated heterocycles.[1−5] A number of reactions are performed catalytically with complexes of late transition metals such as Pd(0),[2] Rh(I),[3] and Ni(0).[3]

Scheme 1



Although stoichiometric alkoxycarbonylation[4,5] is less economical, it may be accessible to more complex molecules if stereocontrolled functionalization can be implemented sequentially. Tungsten−propargyl compounds undergo facile proton-catalyzed alkoxycarbonylation[6] to yield tungsten−η^3-allyl compounds as shown in Scheme 1; this reaction allows three chemical bonds to form simultaneously. We here report efficient diastereoselective syntheses of acyclic oxygenated compounds with intramolecular alkoxycarbonylation of propargyl compounds as the initial step. The resulting tungsten-η^3-γ, -δ, and -ϵ-lactonyl compounds are subsequently transformed to complex α-methylene butyrolactones in a one-pot operation. The two reactions proceed highly stereoselectively; the stereochemical courses are discussed later in detail. These resulting lactones provide trisubstituted 1,3-,[7−8] 1,4-,[9] and 1,5-diols[10] after opening of the lactone ring. Stereoselective syntheses of acyclic diols at remote positions are challenging issues[7−10] in organic chemistry.

[†] National Tsing Hua University.

[‡] National Taiwan University.

[⊗] Abstract published in *Advance ACS Abstracts,* September 15, 1996.

(1) (a) Heck, R. F.; Wu, G.; Tao, W.; Rheingold, A. L. In *Catalysis of Organic Reactions;* Blackburn, D. W., Ed.; Marcel Decker Inc.: New York, 1990; p 169. (b) Collman, J. P.; Hegedus, L. S.; Norton, J. R.; Finke, R. G. *Principles and Application of Organotransition Metal Chemistry*; University Science Books: Mill Valley, CA, 1987; Chapter 12, p 619. (c) Hegedus, L. S. *Transition Metals in the Synthesis of Complex Organic Molecules*; University Science Books: Mill Valley, CA, 1994; Chapter 4, p 103. (d) Bates R. W. In *Comprehensive Organometallic Chemistry, Vol. 12: Transition Metal Organometallics In Organic Synthesis:* Abel, E. W., Stone, F. G. A., Wilkinson, G, Eds.; Pergamon Press: Oxford, UK, 1995; Chapter 4, p 349.

(2) For representative examples of catalytic alkoxycarbonylation using palladium complexes: (a) Murray, T. F.; Norton, J. R. *J. Am. Chem. Soc.* **1979,** *101*, 4107. (b) Negishi, E. I.; Sawada, H.; Tour, J. M.; Wei, Y. *J. Org. Chem.* **1988**, *53*, 913. (c) Tsuji, Y.; Kondo, T.; Watanabe, Y. *J. Mol. Catal*. **1987**, *40*, 295. (d) Shinoyama, I.; Zhang, Y.; Wu, G.; Negishi, E.-I. *Tetrahedron Lett*. **1990**, *31*, 2841.

(3) Ni(0) and Rh(1) complexes for catalytic alkoxycarbonylation See representative examples: (a) Semmelhack, M. F.; Brickner, S. J. *J Am. Chem. Soc.* **1981**, *103*, 3945. (b) Sammelhack, M. F.; Brincker, S. J. *J. Org. Chem.* **1981**, *46*, 1723. (c) Eguchi, M.; Zeng, Q.; Korda, A.; Ojima, I. *Tetrahedron Lett.* **1993**, *34*, 915. (d) Matsuda, I.; Ogiso, A.; Sato, S. *J. Am. Chem. Soc.* **1990**, *112*, 6120. (e) Matsuda, I. *Chem. Lett.* **1978**, 773.

(4) For examples of stoichiometric cyclocarbonylation, see: (a) Schrieber, S. L.; Semmekia, T.; Crowe, W. E. *J. Am. Chem. Soc.* **1986**, *108*, 3128. (b) Billington, D. C.; Pauson, P. L. *Organometallics* **1982**, *1*, 1560. (c) Magnus, P.; Principe, M. J.; Slater, J. *J. Org. Chem*. **1987**, *52*, 1483. (d) Berk, S. C.; Grossman, S. L.; Buchwald, S. L. *J. Am. Chem. Soc.* **1993**, *115*, 4912. (e) Frank-Neuman, M.; Michelotti, E. L.; Simler, R.; Vernier, J. M. *Tetrahedron Lett*. **1992**, *33*, 7361.

(5) For examples of stoichiometric alkoxycarbonylation, see: (a) Ley, S, V. *Philos. Trans. R. Soc. London A* **1988**, *326*, 633. (b) Caruso, M.; Knight, J. G.; Ley, S. V. *Synlett* **1990**, 331 (c) Ring, H.; Auman, R.; Frohlich, K. *Angew. Chem.,Int. Ed. Engl.* **1974**, *13*, 275. (d) Moriarty, R. M.; Deboer, B. J.; Churchill M. R.; Yeh, H. J. S.; Chen, K. N. *J. Am. Chem. Soc.* **1975**, *97*, 5602. (e) Liebeskind, L. S.; Welker, M., Fengl, R. W. *J. Am. Chem. Soc.* **1986**, *108*, 6328. (f) Davies, S, G.; Dordor-Hedgecock, I. M.; Warnrer, P. L. *Tetrahedron Lett*. **1985**, *26*, 2125.

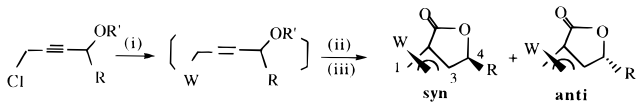
(6) For alkoxylcarbonylation of metal−η^1-propargyl compounds, see: (a) Charrier, C.; Collin, J.; Merour, J. Y.; Roustan, J. L. *J. Organomet. Chem.* **1978**, *162*, 57. (b) Cheng, M.-H.; Ho, Y. H.; Chen, C. H.; Lee, G. H.; Peng, S. M.; Chu, S. Y.; Liu, R. S. *Organometallics* **1994**, *13*, 4082. (c) Lin, S. H.; Vong, W. J.; Liu, R. S. *Organometallics* **1995**, *14*, 1619.

(7) Oishi, T.; Nakata, T. *Synthesis* **1990**, 635

(8) Representative examples for stereoselective synthesis of 1,3-diols. See the review paper[7] and: (a) Evans, D. A.; Chapman, K. T.; Carreira E. M. *J. Am. Chem. Soc*. **1988**, **110**, 3560 (b) Evans, D. A.; Hoveyda, A. H. *J. Org. Chem*. **1990**, *55*, 5190. (c) Rychnovsky, S. D.; Griesgraber, G.; Zeller, S.; Skalitzky, D. L. *J. Org. Chem*. **1991**, *56*, 5161. (d) Hanamoto, T.; Hiyama, T. *Tetrahedron Lett.* **1988**, *29*, 6467. (e) Narasaka, K.; Pai, F.-C. *Chem. Lett*. **1980**, 1415.

S0002-7863(96)01780-5 CCC: $12.00

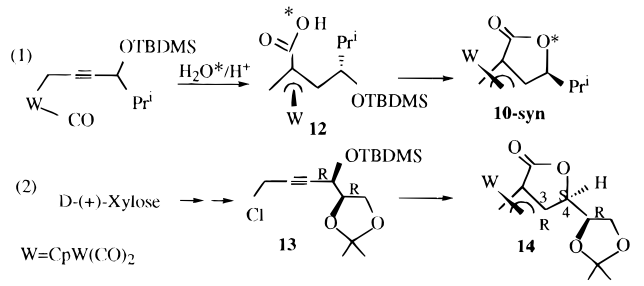
Scheme 2



propargyl chloride	π-lactone(syn/anti)	yields
R' = H		
R = Et **1**	**8** (71/29)	80%
i-Bu **2**	**9** (62/38)	81%
i-Py **3**	**10** (49/51)	80%
R' = $SiMe_2$(t-Bu)		
R = Me **4**	**11-syn**	83%
Et **5**	**8-syn**	82%
i-Bu **6**	**9-syn**	81%
i-py **7**	**10-syn**	80%

W = $CpW(CO)_2$, (i) $CpW(CO)_3Na$ (1.0 equiv., 23° C, 4 h) (ii) CF_3SO_3H (0.25 equiv, - 40° C, 1h) (iii) R = $SiMe_2$(t-Bu), H_2O (1.0-2.0 equiv.).

Scheme 3



Results

Stereoselective Syntheses of Tungsten−η^3-γ, -δ, and -ϵ-Lactonyl Compounds. Treatment of 4-chloro-2-yn-1-ols[11] **1**−**3** with $NaCpW(CO)_3$ (1.0 equiv) in tetrahydrofuran (THF) (23 °C), followed by acidification of the resulting η^1-propargyl compounds with catalyst CF_3SO_3H (0.15 equiv) in cold CH_2Cl_2 (−40 °C, 4 h), delivered η^3-γ-lactonyl compounds **8**−**10** as a mixture of *syn* and *anti* diastereomers (*syn*/*anti* = 2.5−1.0); the overall yields exceeded 80% (Scheme 2). The two diastereomers are distinguishable by proton NMR spectra that showed coupling constants $J_{34} = 0$ Hz for the *anti* isomer and $J_{34} = 3-4$ Hz for the *syn* isomer. Separation of the mixtures by fractional crystallization and column chromatography was very difficult. To circumvent this stereochemical problem, we discovered that acidification of α-(silyloxy)tungsten−η^1-propargyl species with CF_3SO_3H in cold CH_2Cl_2 (−40 °C, 3 h) yielded only *syn* isomers of **8**−**11,** even for the bulky isopropyl group; the overall yields also exceeded 80% propargyl chloride π-lactone(syn/anti)yields (Scheme 2). A little water (1.0−2.0 equiv) is a prerequisite for this *syn* stereoselection. The *syn* isomer of **9** was characterized by an X-ray diffraction study.[12,13] The effect of the α-(*tert*-butyl)dimethylsilyl group on *syn* stereoselectivity deserves attention. As depicted in Scheme 3, we monitored the CF_3SO_3H/H_2O acidification of an α-silyloxy

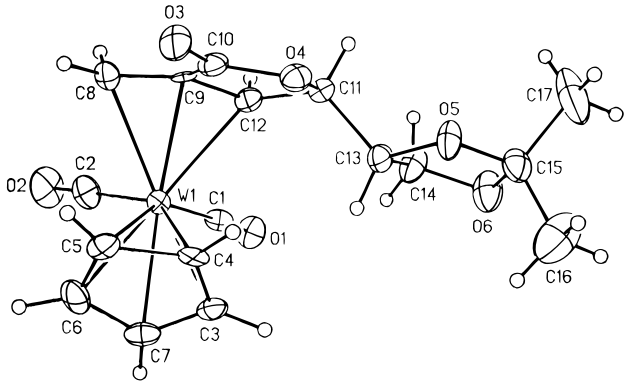


Figure 1. ORTEP drawing of chiral tungsten−η^3-allyl complex **14.** Selected bond distances (Å): W(1)−C(8) = 2.320(12); W(1)−C(9) = 2.221(10); W(1)−C(12) = 2.361(12); C(9)−C(10) = 1.506(15); C(10)−O(3) = 1.192(13).

η^1-propargyl complex in proton NMR experiments (−40 °C, $CDCl_3$). After a brief interval ($t = 3$ min), the solution species consisted of tungsten−allyl complex **12** (∼90% yield) and *syn*-η^3-lactonyl species **10** (∼10%). Species **12** was kinetically unstable in this acidic medium. After a prolonged period ($t =$ 3 h), the NMR signals of **12** disappeared completely to leave **10**-syn as the only species (∼96%) remaining in solution. Quenching the solution with $NaHCO_3$ after a brief time ($t = 3$ min) allowed isolation of **12** in 51% yield. Alternatively, treatment of the η^1-propargyl complex with CF_3CO_2H/H_2O in cold CH_2Cl_2 (−40 °C, 2 h) yielded **12** in 73% yield. In the latter case, when 1.0 equiv of $H_2{}^{18}O$ was used, the isotopic content of the resulting lactone **10**-syn was 80−85%. We prepared chiral propargyl chloride **13**[14] derived from D-(+)-xylose to understand the reaction mechanism for *syn* stereoselection. The chiral *syn*-lactone **14** ([α] = 110.9°, $c = 0.10$, CH_2Cl_2) was produced smoothly from **13** in an overall yield of 70%. The molecular structure of **14** (Figure 1) revealed that the C(3) and C(4) carbon configurations are *R* and *S*, respectively; this configuration at C(4) implies that formation of the C(4)−O bond of **14** proceeds with retention of stereochemistry relative to **13**.

Following the same method, tungsten−η^3-δ-lactonyl compounds **18**−**20** were obtained from the reactions between $CpW(CO)_3Na$ and 5-chloro-3-yn-1-ols as depicted in Scheme 4. This alkoxycarbonylation proceeds with excellent diastereoselectivity to yield only *anti* diastereomer according to X-ray structures of **18** and **19**;[12] the overall yields exceeded 80%. Further treatment of **19** with $NOBF_4$ (1.0 equiv) in CH_3CN (0 °C) produced an allyl cation[15] which reacted with Bu_4NBH_4 to yield unsaturated lactone **21** in 86% yield. Scheme 4 also shows the formation of tungsten−η^3-ϵ-lactonyl compounds **24** and **25** derived from 6-chloro-4-yn-1-ols **22** and **23**;[11] the overall yields exceeded 80%. Likewise, the reactions proceeded with such excellent diastereoselectivity that only one diastereomer was observed according to variable temperature NMR spectra. Proton NMR spectra at −40 °C revealed that compounds **24** and **25** exist as two conformational isomers; the *endo*/*exo* ratios[16] were **1**/**2** and **2**/**5** for compounds **24** and **25**, respectively. Activation energies for the *endo*/*exo* exchange were estimated to be 13.8 and 13.9 kcal/mol for **24** and **25**, respectively. The

(9) Examples for stereoselective synthesis of 1,4-diols, see: (a) Narasaka, K.; Ukaji, Y.; Watanabe, K., *Bull. Chem. Soc. Jpn.* **1987**, *60*, 1457. (b) Reetz, M. T.; Kesseler, K.; Schmidtberger, S.; Wenderoth, B.; Steinbach, R. *Angew. Chem., Int. Ed. Engl. 1983*, **22**, 989. (c) Bartlett, P. A., Jernstedt, K. K. *J. Am. Chem. Soc.* **1977**, *99*, 4829. (d) Wilson, S. R.; Price, M. F. *Tetrahedron Lett*. **1983**, *24*, 569.

(10) Examples for stereoselective synthesis of 1,5-diols. See: (a) Zheng, H.-C.; Costanzo, M. J.; Maryanoff, B. *Tetrahedron Lett*. **1994**, *35*, 4891. (b) Solladie, G.; Huser, N. *Tetrahedron Lett*. **1994**, *35*, 5297. (c) Burk, M. J.; Feaster, J. E.; Harlow, R. L. *Tetrahedron: Asymmetry* **1991**, *2*, 569. (d) Panek, J. S.; Yang, M.; Solomon, J. S., *J. Org. Chem.* **1993**, *58*, 1003. (e) Short, R. P.; Kennedy, R. M.; Masamune, S. *J. Org. Chem*. **1989**, *54*, 1755.

(11) Brandsma, L.; Verkruijsse, H. D. *Synthesis of Acetylenes, Allenes and Cumulenes*; Elsevier: New York, 1984; Chapter 1.

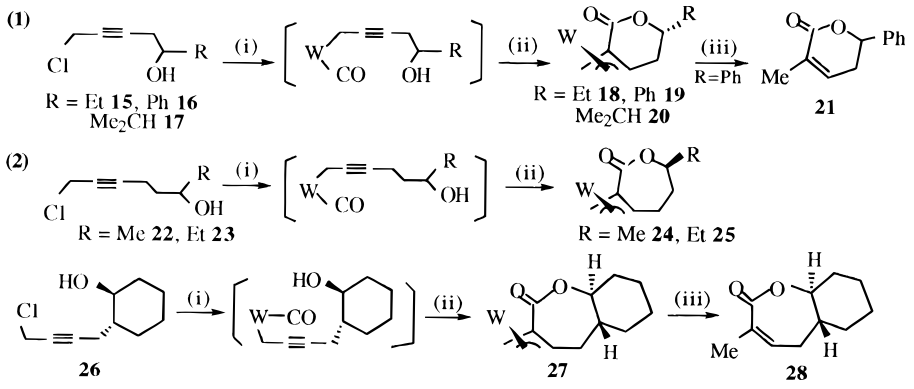
(12) Crystal data, ORTEP drawing, and structure factors of compounds **9**, **18**, **19**, **24,** and **27** have appeared in the communication of this work;[13] these repetitive data will not be reported in this article.

(13) Preliminary results of this work: Chen, C.-C.; Fan, J.-S.; Lee, G.-H.; Peng, S.-M.; Wang, S.-L.; Liu, R.-S. *J. Am. Chem. Soc*. **1995**, *117*, 2933.

(14) (a) Yadav, J. S.; Chander, M. C.; Joshi, B. V. *Tetrahedron Lett*. **1988**, 2737. (b) Takano, S.; Akiyama, M.; Sugihara, T.; Ogasawara, K. *Heterocycles* **1992**, *33*, 831.

(15) Faller, J. W.; Chen. C. C.; Mattina, M. J.; Jakubowski, A. *J. Organomet. Chem.* **1973**, *52*, 361.

Scheme 4



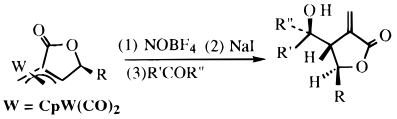
W = $CpW(CO)_2$, (i) $CpW(CO)_3Na$ (THF, 23 °C, 4 h) (ii)CF_3SO_3H (0.25 equiv., CH_2Cl_2 - 40 °C, 1 h) (iii) $NOBF_4$(1.0 equiv, CH_3CN, 0 °C), Bu_4NBH_4 (3.0 equiv, 0 °C)

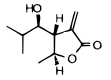
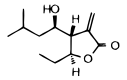
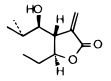
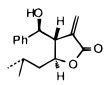
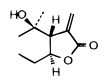
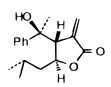
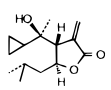
crystal structures of **24** was determined from X-ray diffraction studies[12] that confirmed the *syn* configuration i. e., the ethyl group lies on the metal side. To apply this method to a more complex molecule, we synthesized the propargyl halide **26**, further converting it to an η^1-propargyl species, and finally yielding η^3-bicyclic lactone **27** in overall yield 76%. The X-ray structure of **27**[12] revealed that the cyclization also follows *syn* stereoselection. Sequential treatment of **27** with $NOBF_4$[16] and Bu_4NBH_4 in CH_3CN afforded bicyclic unsaturated lactone **28** in 91% yield.

Condensation of η^3-Lactonyl Complexes with Organic Carbonyls. $CpMo(NO)X(\pi$-allyl) (X = halide)[17,18] reacted with aldehydes to yield homoallylic alcohols with high diastereoselectivity. This method was developed by Faller[17,18] for molybdenum complexes. We discovered that the reaction is applicable to our tungsten η^3-lactonyl compounds for stereocontrolled syntheses of complex α-methylene butyrolactones; the operation is carried out in a one-pot procedure to achieve maximum yields. In a typical example, treatment of *syn*-η^3-γ-lactonyl **11**-syn with $NOBF_4$ (1.0 equiv) in CH_3CN (0 °C), followed by addition of NaI (2.0 equiv), gave a $CpW(NO)I(\pi$-allyl) species (*vide infra*) that reacted *in situ* with aldehydes (CH_3CN, 23 °C, 4 h) to give **29** in overall yield 65% after workup. Scheme 5 summarizes all results for condensation of η^3-lactonyl compounds **8**, **9**, and **11** with various organic carbonyl compounds. All the reactions in this scheme proceeded with good diastereoselectivities such that one dominant product was formed. Although $CpMo(NO)X(\pi$-allyl) (X = halide) failed to react with ketones, condensation of several methyl ketones with **8**-syn or **9**-syn yielded the corresponding α-methylene butyrolactones **33**−**35** in reasonable yields, 55−60% (entries 5−7). The reaction between **9**-syn and diethyl ketone failed to yield α-methylene butyrolactone even after 48 h. $CpW(NO)I(\pi$-allyl) compounds were more reactive than molybdenum analogs without loss of diastereoselectivities. The stereochemical outcome shown in Scheme 5 reveals that the forming carbon−carbon bonds proceed via inversion of stereochemistry relative to the tungsten fragment.

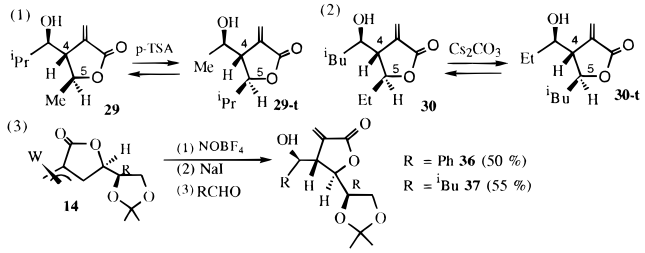
Compounds **29, 30**, and **33** have a *trans* configuration according to NOE effects and the proton coupling constant J_{45} = 3−4 Hz. The magnitude of the *cis* coupling constant is ~J_{45} = 8−10 Hz.[6c] Treatment of **29** with *p*-toluenesulfonic acid (*p*-TSA) (20 mol %) in CH_2Cl_2 (23 °C, 4 days) produced a *trans* esterification isomer **29**-t that attained an equilibrium with **29** in a ratio **29**-t/**29** = 3/1, further separable on a silica TLC plate. Proton NOE spectra of **29**-t indicated a *trans* configuration of the lactone. Similarly heating of **30** with Cs_2CO_3 in THF for 4 h produced **30** and **30**-t in equal proportion. Compound **30**-t likewise has a *trans* configuration according to the proton NOE

Scheme 5



Entry	Allyl	R'COR"	Product	Product no (Yields)
1	R = Me **11-syn**			**29** (65%)
2	R = Et **8-syn**			**30** (65%)
3	R = Et **8-syn**			**31** (61%)
4	R = iBu **9-syn**			**32** (67%)
5	R = Et **8-syn**			**33** (61%)
6	R = iBu **9-syn**			**34** (60%)
7	R = iBu **9-syn**			**35** (55%)

Scheme 6

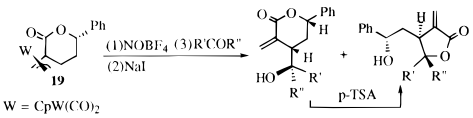


(16) Adams, R. D.; Chodosh, D. F.; Faller, J. W.; Rosan, A. M. *J. Am. Chem. Soc.* **1979**, *101*, 2570.

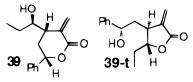
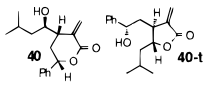
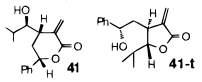
(17) (a) Faller, J. W.; Linebarrier, D. L. *J. Am. Chem. Soc.* **1989**, *111*, 1937. (b) Faller, J. W.; John, J. A.; Mazzier, M. R. *Tetrahedron Lett.* **1989**, *32*, 1769. (c) Faller, J. W.; DiVerdi, M. J.; John, J. A.; *Tetrahedron Lett.* **1989**, *32*, 1271. (d) Faller, J. W.; Naguyen, J. T.; Ellis, W.; Mazzieri, M. R. *Organometallics* **1993**, *12*, 1434.

(18) Faller, J. W.; Ma, Y. *J. Am. Chem. Soc.* **1991**, *113*, 1579. (b) Faller, J. W.; Chase, K. J.; Mazzieri, M. R. *Inorg. Chim. Acta* **1995**, *229*, 39. (c) Faller, J. W. Nguyen, J. T.; Mazzieri, M. R. *Appl. Organomet. Chem.* **1995**, *9*, 291.

Scheme 7



W = CpW(CO)$_2$

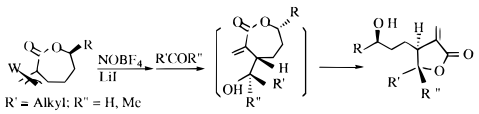
Entry	Allyl	R'COR"	Product	Isolated Yield(%)
1	**19**		 **38**	68%
2	**19**		 **39** **39-t**	**39** (10%) **39-t** (58%)
3	**19**		 **40** **40-t**	**40** (20%) **40-t** (48%)
4	**19**		 **41** **41-t**	**41** (16%) **41-t** (51%)
5	**19**		 **42**	57%

effect, thus establishing the complete stereochemistry of the products. Equation 3 shows the application to the syntheses of chiral compounds **36** ([α] = −23.0, *c* = 0.76, $CHCl_3$) and **37** ([α] = +9.4, *c* = 1.26, $CHCl_3$) in yields 50 and 57%, respectively. **36** has a *trans* configuration according to proton NMR data.

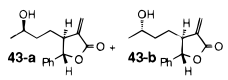
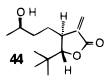
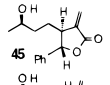
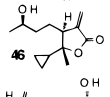
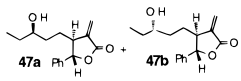
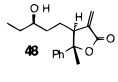
Scheme 7 presents the results for condensation of η^3-*δ*-lactonyl **19** with aldehydes and ketones according to the same procedure. As a specific instance, the reaction between propanal and **19** afforded a mixture of **39** (10%) and **39**-t (58%, a *trans* esterification isomer of **39**), separable on a silica TLC plate. Compounds **39** and **39**-t were identified to be *δ*- and *γ*-lactone, respectively, according to ^{1}H and ^{13}C NMR data. Treatment of *δ*-lactone **39** with *p*-TSA catalyst (10 mol %) in $CDCl_3$ (23 °C, 6 h) regenerated **39**-t in an equilibrium ratio **39**/**39**-t = 1/10, confirming the structural relationship between the two compounds. Proton NOE effects revealed *cis* and *trans* configurations of **39** and **39**-t, respectively (see the Experimental Section), thus establishing the complete stereochemistry of the products. Likewise, treatment of **40** and **41** with *p*-TSA (10 mol %) in $CDCl_3$ (23 °C, 4 h) produced their respective isomers **40**t and **41**t with equilibria in favor of *γ*-lactones (**40**/**40**t = 1/10, **41**/**41**t = 1/13). The reaction of **19** with acetone gave a 57% yield of **42** (entry 5), which was not converted to *γ*-lactone by *p*-TSA in $CDCl_3$ (23 °C, 4 h).

Scheme 8 shows the results for η^3-*ϵ*-lactone complexes **24** and **25** according to the same method; in most cases only a single isomer of α-methylene butyrolactone was formed. In entry 1, ^{1}H NMR spectra of **43a** and **43b** (∼5/1 ratio) are similar but are distinct through their methyl signals; the existence of two diastereomers was clearly indicated in ^{13}C NMR spectra. The two diastereomers of **43a**−**b** and **47a**−**b** appear to have the same configurations at the *γ*-lactone ring because of slight differences ($\Delta\delta$ < 0.02 ppm) in the proton NMR chemical shifts. Proton NOE spectra of **43a** and **48** show a *trans* configuration. To determine the complete stereochemistry, as shown in Scheme 9, we converted the major diastereomer **43a** to its triethylsiloxy derivative **49**, followed by treatment with excess MeLi to yield **50** as a crystalline solid. The molecular structure of **50** was determined from an X-ray diffraction study.[19] Intramolecular cyclization of the mesylate derivative **51** afforded tetrahydropyran **52** in 92% yield. The proton NOE results and proton coupling constants of **52** establish the stereochemistry (see Experimental Section) that is consistent with the X-ray structure

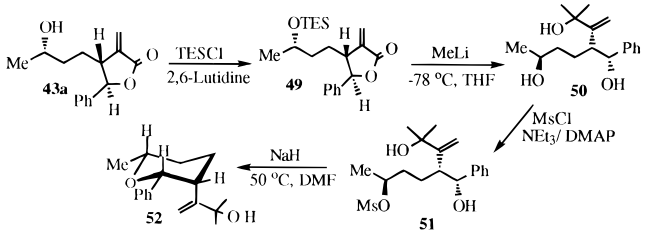
Scheme 8



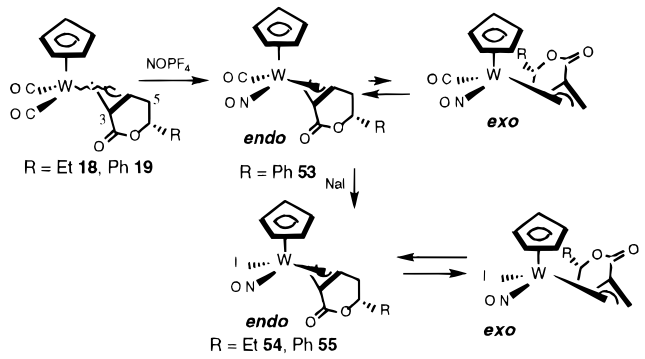
R' = Alkyl; R" = H, Me

Entry	Reagents	R'COR"	Products	Isolated Yield(%)
1	R = Me **24**		 **43a** **43b**	**43a**(54%) **43b**(10%)
2	R = Me **24**		 **44**	46%
3	R = Me **24**		 **45**	60%
4	R = Me **24**		 **46**	43%
5	R = Et **25**		 **47a** **47b**	**47a**(53%) **47b**(11%)
6	R = Et **25**		 **48**	58%

Scheme 9



Scheme 10



of **50**. As shown in Scheme 8, *cis*-*ϵ*-lactones are envisaged to be the primary reaction products that undergo rapid *trans* esterification to yield the observed single (major) diastereomer. Minor products **43b** and **47b** are derived from the primary *trans*-*ϵ*-lactone form. Formation of *cis*-*ϵ*-lactones indicates that the carbonyl addition at the tungsten allyl group occurs preferentially on the same side as the tungsten fragment, i.e., with retention of stereochemistry.

Characterization of CpW(NO)I(η^3-Lactonyl) Complexes. To clarify the structure of CpW(NO)I(η^3-lactonyl), it is very useful to elucidate the stereochemical courses of the preceding organic reactions. Scheme 10 shows syntheses of the CpW(CO)NO$^+$ and CpW(NO)I compounds **53**−**55** derived from **18** and **19**. Preparation of pure **55** from nitrosyl salt **53** was achieved in 83% yield by fractional crystallization from acetonitrile/diethyl ether. Sequential treatment of **18** with $NOPF_6$ and then NaI in CH_3CN (5 mL) at 0 °C gave **54** in an

(19) The ORTEP drawing and crystal data of 1,5-diol **50** were prepared as supporting information.

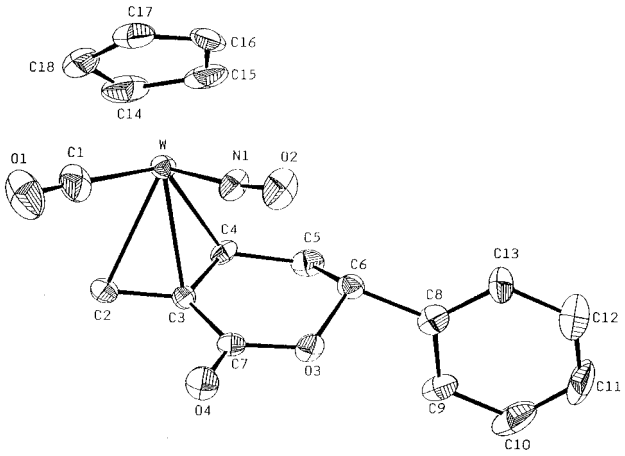


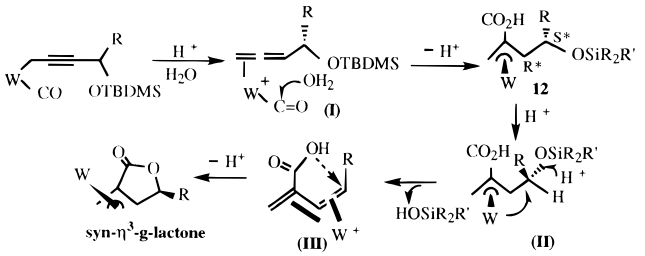
Figure 2. ORTEP drawing of compound **53.** Selected bond distances (A): W−C(2) = 2.348(12); W−C(3) = 2.315(10); W−C(4) = 2.364-(10); C(3)−C(7) = 1.486(16); C(7)−O(4) = 1.197(12).

overall yield of 72% after recrystallization. As expected, the reaction of **55** with acetaldehyde in CH_3CN (23 °C, 4 h) afforded only **38**, consistent with the result from a direct synthesis (Scheme 7, entry 1); the latter is more convenient and efficient. Only one diastereomer was found for **53** according to ^{1}H NMR spectra at various temperatures. The molecular structure of the nitrosyl salt **53** appears in Figure 2**.** The ORTEP drawing reveals an *endo* conformation, i.e., the allyl mouth faces the cyclopentadienyl group; the nitrosyl group is *trans* to the CH_2 terminus. Variable-temperature ^{1}H NMR spectra of **54** (supporting information) in CD_2Cl_2 showed the presence of two species at 30 °C in a 7/1 ratio, but only one conformer was present in solution at −40 °C. The minor conformer undergoes rapid conversion to the more stable species at low temperature. The proton NMR patterns of the ring protons of **54** and **55** bear close resemblance to those of **18**, **19**, and **53**, particularly for the C(5) methylene protons which appear as dd (d = doublet, J = 17, 10 Hz), and dt (t = triplet, J = 17, 3−4 Hz) pattern, respectively. Hence we assign the two species to be *anti* isomers that undergo rapid *endo*−*exo* conformational exchange following a $\eta^3 \rightarrow \eta^1 \rightarrow \eta^3$ process.[20] The stereochemistries of **54** and **55** were deduced from the structures of **53** as substitution of iodide for the carbonyl group of **53** proceeded via a retention pathway.[20] Notably the stereochemistries of **54** and **55** differ from that of CpMo(NO)X(η^3-1-*R*-allyl) (X = halide),[17,18] which has a nitrosyl *cis* to the CH_2 terminus in an *endo* conformation. Despite this difference, complexes of these two types undergo diastereoselective addition with aldehydes.

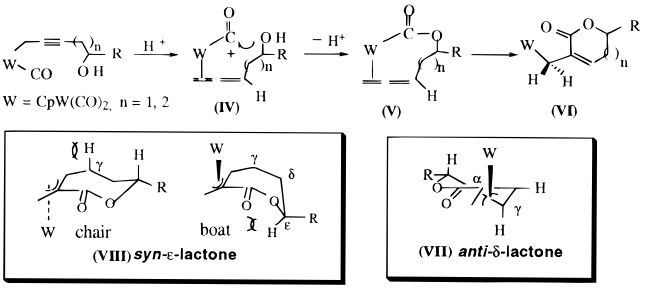
Discussion

Stereochemical Course of Intramolecular Alkoxycarbonylation. The fact that an α-(*tert*-butyl)dimethylsiloxyl group effects *syn* stereoselection for formation of tungsten η^3-γ-lactones is an interesting issue in organometallic reaction. The reaction mechanism is distinct from those of formation of η^3-δ- and -ϵ-lactones because the former requires water. The results in Scheme 3 enable us to elucidate the mechanism. Isolation of complex **12** together with an $H_2{}^{18}O$ labeling experiment indicate a mechanism in Scheme 11 that involves an intramolecular alkoxycarboxylation via attack of water at the carbonyl group of η^2-allene cation **I** to yield **12**. The most stable configuration of **12** is attained on arranging its most bulky $OSiMe_2$(*t*-Bu) group and allyl carbons in a zigzag conformation

Scheme 11



Scheme 12



with the R substituent opposite the metal, as represented in **12**. The X-ray structure of optically active complex **14** is significant because it not only confirms the 3*R**,4*S** configuration of **12** (Scheme 12) but also shows the retention of stereochemistry on substitution of the OTBDMS group by COOH. We propose that in the presence of protons **12** undergoes intramolecular metal-assisted ionization to yield a *cis*-η^4-*s*-*trans*-diene cation **III**.[21,22] In this ionization, the leaving siloxyl group prefers to be opposite the tungsten fragment to facilitate ionization. Subsequent *exo* attack of COOH on the ═CR carbon of species **III** is expected to yield *syn*-η^3-γ-lactone. Retention of stereochemistry is thus achieved on double inversions of the C(4) carbon of **12**. Such a metal-assisted ionization mechanism has been previously observed for low-valent transition metal complexes.[23−25]

Scheme 12 rationalizes the highly stereselective formation of tungsten−η^3-δ- and -ϵ-lactones; the initial step involves intramolecular hydroxyl attack on the η^2-allene cation to yield species **V**. Subsequent insertion of the WCO group into the central η^2-allene carbon of **V** yielded a 16-electron intermediate **VI**. The W−CH_2 σ bond of **VI** is parallel to the C_α−CO bond to follow *cis* insertion. Therefore, the ultimate control of the stereoselectivity of η^3-δ- and -ϵ lactones depends on direction of rotation of the WCH_2−C_α bond of **VI** to form the most stable π-allyl complex. Corresponding to **VI** are the two states **VII** and **VIII** that show conformational effects of six- and seven-membered rings on π-allyl formation. State **VII** has a chairlike conformation with R in a pseudoequatorial position. A preferable *anti* configuration is generated on rotating the WCH_2−C_α σ bond away from the axial C_γH axial hydrogen. State **VIII** represents a twisted boat or chair conformation for ϵ-lactones. In the former, the formation of *anti* isomer is prohibited by a direct confrontation between $CpW(CO)_2$ and the axial C_ϵH bond.

(20) (a) Faller, J. W.; Shvo, Y.; Chao, K.; Murray, H. H. *J. Organomet. Chem.* **1982**, *226*, 251. (b) Faller, J. W.; Shvo, Y. *J. Am. Chem. Soc.* **1980**, *102*, 5396.

(21) (a) Erker, G.; Wicker, J.; Engel, K.; Rosenfeldt, F.; Dietrich, W.; Kruger, C. *J. Am. Chem. Soc.* **1980**, *102*, 6344. (b) Nakamura, A.; Yasuda, H. *Angew. Chem., Int. Ed. Engl.* **1987**, *26*, 723.

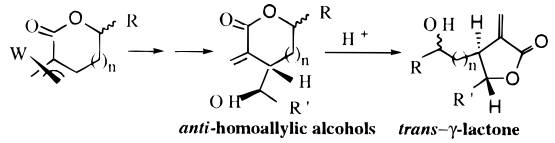
(22) Benyunes, S. A.; Green, M.; Grimshire, M. J. *Organometallics* **1989**, *8*, 2268.

(23) (a) Little, W. F.; Lynam, K. W.; Williams, R., *J. Am. Chem. Soc.* **1964**, *86*, 3055. (b) Beckwich, A. L. J.; Leydon, R. J., *J. Am. Chem. Soc.* **1964**, *86*, 953. (c) Trifan, D. S.; Nicholas, L. *J. Am. Chem. Soc.* **1957**, *79*, 2746.

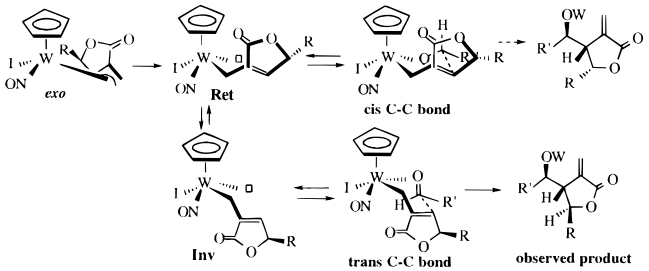
(24) Gree, R. *Syntheses* **1989**, 341.

(25) Vong, W.-J.; Peng, S. -M.; Lin, S.-H.; Lin, W.-J.; Liu, R.-S. *J. Am. Chem. Soc.* **1991**, *113*, 573.

Scheme 13



Scheme 14

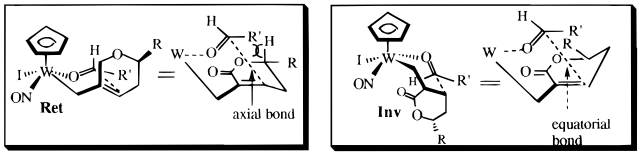


The chair conformation also leads to the same stereoselection because generation of *anti* isomer is hindered by the steric effect of the axial C_γ−H bond.

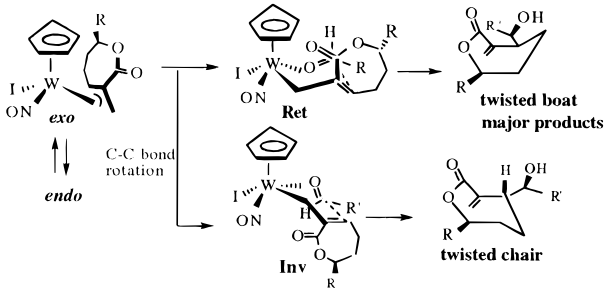
Stereochemical Course of Synthesis of Complex α-Methylene Lactones. A $CpW(CO)_2(\eta^3$-lactonyl) compound is a convenient source for stereoselective syntheses of complex α-methylene lactones; the operation is best performed in a single step to achieve maximum yields. Although many transition metal π-allyl compounds function as allyl anions,[26−30] because of the simplicity of allyl structure, few are suitable for stereoselective synthesis of complex acyclic homoallylic alcohols. Although three stereogenic carbons are created in the reaction; structural analyses of the resulting products reveal that all have a common *anti* configuration at the subunit of the homoallylic alcohol as shown in Scheme 13. Proton-catalyzed *trans* esterification of this functionalty gave *trans*-α-methylene butyrolactones; hence a cyclic transition state controls the stereochemistry.[17,18]

Additions of aldehydes and ketones to tungsten−η^3-γ- and -δ-lactones preferentially proceed from the opposite face relative to the metal fragment. We first rationalize this inversion of stereochemistry with a plausible mechanism (Scheme 14). According to the structures of **54** and **55** (Scheme 10), the π-allyl carbon terminus *trans* to NO is prone to dissociation[17,18] to leave a coordination site to give Ret (retention of conformation); in this manner, the active species is *exo* conformer rather than *endo* conformer. Coordination of the aldehyde to Ret forms a chairlike conformation in which the R′ substituent of the aldehyde is located in an equatorial position to minimize steric hindrance. Generation of the carbon−carbon bond in this transition state, however, suffers from a *cis* 1,2-steric interaction with lactone R substituent. Therefore we propose that rotation of the carbon−carbon bond of Ret produces a new transition state Inv (inversion of conformation) in which formation of the *trans* carbon−carbon bond proceeds more feasibly than that in Ret. The α-methylene butyrolacyones given by Inv are consistent with the observed products in Scheme 5.

Scheme 15



Scheme 16



According to this late transition-state hypothesis, as shown in Scheme 15, the *exo* isomer of **56** generates two transition states Ret and Inv in which addition of aldehydes the allyl C(3) carbon proceeds on the same or opposite metal face, respectively. If a δ-lactonyl R substituent is a bulky phenyl group, Ret becomes less favorable because the forming carbon−carbon bond suffers a 1,3-axial steric hindrance. In contrast, carbonyl addition in Inv proceeds more feasibly than that in Ret because the forming carbon−carbon bond is situated in a less hindered equatorial position; the resulting products from Inv have the same structures as those in Scheme 8.

The mechanisms above show that the key transition states bear productlike structures to determine stereoselection of α-methylene γ- and δ-lactone products. Addition of organic carbonyls to tungsten−η^3-ϵ-lactones occurs from the same side as the tungsten fragment, indicating a kinetic influence. As shown in Scheme 16, the *cis* and *trans* diastereomeric products are of comparable energy,[31] shown by their representative twisted boat and chair conformations. Both structures have the four sp^3-hybridized carbons in mutually staggered conformations, as well as the alkyl substituents in less hindered equatorial positions. Therefore, formation of carbon−carbon bonds in these two structures occurs at equal rates. In an overall reaction, state Ret however becomes more important than Inv because generation of the latter requires an additional energy on rotation of the σ C−C bond of Ret.

Conclusion

In this work, two tungsten-mediated stereocontrolled reactions are described, and the stereochemistries and reaction mechanisms are discussed in detail. The two reactions effect stereoselective transformation of chloroalkynols to β-(hydroxylalkyl)-

(26) For a comprehensive review in the electrophilic alkylations of metal−allyl complexes, see: Yamamoto, Y.; Asao, N. *Chem. Rev.* **1993,** *93*, 2207.

(27) For representative examples of nickel allyl complexes, see: (a) (a) Corey, E. J.; Semmelhack, M. F. *J. Am. Chem. Soc.* **1967**, *92*, 2756. (b) Mackenzie, P. B.; Grisso, B. A.; Johnson, J. R. *J. Am. Chem. Soc.* **1992**, *114*, 5160. (c) Johnson, J. R.; Tully, P. S.; Mackenize, P. B.; Sabat, M. *J. Am. Chem. Soc.* **1991**, *113*, 6172.

(28) Titanium allyl complexes, see: (a) Kobayashi, Y.; Umeyama, K.; Sato, F. *J. Chem. Soc., Chem. Commun.* **1984**, 621. (b) Sato, F.; Uchiyama, H.; Iida, K.; Kobayashi, Y.; Sato, M. *J. Chem. Soc., Chem. Commun.* **1983**, 921. (c) Sato, F,; Iijima, S.; Sato, M. *Tetrahedron Lett.* **1981**, *22*, 243. (d) Sato, F.; Suzuki, Y.; Sato, M. *Tetrahedron Lett.* **1982**, *23*, 4589. (e) Collins, S.; Dean, W. P.; Ward, D. G. *Organometallics* **1988**, *7*, 2289. (f) Collins, S.; Kuntz, B. A.; Hong, Y. *J. Org. Chem.* **1989**, *54*, 4154.

(29) Iron and ruthenium allyl complexes. See: (a) Itoh, K.; Nakanishi, S.; Otsuji, Y. *J. Organomet. Chem.* **1994**, *473*, 215. (b) Kondo, T; Ono, H.; Satake, N,; Mitsudo, T,-A.; Watanabe, Y. *Organometallics* **1995**, *14*, 1945.

(30) Palladium allyl complexes. See: (a) Trost, B. M.; Herndon, J. W. *J. Am. Chem. Soc.* **1984**, *106*, 6835. (b) Masuyama, Y.; Kinugawa, N.; Kurusu, Y. *J. Org. Chem.* **1987**, *52*, 3702. (c) Takahara, J. P.; Masuyama, Y.; Kurusu, Y. *J. Am. Chem. Soc.* **1992**, *114*, 2577. (d) Trost, B. M.; Tometzki, G. B. *J Org. Chem.* **1988**, *53*, 915. (e) Tabuchi, T.; Inanaga, J.; Yamaguchi, M. *Tetrahedron Lett.* **1987**, *28*, 215. (f) Tabuchi, T.; Inanaga, J.; Yamaguchi, M. *Tetrahedron Lett.* **1986**, *27*, 1195.

(31) Bocian, D. F.; Pickett, H. M.; Rounds, T. C.; Strauss, H. L., *J. Am. Chem Soc.* **1975**, *97*, 687.

α-methylene butyrolactones efficiently. As starting materials chloroalkynols are readily prepared in chiral forms, we prepared two chiral α-methylene butyrolactones according to our new methods. In principle, these α-methylene butyrolactones make accessible 1,3- 1,4-, and 1,5-diols, as well as pyrans and furans upon ring opening of lactones. In accordance with this speculations, we provide a specific instance of conversion of *β*-(2′-hydroxypentyl)-α-methylene butyrolactone to a trisubstituted 1,5-diol and pyran.

Experimental Section

Unless otherwise noted, all reactions were carried out under a nitrogen atmosphere in oven-dried glassware using standard syringe, cannula, and septa apparatus. Benzene, diethyl ether, tetrahydrofuran, and hexane were dried with sodium benzophenone and distilled before use. Dichloromethane was dried over CaH_2 and distilled before use. $W(CO)_6$, $BF_3{\cdot}Et_2O$, dicyclopentadiene, propargyl alcohol, and sodium were obtained commercially and used without purification. Organic substrates **1**−**7**,[11] **13**−**17**,[11] **22**−**23**,[11] and **26**[11] were prepared according to literature reports. Syntheses and spectral data of compounds of the same family **9**−**11**, **19**, **20**, **25**, **27**, **30**−**35**, **37**, **40**−**42**, and **44**−**48** in the repetitive operations are listed in supporting information.

Elemental analyses were performed at National Cheng Kung University, Taiwan. Mass data of tungsten and rhenium compounds were reported according to ^{184}W and ^{187}Re isotopes.

(1) General Procedure for Synthesis of $CpW(CO)_2(\eta^3$-γ-Lactonyl) Compounds. **Synthesis of 8.** In a typical reaction, to a THF solution (100 mL) of $CpW(CO)_3Na$ (∼11.0 mmol) was slowly added 6-chlorohex-4-yn-3-ol (**1**; 1.46 g, 11.0 mmol) in THF (5 mL); the mixture was stirred for 5 h at 23 °C. The solution was evaporated to dryness, and the resulting η^1-propargyl complex was chromatographed over a short alumina column under medium pressure. To this compound (4.57 g, 10.6 mmol) in cold CH_2Cl_2 (20 mL, −40 °C) was slowly added CF_3SO_3H (0.22 mL, 2.50 mmol), and the mixture was stirred for 1 h before the temperature was raised to 0 °C. To the solution was added a saturated $NaHCO_3$ solution, followed by evaporation to half volume. The organic layer was extracted with diethyl ether (2 × 20 mL), concentrated, and eluted through a silica column (diethyl ether/hexane = 1/1) to give a yellow band of **8** (R_f = 0.56, 3.64 g, 8.48 mmol, 80%): IR (Nujol, cm^{-1}) υ(CO) 1950(s), 1867(s), 1750(m). *Syn* isomer (71%): ^1H NMR (400 MHz, C_6D_6) δ4.65 (5H, s), 4.21 (1H, dt, J = 4.1, 2.5 Hz), 3.00 (1H, d, J = 3.0 Hz), 2.94(1H, d, J = 2.0 Hz), 1.34 (1H, dq, J = 5.6, 4.1 Hz), 1.26 (1H, d, J = 2.0 Hz), 1.15 (1H, dq, J = 5.6, 4.1 Hz), 0.89 (3H, t, J = 5.6 Hz); ^{13}C NMR (100 MHz, C_6D_6) δ.225.7, 220.6, 174.8, 93.4, 81.9, 70.4, 70.1 , 32.2, 19.7, 10.7. *Anti* isomer (29%): ^1H NMR (400 MHz, C_6D_6) δ 4.69 (5H, s), 4.14 (1H, t, J = 6.0 Hz), 3.00 (1H, d, J = 2.4 Hz), 2.83 (1H, s), 1.35 (2H, dq, J = 7.1, 6.0 Hz), 1.30 (1H, d, J = 2.4 Hz), 0.74 (3H, t, J = 7.1 Hz); ^{13}C NMR (100 MHz, C_6D_6, 298 K) δ 226.4, 220.2, 175.1, 93.8, 84.4, 69.5, 66.9, 30.9, 21.2, 8.6; MS (EI, 12 eV, *m*/*e*) 430 (M^+). Anal. Calcd for $C_{14}H_{14}WO_4$: C, 39.10; H, 3.28. Found: C, 39.02; H, 3.29.

(2) Synthesis of (3*R, 4*S**)-$CpW(CO)_2$(2-Carboxylic acid-4-[(*tert*-butyl) dimethylsiloxyl]-5-methyl-2-hexen-1-yl) (12).** This compound was similarly prepared from 1-chloro-4-[(t-butyl)dimethylsiloxyl]-2-hexyne (1.50 g, 5.74 mmol) and $CpW(CO)_3Na$ (5.50 mmol) except that CF_3CO_2H (0.10 mL, 1.20 mmol) and water (0.20 mL, 11 mmol) were employed in the reaction; the yield of **12** was 73% (2.39 g, 4.16 mmol): IR (Nujol, cm^{-1}) υ(CO) 1968, 1907(vs), 1659(s); ^1H NMR (300 MHz, $CDCl_3$) δ 5.29 (5H, s), 4.76 (1H, dd, J = 9.3, 2.8 Hz), 2.93 (1H, s), 2.26 (1H, d, J = 9.3 Hz), 1.98 (1H, m), 1.11 (1H, s), 0.91(3H, s), 0.90(3H, s), 0.89 (15H, s), 0.12 (3H, s), 0.10 (3H, s); ^{13}C NMR (75 MHz, $CDCl_3$) δ 222.3, 222.2, 175.6, 88.8, 75.7, 75.5, 55.7, 37.7, 26.3, 23.1, 18.5, 17.7, 17.4; MS (FAB, *m*/*e*) 576. Anal. Calcd for $C_{21}H_{32}WSiO_5$: C, 43.76; H, 5.60; Found: C, 43.72; H, 5.52.

(3) Synthesis of Chiral (+)-$CpW(CO)_2(\eta^3$-γ-lactonyl) Complex (14). This optically active compound was similarly prepared from **13** (5.00 g, 15.7 mmol) and $CpW(CO)_3Na$ (17.2 mmol), followed with acidification with CF_3SO_3H (0.34 mL, 3.90 mmol) and water (0.28 mL, 15.7 mmol). The yield of **14** was 70% (5.50 g, 11.0 mmol): IR (Nujol, cm^{-1}) υ(CO) 1957(s), 1873(s), 1747(s); ^1H NMR (400 MHz, $CDCl_3$) δ 5.38 (5H, s, Cp), 4.97 (1H, dd, J = 8.5, 3.5 Hz), 4.30 (1H, dd, J = 8.7, 6.3 Hz), 3.96 (1H, dd, J = 8.7, 5.3 Hz), 3.68 (1H, ddd, J = 8.6, 6.3, 5.3 Hz), 3.30 (1H, d, J = 3.5 Hz), 3.12 (1H, d, J = 3.8 Hz), 1.52 (1H, d, J = 3.8 Hz); ^{13}C NMR (100 MHz, $CDCl_3$) δ 224.9, 218.7, 170.5, 110.7, 93.7, 81.1, 69.7, 65.9, 62.0, 26.6, 25.3, 20.9; MS (12 eV, *m*/*e*) 502 (M^+), 474 (M^+ − CO); $[\alpha]^{24}_D$ +110.9° (*c* = 0.10, CH_2Cl_2). Anal. Calcd for $C_{17}H_{18}WO_6$: C, 40.66; H, 3.61. Found: C, 40.48; H, 3.55.

(4) General Procedure for Synthesis of $CpW(CO)_2(\eta^3$-δ-Lactonyl) Compounds. Synthesis of 18. This compound was similarly prepared from 7-chloro-3-hydroxy-5-heptyne (**15**; 5.00 g, 34.2 mmol) and $CpW(CO)_3Na$ (37.7 mmol) in CH_2Cl_2, followed by acidification with CF_3SO_3H (0.45 mL, 5.13 mmol) at −40 °C; the yield of **18** was 82% (12.5 g, 28.0 mmol): IR (Nujol, cm^{-1}) υ(CO) 1946(s), 1868(s), 1703(s); ^1H NMR (300 MHz, C_6D_6) δ 4.66 (s, 5H), 3.35 (1H, m), 2.70 (1H, d, J = 2.2 Hz), 2.13 (1H, dt, J = 16.2, 3.3 Hz), 1.96 (1H, d, J = 3.0. Hz), 1.82 (1H, ddd, J = 16.2, 10.0 Hz), 1.44 (1H, m), 1.29 (1H, m), 0.78 (3H, t, J = 7.4 Hz), 0.66 (1H, d, J = 2.2 Hz); ^{13}C NMR (300 MHz, C_6D_6) δ 225.5, 217.7, 170.4, 91.9, 78.0, 61.8, 61.7, 30.1, 28.2, 19.6, 9.8; MS (EI, *m*/*e*) 444 (M^+). Anal. Calcd for $C_{15}H_{16}WO_4$: C, 40.57; H, 3.36. Found: C, 40.49; H, 3.63.

(5) Demetalation of 19. To **19** (0.25 g, 0.51 mmol) in CH_3CN (2 mL) was added $NOBF_4$ (58.9 mg, 0.51 mmol) at 0 °C, and the mixture was stirred for 1 h before addition of Bu_4NBH_4 (0.16 g, 0.61 mmol). After stirring for 1 h, to the solution was added $(NH_4)_2Ce(NO_3)_6$ (0.56 g, 1.02 mmol) at 0 °C with stirring for 20 min. The resulting solution was concentrated and chromatographed on a preparative silica TLC (diethyl ether/hexane = 1/2) to give **21** as an colorless oil (R_f = 0.58, 81 mg, 0.42 mmol, 86% yield): IR(Nujol, cm^{-1}) υ(CO) 1730(s), υ-(C═C) 1648(w); ^1H NMR (400 MHz, $CDCl_3$) δ 7.39−7.30 (5H, m), 6.64 (1H, dd, J = 5.9, 1.8 Hz), 5.39 (1H, dd, J = 10.9, 4.2 Hz), 2.63 (1H, ddd, J = 17.6, 10.9, 1.8 Hz), 2.52 (1H, ddd, J = 17.6 , 5.9, 4.2 Hz), 1.96 (3H, s); ^{13}C NMR (100 MHz, $CDCl_3$) δ 165.7, 138.7, 138.6, 128.8, 128.5, 128.4, 126.0, 79.3, 32.0, 17.1; MS (EI, 75 eV, *m*/*e*) 188 (M^+); HRMS calcd for $C_{12}H_{12}O_2$ 188.0837 (M^+), found 188.0829.

(6) General Procedure for Synthesis of $CpW(CO)_2(\eta^3$-ϵ-Lactonyl) Compounds. Synthesis of 24. This compound was similarly prepared from 7-chlorohept-5-yn-2-ol (2.31 g, 15.7 mmol) and $CpW(CO)_3Na$ (17.3 mmol) in CH_2Cl_2, followed by acidification with CF_3SO_3H (0.23 mL, 2.60 mmol) at −40 °C; the yield of **24** was 80% (5.60 g, 12.6 mmol): IR (Nujol, cm^{-1}) υ(CO) 1953(s), 1872(s), 1711(s); ^1H NMR (400 MHz, CD_2Cl_2, −30 °C) *exo* isomer, δ 5.50 (5H, s), 5.12 (1H, m), 2.91 (1H, d, J = 1.8 Hz), 2.38 (1H, m), 1,94 (1H, m), 1.78−1.72 (m, 2H), 1.57 (1H, m), 1.47 (3H, d, J = 6.0 Hz), 1.17 (1H, d, J = 1.8 Hz); *endo* isomer, δ 5.32 (5H, s), 5.04 (1H, m), 2.97 (1H, s), 2.50 (1H, m), 2.24 (1H, m), 1.78 (1H, s), 1.42 (3H, d, J = 7.2 Hz), the rest signals were masked by signals of the *exo* isomer in the region δ 1.78−1.72 ppm; ^{13}C NMR (100 MHz, CD_2Cl_2, 243 K) *exo* conformer, δ 224.5, 220.8, 176.6, 94.8, 76.8, 69.3, 51.4, 37.7, 31.4, 26.2, 21.0; *endo* conformer δ 226.8, 225.0, 174.2, 89.3, 88.1, 76.1, 41.9 , 38.2, 33.4, 31.3, 21.0; MS (EI, 12 eV, *m*/*e*): 444 (M^+). Anal. Calcd for $C_{15}H_{16}WO_4$, 40.57; H, 3.63. Found: C, 40.47; H, 3.71.

(7) Demetalation of 27. To **27** (0.56 g, 1.16 mmol) in CH_3CN (2 mL) was added $NOBF_4$ (1.34 g, 1.16 mmol) at 0 °C; the mixture was stirred for 20 min before addition of Bu_4NBH_4 (0.36 g, 1.39 mmol). After stirring for 1 h, to the solution was added $(NH_4)_2Ce(NO_3)_6$ (1.27 g, 2.32 mmol) at 0 °C with stirring for 20 min. The resulting solution was concentrated and chromatographed on a preparative silica TLC (diethyl ether/hexane = 1/2) to give **28** as an colorless oil (R_f = 0.56, 186 mg, 1.05 mmol, 91% yield): IR(Nujol, cm^{-1}) υ(CO) 1730(s), υ-(C═C) 1648 (w); ^1H NMR (400 MHz, $CDCl_3$, 25 °C) δ, 6.12 (1H, br t, J = 6.0 Hz), 3.96 (1H, td, J = 11.2, 4.0 Hz), 2.58 (1H, m), 2.05 (1H, m), 1.94 (3H, s), 1.88 (1H, m), 1.80 (1H, m), 1.56−1.64 (4H, m), 1.18−1.23 (3H, m); ^{13}C NMR (100 MHz, $CDCl_3$) δ, 171, 132.0 130.3, 80.0, 42.0, 31.6, 30.4, 29.5, 24.2, 23.4, 18.5; HRMS calcd for $C_{11}H_{16}O_2$ 180.1150, found 180.1152.

(8) General Procedure for Condensation of $CpW(CO)_2(\eta^3$-γ-Lactonyl) with Organic Carbonyls. Synthesis of (4*R,5*S**)-[5-Methyl-4-[(1*R**)-1-hydroxy-2-methylpropyl]-3-methylenedihydrofuran-2-one] (29).** To a stirring CH_3CN (3 mL) of solution **11** (*syn* isomer) (1.00 g, 2.40 mmol) was slowly added a CH_3CN solution of $NOBF_4$ (0.31 g, 2.64 mmol) at 0 °C; after 30 min, NaI (0.72 g, 4.80 mmol) was added to the solution. The mixture was stirred for 30 min

and then treated with *i*-BuCHO (0.65 g, 7.20 mmol) at 0 °C. The solution was warmed to 23 °C and stirred for 4 h to produce a dark orange precipitate. The solution was treated with $NaHCO_3$ (2 mL), concentrated, and eluted on a preparative TLC plate (diethyl ether/hexane = 1/1) to give **29** as an oil (R_f = 0.56, 0.32 g, 1.56 mmol, 65%): IR (neat, cm^{-1}) 3437, 1750, 1652; ^1H NMR (300 MHz, $CDCl_3$) δ 6.35 (1H, d, J = 2.2 Hz), 5.76 (1H, d, J = 2.2 Hz), 4.48 (1H, qd, J = 6.5, 3.2 Hz), 3.28 (1H, t, J = 7.6 Hz), 2.76 (1H, m), 1.78 (1H, m), 1.35 (3H, d, J = 6.5 Hz), 0.99, 0.96 (3H, d, J = 6.5 Hz); ^{13}C NMR (75 MHz, $CDCl_3$) δ 170.2. 135.6, 125.1, 77.1, 49.2, 21.9, 19.9, 16.7, MS (75 eV, *m/e*) 185 (M^+), HRMS calcd for $C_{10}H_{16}O_3$ 184.1099, found 184.1192.

(9) *Trans* Esterfication of 29. To a CH_2Cl_2 solution (1 mL) of **29** (0.51 g, 2.51 mmol) was added *p*-TSA (67.2 mg, 0.50 mmol); the mixture was stirred for 4 days before addition of $NaHCO_3$ solution. The solution was concentrated and eluted on a preparative TLC plate (diethyl ether/hexane = 1/1) to yield a new band of **29**t (R_f = 0.52, 291 mg, 1.43 mmol, 57%): IR (neat, cm^{-1}): 3438(br), 1750(s), 1658-(m), 1467(m); ^1H NMR (400 MHz, $CDCl_3$) δ 6.29 (1H, d, J = 2.1 Hz), 5.69 (1H d, J = 1.9 Hz), 4.21 (1H, dd, J = 5.6, 2.3 Hz), 3.82 (1H, t, J = 6.3 Hz), 2.79 (1H, m), 1.80 (1H, m), 1.18 (3H, d, J = 6.3 Hz), 0.91 (3H, d, J = 5.0 Hz), 0.90 (3H, d, J = 5.0 Hz); ^{13}C NMR (100 MHz, $CDCl_3$) δ 170.5, 136.0, 124.2, 84.2, 69.2, 48.5, 33.2, 19.4, 18.6, 16.8; MS (75ev, *m/e*) 184 (M^+), 140, 125; HRMS $C_{10}H_{16}O_3$ calcd 184.1099, found 184.1103.

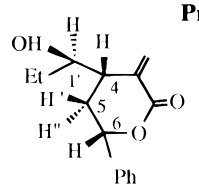
(10) *Trans* Esterfication of 30. To a THF solution (5 mL) of **30** (265 mg, 1.25 mmol) was added Cs_2CO_3 (0.82 g, 2.50 mmol); the mixture was heated for 4 h. The solution was concentrated and eluted through a short silica column to yield a 1/1 mixture of **30** and **30**t. Spectral data for **30**t: IR (neat, cm^{-1}) 3433(br), 1752(s), 1653(m), 1467-(m); ^1H NMR (400 MHz, $CDCl_3$) δ 6.33 (1H, d, J = 1.5 Hz), 5.72 (1H, d, J = 1.5 Hz), 4.47 (1H, td, J = 7.4, 3.5 Hz), 3.53 (1H, ddd, J = 9.3, 7.6, 4.0 Hz), 2.67 (1H, dd, J = 7.6, 3.5 Hz), 1.80 (1H, m), 1.60 (2H, m), 1.55−1.41 (2H, m), 0.85−0.98 (9H, m); ^{13}C NMR (100 MHz, $CDCl_3$) δ 170.0, 136.1, 124.2, 78.6, 74.5, 50.8, 46.3, 26.7, 24.8, 23.0, 21.9, 10.1; HRMS $C_{12}H_{20}O_3$ calcd 212.1412, found 212.1416.

(11) Synthesis of (−)-(4*S*,5*R*)-[5-[(4*R*)-(2,2-Dimethyl[1,3]dioxolan-4-yl]-4-[(1*R*)-1-hydroxy-1-phenylmethyl]-3-methylenedihydrofuran-2-one] (36). This compound was similarly prepared from chiral tungsten−allyl **14** (0.20 g, 0.39 mmol), $NOBF_4$ (51 mg, 0.43 mmol), and NaI (120 mg, 0.78 mmol) and finally treated with benzaldehyde (85 mg, 0.78 mmol) at 23 °C to yield **36** (67 mg, 0.20 mmol, 50%) as a colorless oil: IR (neat, cm^{-1}) 3465(br s), 1747(s), 1667(m); ^1H NMR (400 MHz, $CDCl_3$) δ 7.39−7.29 (5H, m), 6.30 (1H, d, J = 2.2 Hz), 5.60 (1H, d, J = 2.2 Hz), 4.73 (1H, d, J = 7.1 Hz), 4.26 (1H, t, J = 2.0), 3.90−3.70 (3H, m), 3.34 (1H, dd, J = 7.1, 2.0 Hz), 1.30 (3H, s), 1.27 (3H, s); ^{13}C NMR (100 MHz, $CDCl_3$) δ 170.0, 140.3, 134.8, 128.9, 128.6, 125.0, 110.6, 76.7, 67.9, 65.0, 48.1, 25.6, 25.3; HRMS calcd for $C_{17}H_{20}O_5$ 304.1310, found 304.1318; $[\alpha]^{24}_D$ −23.04 (*c* = 0.76, $CHCl_3$).

(12) General Procedure for Condensation of $CpW(CO)_2(\eta^3$-δ-Lactonyl) (19) with Organic Carbonyls. Synthesis of (4*S,5*R**)-[4-[(2*S**)-2-Hydroxy-2-phenylethyl]-5-methyl-3-methylenedihydrofuran-2-one] (38).** This compound was similarly prepared from **19** (0.35 g, 0.71 mmol), $NOBF_4$ (100 mg, 0.85 mmol), and NaI (213 mg, 1.42 mmol) and finally treated with acetaldehyde (62.5 mg, 1.42 mmol) at 23 °C to yield **38** as a colorless oil (107 mg, 0.46 mmol, 65%): IR (neat, cm^{-1}) 3447(br s), 1750(s), 1661(m); ^1H NMR (300 MHz, $CDCl_3$) δ 7.37−7.26 (5H, Ph), 6.29 (1H, d, J = 2.3 Hz), 5.68 (1H, d, J = 2.3 Hz), 4.79 (1H, dd, J = 9.3, 4.0 Hz), 4.39 (1H, d, J = 6.2, 3.9 Hz), 2.87 (1H, ddd, J = 7.5, 6.8, 3.9 Hz), 2.01 (1H, ddd, J = 14.1, 9.3, 6.8 Hz), 1.83 (1H, ddd, J = 14.1, 7.5, 4.0 Hz), 1.36 (3H, d, J = 6.2 Hz); ^{13}C NMR (75 MHz, $CDCl_3$) δ 170.5, 144.0, 139.2, 128.8, 128.2, 125.6, 122.9, 80.4, 72.2, 43.9, 43.1, 21.4. MS (75eV *m/e*) 232 (M^+); HRMS calcd for $C_{14}H_{16}O_3$ 232.1099, found 232.1107.

(13) Synthesis of (4*S,6*S**)-[4-[(1*R**)-1-Hydroxypropyl]-3-methylene-6-phenyltetrahydropyran-2-one] (39) and (4*S**,5*R**)-[5-Ethyl-4-[(2*S**)-2-hydroxy-2-phenylethyl]-3-methylenedihydrofuran-2-one] (39t).** These two cpmounds were similarly prepared from sequential treatment of **19** with $NOBF_4$, NaI, and propanal in CD_3CN. Separation of crude product on a silica TLC afforded **39** and **39**t in 10 and 58%, respectively. Spectral data for **39**: IR (neat, cm^{-1}) υ(OH), 3447(vs), υ(CO) 1717(s); ^1H NMR (300 MHz, $CDCl_3$) δ 7.42−7.28 (5H, m, Ph), 6.34 (1H, d, J = 2.0 Hz′), 5.67 (1H, d, J = 2.0 Hz), 5.10 (1H, dd, J = 11.9, 2.1), 3.49 (1H, ddd, J = 8.9, 6.8, 5.6 Hz), 2.94 (1H, ddd, J = 10.4 Hz, 8.0, 6.8 Hz), 2.23 (1H, ddd, J = 13.9, 8.0, 2.1 Hz), 1.87 (1H, ddd, J = 13.9, 11.9, 10.4 Hz), 1.55 (1H, m), 1.40 (1H, m), 0.97 (3H, t, J = 7.4 Hz); ^{13}C NMR (75 MHz, $CDCl_3$): δ 168.4, 138.7, 136.5, 128.6, 128.5, 128.2, 125.9, 79.1, 75.2, 43.1, 33.5, 26.1, 10.2; MS (75eV *m/e*) 246 (M^+); HRMS calcd for $C_{15}H_{18}O_3$ 246.1255, found 246.1257.

Proton NOE map of 39



irradiation at C(4)H proton

Intensity increase
C(5)H' 6.8 %; C(5)H" 2.0 %
C(6)H 3.3 %; C(1')H 2.8 %

Spectral data for **39**t: IR (neat, cm^{-1}) υ(OH), 3447, υ(CO) 1749, 1661; ^1H NMR (300 MHz, $CDCl_3$) δ 7.35−7.23 (5H, m), 6.24 (1H, d, J = 2.3 Hz), 5.66 (1H, d, J = 2.3 Hz), 4.76 (1H, dd, J = 9.4, 4.0 Hz), 4.16 (1H, ddd, J = 7.3, 6.1, 4.9 Hz), 2.94 (1H, ddd, J = 8.9, 6.1, 4.6 Hz,), 1.98 (1H, ddd, J = 12.9, 4.6, 4.0 Hz), 1.82 (1H, ddd, J = 12.9, 9.4 ,8.9 Hz), 1.68 (1H, m), 1.59 (1H, m), 0.94 (3H, t, J = 7.3 Hz); ^{13}C NMR (75 MHz, $CDCl_3$) δ 170.6, 144.2, 139.2, 128.8, 128.1, 125.7, 123.0, 85.4, 71.8, 43.6, 41.5, 28.6, 9.3, MS (75eV *m/e*) 246 (M^+); HRMS calcd for $C_{15}H_{18}O_3$ 246.1255, found 246.1257.

(14) General Procedure for Condensation of $CpW(CO)_2(\eta^3$-ϵ-Lactonyl) with Organic Carbonyls. Synthesis of (4*R,5*R**)-{4-[(3*S**)-3-hydroxybutyl]-3-methylene-5-phenyl-dihydrofuran-2-one} (43a) and (4*R**,5*R**){4-[(3*R**)-3-hydroxybutyl]-3-methylene-5-phenyldihydrofuran-2-one} (43b).** This compound was similarly prepared from chiral tungsten−allyl compound **14** (2.00 g, 4.50 mmol), $NOBF_4$ (0.53 g, 4.50 mmol), and NaI (1.35 g, 9.10 mmol) and finally treated with benzaldehyde (0.96 g, 9.00 mmol) at 23 °C to yield a mixture of **43a** and **43b** (0.71 g, 2.88 mmol, 64%, **43a**/**43b** = 5.4/1) as a colorless oil. Pure **43a** (0.45 g, 1.85 mmol) was obtained in 41% after elution from a preparative HPLC column (Merck, Lichroprep Si60): IR (neat, cm^{-1}) 3034(br s), 1770(s), 1664(m); ^1H NMR (400 MHz, $CDCl_3$) for **43a**, δ 7.36−7.24 (5H, m), 6.30 (1H, d, J = 2.5 Hz), 5.62 (1H, d, J = 2.5 Hz), 5.10 (1H, d, J = 5.0 Hz), 3.73 (1H, m), 2.97 (1H, m), 1.91−1.44 (4H, m), 1.14 (3H, d, J = 6.2 Hz); for **43b**, selected signals, 3.75 (1H, m), 1.17 (3H, d, J = 6.2 Hz), the remaining signals masked exactly with those of **43a**; ^{13}C NMR (100 MHz, $CDCl_3$) **43a**, δ 170.3, 139.3, 138.5, 128.8, 128.6, 125.7, 122.7, 84.2, 67.6, 47.4, 35.3, 29.6, 25.6, **43b,** δ 170.3, 139.3, 138.5, 128.8, 128.6, 125.7, 122.7, 84.1, 67.4, 47.3, 35.3, 29.6, 23.6; MS (75eV *m/e*) 246 (M^+); HRMS calcd for $C_{15}H_{18}O_3$ 246.1256, found 246.1249.

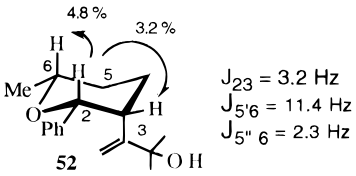
(15) Synthesis of (4*R,5*R**)-[3-methylene-4-[(3*S**)-3-(triethylsiloxy)butyl]-5-phenyldihydrofuran-2-one] (49).** To a DMF solution (5 mL) of **43a** (0.59 g, 2.40 mmol) and 2,6-lutidine (0.42 g, 3.60 mL) was added triethylsilyl chloride (0.40 g, 2.40 mmol); the mixture was stirred for 8 h before sequential addition of an aqueous NH_4Cl (2 mL). The solution was extracted with diethyl ether (3 × 20 mL) and flash chromatographed through a short silica cloumn to yield **49** as a colorless oil (0.80 g, 2.21 mmol, 92%): IR (neat, cm^{-1}) 3035(br s), 1770(s), 1664(m), 1604(m); ^1H NMR (400 MHz, $CDCl_3$) δ 7.37−7.24 (5H, m), 6.33 (1H, d, J = 2.6 Hz), 5.61 (1H, d, J = 2.6 Hz), 5.10 (1H, d, J = 5.1 Hz), 3.75 (1H, m), 2.96 (1H, m), 1.86−1.43 (4H, m), 1.10 (3H, d, J = 6.4 Hz), 0.91 (9H, t, J = 7.6 Hz) 0.56 (6H, q, J = 7.6 Hz); ^{13}C NMR (100 MHz, $CDCl_3$) δ 170.2, 139.5, 138.8, 128.8, 128.6, 125.8, 122.4 , 84.0, 67.9, 47.6, 35.9, 29.3, 23.8, 6.8, 4.9; MS (75eV *m/e*) 360 (M^+); HRMS calcd for $C_{21}H_{32}SiO_3$ 360.2121, found 360.2118.

(16) Synthesis of (4*R,7*S**)-[4-[(*R**)-hydroxyphenylmethyl]-2-methyl-3-methyleneoctane-2,7-diol] (50).** To a THF (5.0 mL) solution of **49** (0.70 mg, 1.94 mmol) was added a hexane solution of MeLi (1.6 M, 6.08 mL) at −78 °C, and the solution was brought to 23 °C. The solution was treated with aqueous NH_4Cl (5.0 M, 1 mL), concentrated to ∼3 mL, and extracted with diethyl ether (2 × 5 mL). Flash chromatography afforded **50** as a colorless solid (0.44 g, 1.57 mol, 81%): IR (neat, cm^{-1}) 3306(br vs), 1640(m); ^1H NMR (400 MHz, $CDCl_3$) δ 7.36−7.26 (5H, m), 5.27 (1H, s), 5.02 (1H, s), 4.29 (1H, d,

J = 9.5 Hz), 3.69 (br, OH), 3.53 (1H, m), 3.10 (br), 2.81 (1H, ddd, J = 9.5, 8.8, 8.5 Hz), 1.69 (br, OH), 1.46 (3H, s), 1.36−1.00 (4H, m), 1.27 (3H, s), 0.99 (3H, d, J 6.1 Hz); ^{13}C NMR (100 MHz, $CDCl_3$) δ 157.6, 143.6, 128.5, 128.2, 127.2, 108.5, 81.4, 72.2, 68.2, 45.9, 36.9, 29.9, 29.7, 28.8, 23.2; MS (75eV *m/e*) 278 (M^+); HRMS calcd for $C_{17}H_{26}O_3$ 278.1881, found 278.1881.

(17) Synthesis of (1*R,2*R**)-[2-[(3*S**)-3-methanesulfonylbutyl]-4-methyl-3-methylene-1-phenylpentane-1,4-diol] (51).** To **50** (0.43 g, 1.55 mmol) in Et_3N (0.43 mL) was added DMAP (57.1 mg, 0.47 mmol) and methanesulfonic chloride (20.0 μL, 1.55 mmol). The solution was stirred for 1 h before aqueous NH_4Cl was added. Flash chromatography gave **51** (0.53 g, 1.47 mmol, 95%): IR (neat, cm^{-1}) 3454(br vs) 1644(m); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.31−7.24 (5H, m), 5.26 (1H, s), 4.99 (1H, s), 4.51 (1H, m), 4.23 (1H, d, J = 9.6 Hz), 3.66 (br, OH), 2.75 (1H, m), 2.69 (3H, s), 1.51−1.17 (4H, m), 1.44 (3H, s), 1.25 (3H, s), 1.22 (3H, d, J = 6.3 Hz); ^{13}C NMR (100 MHz, $CDCl_3$) δ 157.6, 143.6, 128.5, 128.2, 127.2, 108.7, 81.5, 80.3, 72.0, 45.7, 38.3, 34.3, 29.8, 29.6, 28.1, 21.1; MS (75eV *m/e*) 356 (M^+); HRMS calcd for $C_{18}H_{28}SO_5$ 356.1657, found 356.1654.

(18) Synthesis of [2-methyl-3-[(2*R,3*R**,6*R**)-6-methyl-2-phenyltetrahydropyran-3-yl]but-3-en-2-ol] (52).** To **51** (0.41 g, 1.15 mmol) in DMF (5 mL) was added NaH (0.11 g, 4.60 mmol), and the mixture was heated at 50 °C for 4 h. The solution was extracted with diethyl ether (3 × 15 mL), and flash chromatographed through a short silica column to yield **52** as a colorless solid (0.28 g, 1.06 mmol, 92%): IR (neat, cm^{-1}) 3431(br vs), 1642 (m); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.40−7.11 (5H, m), 5.55 (1H, s), 5.16 (1H, s), 4.70 (1H, d, J = 3.2 Hz), 3.66 (1H, m), 2.72 (1H, m), 2.03 and 1.82 (2H, m), 1.71−1.43 (2H, m), 1.30 (3H, d, J = 6.1 Hz), 0.98 (3H, s), 0.95 (3H, s); ^{13}C NMR (100 MHz, $CDCl_3$) δ 152.1, 142.0, 127.4, 126.5, 126.4, 112.7, 81.9, 74.7, 73.3, 37.7, 29.9, 28.5, 28.1, 27.2, 22.3; MS (75 eV *m/e*) 260 (M^+); HRMS calcd for $C_{17}H_{24}O_2$ 260.1776, found 260.1776. In the proton NOE experiment, irradiation of the C(2)H (δ 4.70) signal enhanced the C(6)H and C(3)H proton intensities by 4.8 and 3.2%, respectively. The magnitudes J_{23} = 2.3 Hz and $J_{5''6}$ = 2.3 Hz are consistent with the axial−equatorial coupling whereas the $J_{5'6}$ = 11.4 Hz value is a typical axial−axial coupling constant. Based on these data, the configuration of **52** was assigned.



52

(19) Synthesis of the Nitrosyl Salt of 19. To a CH_3CN (5 mL) solution of **19** (0.90 g, 1.83 mmol) was added with $NOPF_6$ (0.32 g, 1.83 mmol) at 0 °C; the mixture was stirred for 30 min. The solution was concentrated to ∼1 mL; addition of diethyl ether (20 mL) yielded a yellow viscous solid that was dried in vacuo for 24 h. Recrystallization of this solid in a CH_3CN/diethyl ether solution yielded red orange crystals of **53** (1.00 g, 1.56 mmol, 85%): IR (Nujol, cm^{-1}) υ (CO) 2077(s), 1732(s), υ(NO) 1632(vs); ^{1}H NMR (400 MHz, CD_3CN, −33 °C) δ 7.56−7.48 (5H, m, Ph), 6.48 (5H, s, Cp), 5.32 (1H, dd, J = 11.7, 3.6 Hz), 5.05 (1H, d, J = 3.6 Hz), 5.04 (1H, d, J = 3.4 Hz), 3.84 (1H, ddd, J = 17.8, 11.7 Hz), 3.10 (1H, dt, J = 17.8, 3.6 Hz), 2.73 (1H, d, J = 3.4 Hz); ^{13}C NMR (100 MHz, CD_3CN, 253K) δ 163.6, 108.5, 101.5, 98.2, 80.3, 36.3, 30.2, 28.2, 9.4. Anal. Calcd for $C_{18}H_{16}WO_4NPF_6$: C, 33.80; H, 2.52; N, 2.19. Found: C, 33.86; H, 2.61; N, 2,13.

(20) Synthesis of the Iodo Derivative of 53. To a CH_3CN (5.0 mL) solution of **53** (0.500 g, 1.01 mmol) was added NaI (0.30 g, 2.02 mmol) at 0 °C; the solution was stirred for 30 min and evaporated to dryness. The residue was washed with diethyl ether and then extracted with CH_2Cl_2 (2 × 5 mL). The extract was concentrated and recrystallized from CH_3CN/diethyl ether to give **55** as dark red plates (0.50 g, 0.84 mmol, 83%): IR (Nujol, cm^{-1}) υ(CO) 1717(s), υ(NO) 1640; ^{1}H NMR (400 MHz, $CDCl_3$, 243 K) δ 7.40−7.30 (5H, m, Ph), 6.03 (5H, s, Cp), 5.80 (1H, dd, J = 12.0, 3.4 Hz), 5.11 (1H, d, J = 3.4 Hz), 3.77 (1H, d, J = 4.0 Hz), 3.45 (1H, dd, J = 18.0, 12.0 Hz), 3.09 (1H, dt, J = 18.0, 3.4 Hz), 1.91 (1H, d, J = 4.0 Hz); ^{13}C NMR (100 MHz, $CDCl_3$, −30 °C) δ 163.4, 138.2, 128.8, 128.4, 126.1, 108.4, 100.9, 95.7, 79.3, 36.2, 25.5; MS (12 eV, *m/e*) 593 (M^+). Anal. Calcd for $C_{17}H_{16}O_3$-NIW: C, 34.43; H, 2.72; N, 2.36. Found: C, 34.41; H, 2.72; N, 2.33.

(21) Synthesis of 54. To a stirring CH_3CN (5 mL) solution of **18** (0.50 g, 1.13 mmol) was added with $NOPF_6$ (0.20 g, 1.13 mmol) at 0 °C, and the mixture was stirred for 30 min before addition of NaI (0.34 g, 2.26 mmol). After being stirred for additional 30 min, the solution was evaporated to dryness, washed with diethyl ether, and then extracted with CH_2Cl_2 (2 × 5 mL). The extract was dried in vacuo and recrystallized from CH_3CN/diethyl ether to give **54** as dark red plates (0.43 g, 0.81 mmol, 72%): IR (neat, cm^{-1}) υ(CO) 1720(s), υ(NO) 1641; ^{1}H NMR (400 MHz, CD_2Cl_2) major conformer (−33 °C), δ 5.97 (5H, s), 5.06 (1H, d, J = 3.1 Hz), 4.57 (1H, m), 3.60 (1H, d, J = 4.0 Hz), 3.17 (1H, dd, J = 16.1, 10.6), 2.86 (1H, dt, J = 16.1, 3.1 Hz), 1.80 (1H, d, J = 4.0 Hz), 1.80−1.61 (2H, m), 0.90 (3H, t, J = 6.3 Hz); minor conformer (20 °C), δ, 5.85 (s, 5H), 5.05 (1H, br s), 4.05 (1H, br s), 3.60 (1H, dd, J = 16.0, 10.2 Hz), 3.10 (1H, dt, J = 16.1, 3.1 Hz), 2.40 (1H, br s), the rest signals were masked by those of major diastereomer; ^{13}C NMR (100 MHz, CD_2Cl_2, 243 K) δ 163.6, 108.5, 101.5, 98.2, 80.3, 36.3, 30.2, 28.3, 9.4. MS (12 eV, *m/e*) 529 (M^+). Anal. Calcd for $C_{13}H_{16}O_3WNI$: C, 28.63; H, 2.96; N, 2.57. Found: C, 28.60; H, 2.98; N, 2.55.

X-ray Diffraction Studies of 14, 50, and 53. Crystal data and data collection of **9**, **18**, **19**, **24**, and **27** have appeared in the communication of this article;[13] they will not be reported here. Single crystals of **14**, **50**, and **53** were sealed in glass capillaries under an inert atmosphere. Data for **50** and **53** were collected on a Nonius CAD 4 using graphite-monochromated Mo Kα radiation. The structures of **50** and **53** was solved by direct and heavy-atom methods, respectively; all data reduction and structural refinements were performed with NRCCSDP package. Data for **14** were collected on a Siemens SMART CCD diffractometer using graphite-monochromated Mo Kα radiation, and the structure was solved by direct methods; all data reduction and structural refinement were performed with the Siemens SHELXTL Plus package. Crystal data, details of data collection, and structural analysis of these three compounds are prepared as supporting information. For all structures, all non-hydrogen atoms were refined with anisotropic parameters, and all hydrogen atoms included in the structure factor were placed in idealized positions.

Acknowledgment. The authors wish to thank the National Science Council and National Institute of Health, Taiwan, for financial support of this work.

Supporting Information Available: Syntheses and spectral data of compounds of the same family **9**−**11**, **19**, **20**, **25**, **27**, **30**−**35**, **37**, **40**−**42**, **44**−**48**, and **55** in the repetitive operations; variable-temperature ^{1}H NMR spectra of **54**; tables of crystal data, structural parameters, and ORTEP drawings of **14, 50**, and **53** (32 pages). Ordering information is given on any current masthead page.

JA9617808