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Photoactivated Tungsten Hexacarbonyl-Catalyzed Conversion of Alkynols to Glycals

Peter Wipf* and Thomas H. Graham

Department of Chemistry, University of Pittsburgh, Pittsburgh, Pennsylvania 15260

pwipf+@pitt.edu

Received June 11, 2003

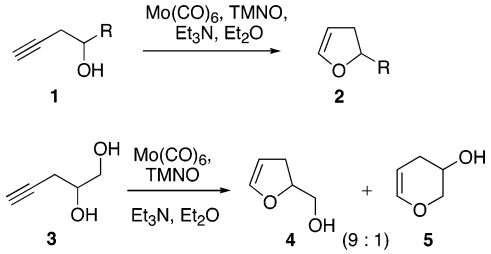
The photoactivated $W(CO)_6$/DABCO/THF system has been used for the formal *endo*-cyclization of alkynes to pyran rings. We found that the regioselectivity of ring closure depends on the relative configuration of the 3,5-dihydroxy-1-alkynes, as well as, more decisively, on the type of *O*-protective group. Oxygen substitution at the propargylic carbon slows the rate of alkyne insertion and allows for dihydrofuran formation through *exo*-cyclization. In contrast, the use of bulky silyl ethers or carbon substituents leads to dihydropyrans through *endo*-cyclization. Substrates bearing leaving groups such as esters, phenols, or thiophenols at the propargylic site eliminate and thus represent a limitation to the cycloisomerization methodology. Propargyl vinyl ethers will rearrange to give dienals instead of glycals. 1,2-Wittig rearrangement products of dihydropyrans are readily prepared and converted to complex bicyclic building blocks for organic synthesis.

Introduction

The use of transition metals to form cyclic oxacarbenes was first demonstrated in 1970 by Chisholm and Clark.[1] Subsequently, many middle to late transition metals have been used to form cyclic carbenes.[2,3] Prior to 1993, the cycloisomerization of alkynols to cyclic enol ethers was accomplished via a two-step procedure: first the oxacarbene was formed, then the metal was removed with a base to give the enol ether.[4] McDonald and co-workers introduced a method for the conversion of alkynols **1** to 2,3-dihydrofurans **2** in one step (Scheme 1).[5] In the same report, alkyne diol **3** was cyclized to a 9:1 mixture of dihydrofuran **4** and dihydropyran **5** in 59% combined yield, suggesting that a one-step synthesis of dihydropyrans would be possible.

In 1996, the McDonald group found tungsten to be superior to molybdenum and chromium for the formation of dihydropyranilidene carbenes.[6] A stoichiometric amount of preformed $W(CO)_5$·THF complex was used to form carbenes at room temperature. Further advances in the tungsten methodology came with the transformation of the dihydropyranilidene carbenes to dihydropyrans with triethylamine.[7] The two-step, one-pot process also used a stoichiometric amount of preformed $W(CO)_5$·THF complex. The resulting mixture was then treated with triethylamine to induce the release of the metal and afford the dihydropyran in modest yield. This process was applied to the iterative synthesis of oligosaccharides.[8] The cycloisomerization methodology was further improved by the discovery that heating the reaction mixture to 50−65 °C while constantly irradiating at 350 nm in the presence of triethylamine and catalytic $W(CO)_6$ (25 mol %) gave glycal **7** in excellent yield (Scheme 2).[9] Control experiments indicated that constant irradiation was indeed required. Irradiation is known to decomplex amines from $W(CO)_5$, thus providing an open coordination site for the alkyne.[10]

SCHEME 1. Single-Step Synthesis of Dihydrofurans and Dihydropyrans from Alkynols



(1) (a) Chisholm, M. H.; Clark, H. C. *J. Chem. Soc., Chem. Commun.* **1970**, 763. (b) Chisholm, M. H.; Clark, H. C. *J. Am. Chem. Soc.* **1972**, *94*, 1532. (c) Chisholm, M. H.; Clark, H. C. *Acc. Chem. Res.* **1973**, *6*, 202.

(2) (a) Clark, H. C.; Manzer, L. E. *J. Organomet. Chem.* **1973**, *47*, C17. (b) Oguro, K.; Wada, M.; Okawara, R. *J. Organomet. Chem.* **1978**, *159*, 417. (c) Bruce, M. I.; Swincer, A. G.; Thomson, B. J.; Wallis, R. C. *Aust. J. Chem.* **1980**, *33*, 2605. (d) Curtis, P. J.; Davies, S. G. *J. Chem. Soc., Chem. Commun.* **1984**, 747. (e) Parlier, A.; Rudler, H. *J. Chem. Soc., Chem. Commun.* **1986**, 514. (f) Dötz, K. H.; Sturm, W.; Alt, H. G. *Organometallics* **1987**, *6*, 1424. (g) Hoover, J. F.; Stryker, J. M. *J. Am. Chem. Soc.* **1990**, *112*, 464. (h) O'Connor, J. M.; Pu, L.; Rheingold, A. L. *J. Am. Chem. Soc.* **1990**, *112*, 6232. (i) Le Bozec, H.; Ouzzine, K.; Dixneuf, P. H. *Organometallics* **1991**, *10*, 2768. (j) Werner, H.; Knaup, W.; Schulz, M. *Chem. Ber.* **1991**, *124*, 1121. (k) Stang, P. J.; Huang, Y. H. *J. Organomet. Chem.* **1992**, *431*, 427.

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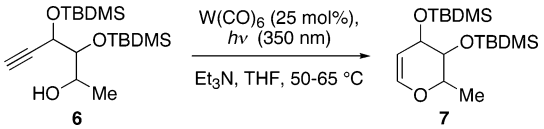
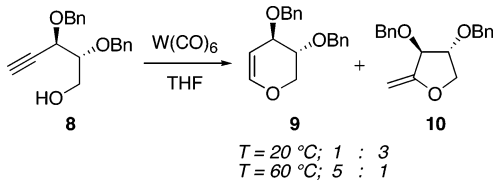
10.1021/jo034813s CCC: $25.00
Published on Web 10/16/2003

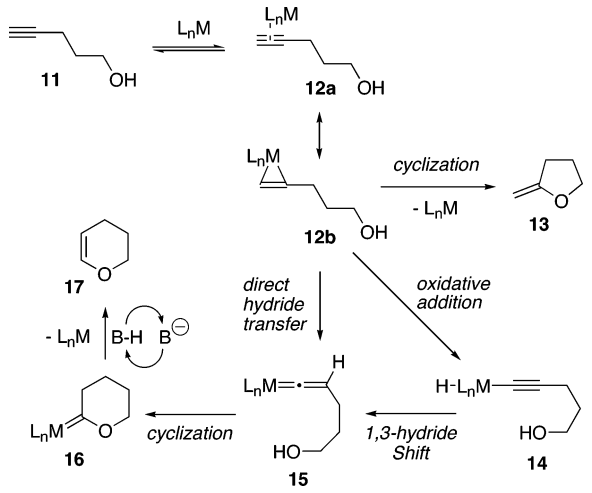
SCHEME 2. Cycloisomerization of Alkynols with Catalytic $W(CO)_6$



SCHEME 3. Temperature Dependence of Regioselectivity



SCHEME 4. A Mechanism for Alkyne Insertion that Explains *endo*- and *exo*-Cyclization Products



Later findings demonstrated that using DABCO as the base gives similar results while allowing the amount of $W(CO)_6$ to be lowered to 10 mol %.[11] Currently, the standard reaction conditions for the cycloisomerization of 4-alkyn-1-ols to 3,4-dihydro-2*H*-pyrans are triethylamine or DABCO in the presence of 5−25 mol % $W(CO)_6$ at 50−65 °C under constant irradiation, using THF as a solvent.[12]

The majority of substrates that have been isomerized to dihydropyrans demonstrate excellent selectivity for a formal *endo*-cyclization pathway. There are indications that the relative configuration of the carbon backbone can have a minor influence on the ratio of *exo*- and *endo*-cyclization products.[9] Experimental data also indicate that an *exo*-cyclization pathway to the 2-methylenefuran competes with the *endo*-cyclization pathway. The benzyl ether **8** was reported to give a temperature-dependent ratio of *endo*- (**9**) and *exo*- (**10**) products (Scheme 3).[13] A yield was not reported. Coincidentally, substrate **8** is

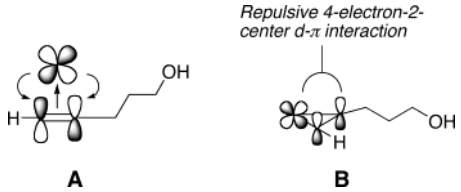


FIGURE 1. (A) Dewar−Chatt−Duncanson model for transition metal−alkyne coordination. (B) Isomerization to the vinylidene is driven by the repulsive interaction between the filled d-orbitals of the metal and the π-orbitals of the alkyne ligand that are orthogonal to the π-orbitals shown in part A.

unique because it possesses a propargylic substituent that is not a silyl ether.

The participation of the *exo*-cyclization pathway can be rationalized by considering the mechanism of vinylidene formation (Scheme 4).[14] Initial complexation of the coordinatively unsaturated metal to alkyne **11** according to the Dewar−Chatt−Duncanson model gives the η^2-complex (**12a**) that can also be depicted as the metallocyclopropene (**12b**) (Figure 1A).[15] Cyclization of **12** could give the *exo*-cyclization product **13**. Alternatively, **12** can form the vinylidene **15** via direct hydride transfer[16] or oxidative addition followed by the equivalent of a 1,3-hydride shift.[17] The alkyne-to-vinylidene rearrangement of **12** to **15** is promoted by an unfavorable four-electron, two-centered interaction between the filled d-orbitals of the metal and the orthogonal π-orbital of the alkyne (Figure 1B).[18] Cyclization of **15** gives the *endo*-cyclization product **17** via the metal-stabilized carbene **16**. Competitive cyclization of the vinylidene and the η^2-alkyne has been demonstrated with Fe(II)[2d] and has been suggested for $W(CO)_5$·THF with carbon nucleophiles.[19]

McDonald and Morokuma recently published a computational study of the cycloisomerization of 4-pentyn-1-ol.[20] The activation barriers for *endo*- and *exo*-cyclization without catalyst were found to be 50−55 kcal/mol. The computational results suggest that the barrier for *exo*-cycloisomerization is not significantly affected by the presence of catalyst and remains at 47 kcal/mol. In the presence of catalyst, the *endo*-cycloisomerization progresses through a rate-determining barrier of 26.4 kcal/mol that involves the migration of the hydride to afford the vinylidene intermediate. The 20.1 kcal/mol difference between *exo*- and *endo*-cycloisomerization pathways suggests the latter will be preferred. The study did not account for the participation of the amine base in the

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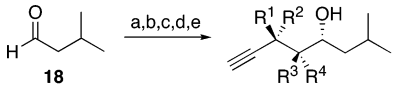
SCHEME 5[a]



19a (R^1 = H; R^2 = OH; R^3,R^4 = H)
19b (R^1 = OH; R^2 = H; R^3,R^4 = H)
19c (R^1 = OH; R^2 = H; R^3= Me, R^4 = H)
19d (R^1 = H; R^2 = OH; R^3 = Me, R^4 = H)
19e (R^1 = OH; R^2 = H; R^3,R^4 = Me)
19f (R^1 = H; R^2 = OH; R^3,R^4 = Me)
19g (R^1 = OH; R^2 = H; R^3= H, R^4 = Me)
19h (R^1 = H; R^2 = OH; R^3= H, R^4 = Me)

[a] Reaction conditions: (1) **19a/19b**: (a) allylMgBr, THF (71%); (b) TBS−Cl, imidazole, DMF (95%) or TES−Cl, imidazole, DMF (98%); (c) O_3, CH_2Cl_2:MeOH (1:1) then DMS (89%); (d) TMS−acetylene, *n*-BuLi, THF (92%); (e) TBAF, THF (92%). (2) **19c/19d**: (a) crotyl bromide, $CrCl_2$, THF (70%); (b) TBS−Cl, imidazole, DMF (95%); (c) O_3, CH_2Cl_2:MeOH (1:1) then DMS (58%); (d) TMS−acetylene, *n*-BuLi, THF (90%); (e) TBAF, THF (63%). (3) **19e/19f**: (a) prenyl bromide, In, DMF (95%); (b) TBS−OTf, 2,6-lutidine, CH_2Cl_2; (c) O_3, CH_2Cl_2:MeOH (1:1) then DMS (71%, 2 steps); (d) TMS−acetylene, *n*-BuLi, THF; (e) TBAF, THF (92%, 2 steps). (4) **19g/19h**: (a) (4*S*)-4-benzyl-3-propionyl-2-oxazolidinone, *n*-Bu_2B−OTf, Et_3N, CH_2Cl_2 (82%); (b) Me(MeO)NH_2Cl, Me_3Al, CH_2Cl_2; (c) TBS−OTf, 2,6-lutidine, CH_2Cl_2 (89%, 2 steps); (d) DiBAL−H, THF (75%); (e) (i) TMS−acetylene, *n*-BuLi, THF (88%), (ii) TBAF, THF (99%).

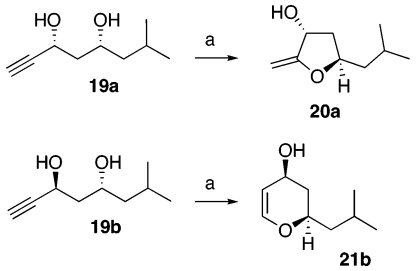
transition states. The results from our studies (vide infra) suggest that the regioselectivity of the cyclization is substrate dependent.

Results and Discussion

As part of our synthetic approaches toward the polyether marine natural products bistramide A and leucascandrolide A,[21,22] we considered the tungsten-catalyzed cycloisomerization of alkynols as a potential methodology for installing the pyran segments in these target molecules. Attractive features of the photoactivated $W(CO)_6$/DABCO/THF system are the relatively mild conditions and the reportedly high selectivity for the formal *endo*-cyclization product. During the course of our studies, we discovered that the regioselectivity of ring closure depends on the relative configuration of the 3,5-dihydroxy-1-alkynes. In addition, we were able to extend the cyclization methodology by incorporating groups that allow further derivatization of the dihydropyran system. Our studies also revealed some limitations of the methodology.

Synthesis of our first model system began with the treatment of isovaleraldehyde with allylmagnesium bromide in THF to afford the homoallylic alcohol in 71% yield (Scheme 5). Protection of the alcohol as the TBS- or TES-ether proceeded in excellent yield. Ozonolysis of the terminal olefin under buffered conditions and treatment of the resulting aldehyde with lithium trimethylsilyl acetylide afforded the corresponding propargylic alcohol in good yields. The diastereomers were separated prior to silyl deprotection to give the alkynols **19a** and **19b**.[23]

SCHEME 6[a]



[a] Reaction conditions: (a) $W(CO)_6$, *hν*, DABCO, THF, 14 h, 56 °C.

When **19a** was subjected to the photoactivated $W(CO)_6$/DABCO/THF conditions, NMR analysis (^{1}H/^{13}C/DEPT 135) of the crude reaction indicated that **20a** was formed exclusively. The 3,5-*anti* diol **19b** resulted in the exclusive formation of the *endo*-cyclic product **21b** in 50% yield after chromatography on silica gel (Scheme 6).[24]

To exclude the possibility that the observed selectivity arose from unforeseen variations in the experimental conditions, a 1:1 mixture of alkyne-diols **19a** and **19b**, $W(CO)_6$, and DABCO in THF was irradiated for 14 h at 56 °C. The ^{1}H NMR spectrum of the crude reaction mixture indicated the presence of furan **20a** and dihydropyran **21b** in a ratio of 1.3:1.0. ^{13}C NMR analysis indicated only 18 signals in addition to DABCO and tungsten ligand signals.[25] Purification by silica gel chromatography confirmed the presence of compounds **20a** and **21b**.

In general, cyclization substrates containing propargylic silyl ethers are considerably more frequently used than substrates containing propargylic hydroxyl groups. McDonald and co-workers demonstrated that a related system with a propargylic benzyl ether gave varying amounts of *exo*- and *endo*-cyclization products (Scheme 3).[13] The latter was slightly favored at elevated temperatures. The McDonald group also observed that the relative configuration of substituents on the carbon backbone can affect the rate and regioselectivity of the cyclization process.[9] To test the dependence of the regioselectivity on the nature of the propargylic oxygen functional group and the relative configuration of the carbon backbone, model compounds **19c**−**h** were synthesized (Scheme 5). Regioselective derivatization of the less sterically hindered hydroxyl group of the 3,5-diols or derivatization of the 1-trimethylsilyl, 5-*O*-trialkylsilyl ether intermediate was accomplished by using standard synthetic strategies.[26] The results of the cyclization

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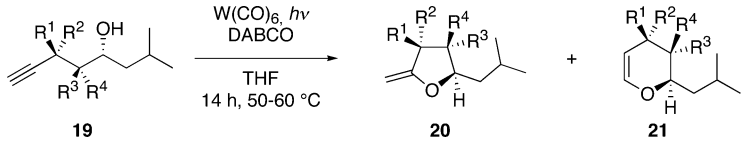
(23) Relative configurations for all diols were assigned by using ^{13}C NMR analysis of the acetonides (2,2-dimethyl-1,3-dioxanes): (a) Rychnovsky, S. D.; Skalitzky, D. J. *Tetrahedron Lett.* **1990**, *31*, 945. (b) Evans, D. A.; Rieger, D. L.; Gage, J. R. *Tetrahedron Lett.* **1990**, *31*, 7099.

(24) Using a stoichiometric amount of $W(CO)_6$ afforded **21b** in lower yield. Specifically, irradiating a mixture of **19b** (50.0 mg, 0.320 mmol, 1.0 equiv), $W(CO)_6$ (112 mg, 0.318 mmol, 1.0 equiv), and DABCO (72.0 mg, 0.638 mmol, 2.0 equiv) in THF (3.0 mL) for 14 h at 55 °C afforded **21b** in 40% yield. Irradiating a mixture of **21b** (25.0 mg, 0.160 mmol, 1.0 equiv), $W(CO)_6$ (14.0 mg, 0.040 mmol, 0.3 equiv), and DABCO (9.0 mg, 0.080 mmol, 0.5 equiv) in THF (1.6 mL) for 14 h at 55 °C led to the re-isolation of **21b** in 83% yield.

(25) The additional tungsten ligand and DABCO signals in the crude spectra: ^{13}C ($CDCl_3$, 75 MHz) δ 202.1(C), 199.4 (C), 57.0 (CH_2), 48.0 (CH_2), 47.2 (CH_2).

(26) See the Supporting Information.

TABLE 1. *endo/exo*-Selectivity in Cyclizations of Alkynols



19 **20** **21**

entry	substrate	R^1 =	R^2 =	R^3 =	R^4 =	**20**:**21**	yield [%][a]
1	**19c**	OH	H	Me	H	1:1	49
2	**19d**	H	OH	Me	H	1:0	49
3	**19e**	OH	H	Me	Me	2:1	50
4	**19f**	H	OH	Me	Me	1:0	44
5	**19g**	OH	H	H	Me	1:2	39
6	**19h**	H	OH	H	Me	1:0	46
7	**19i**	H	OTBDPS	H	H	1:30	15
8	**19j**	H	O*t*-Bu	H	H	1:4	b
9	**19k**	H	OBn	H	H	6:1	54
10	**19l**	OBn	H	H	H	0:1	67
11	**19m**	H	OMe	H	H	8:1	*b*
12	**19n**	$OCH_2CCTIPS$	H	H	H	0:1	14−46
13	**19o**	H	$OCH_2CCTIPS$	H	H	8:1	25
14	**19p**	H	OTBDPS	Me	H	0:1	25
15	**19q**	H	OTIPS	Me	Me	1:4	49 + (43)[c]
16	**19r**	$OCH_2CCTIPS$	H	Me	Me		(53)[c]
17	**19s**	H	$OCH_2CCTIPS$	Me	Me	1:0	32
18	**19t**	OBn	H	Me	Me		(31)[c]
19	**19u**	H	OBn	Me	Me	1:0	61

[a] Combined yield after purification on SiO_2. [b] Decomposed when purification on SiO_2 was attempted. [c] Starting material (%) was recovered.

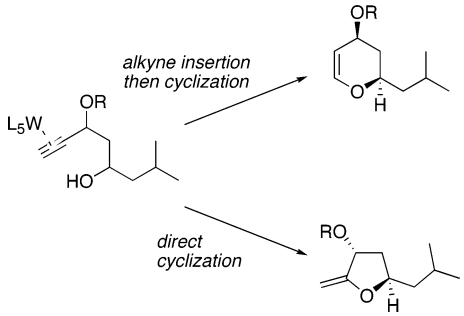


FIGURE 2. The rate of competing pathways may account for the regioselectivity of the cyclization process.

reactions are summarized in Table 1. Ratios were derived from integration of the vinyl proton signals in the ^1H NMR spectra of the crude reaction mixtures after a rapid filtration through a short plug of silica gel.

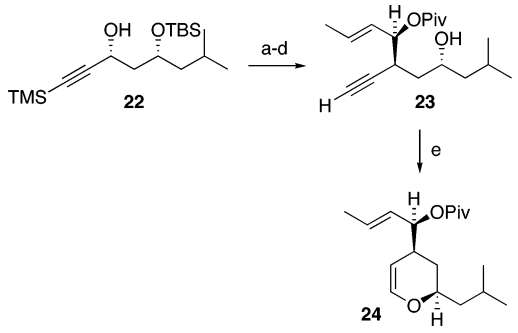
These results suggest a strong correlation between the substituent on the propargylic oxygen atom and the regioselectivity of the cyclization. Cyclization of the initially formed π-complex to the furan may compete with alkyne insertion (Figure 2). Cyclization of the π-complex is known to compete with alkyne insertion in other metal-based systems,[3] but has not, to our knowledge, been clearly demonstrated in the photoactivated $W(CO)_6$/DABCO/THF systems with oxygen nucleophiles.[19] Computational results for the cyclization of 4-pentyn-1-ol suggest that the *endo*-cyclization is energetically preferred.[20] Our experimental results suggest that the regioselectivity of the cyclization is substrate dependent. More specifically, oxygen substitution at the propargylic carbon may allow for chelation between the metal and the propargylic oxygen, slowing the rate of alkyne insertion and allowing for *exo*-cyclization (Table 1, entries 9 and 11 vs 7 and 8).[27] Alternatively, steric compression could destabilize the π-complex relative to the vinylidene complex, thus increasing the rate of alkyne insertion (Table 1, entry 2 vs 14). The regioselectivity could also be a result of the carbon chain conformation. Methyl substitution at the C_4-position of the carbon backbone (Table 1, entries 1 and 3 vs **19b**) leads to a loss in *endo*-selectivity. If cyclization requires a less populated conformation, then degradative pathways can compete and in some cases, starting material is recovered in low yield (Table 1, entries 16 and 18).

To test our hypothesis that oxygen substitution at the propargylic carbon allows for chelation with the metal complex, slowing the rate of alkyne insertion and allowing for *exo*-cyclization, we turned to the chemistry developed by Marshall and co-workers that allows for easy modifications at the propargylic position via mesylate displacement.[28] The propargylic alcohol **22** was first converted to the mesylate, which was subjected to InI, $Pd(OAc)_2$, PPh_3, and crotonaldehyde in THF and HMPA for conversion to the allylic−homopropargylic alcohol (Scheme 7). Acylation with pivaloyl chloride and desilylation with TBAF gave the desired substrate **23** in 47% yield over 4 steps. The relative configuration of **23** was assigned based on the precedent established by Marshall and co-workers. Tungsten-mediated cyclization of this

(27) An internal alkyne did not give any products of cyclization. Irradiating a mixture of (6*S**,4*R**)-2-methylundec-7-yne-4,6-diol (42.7 mg, 0.215 mmol, 1.0 equiv), $W(CO)_6$ (38.0 mg, 0.108 mmol, 0.5 equiv), and DABCO (24.0 mg, 0.213 mmol, 1.0 equiv) in distilled and degassed THF (2.1 mL) for 16 h at 55 °C resulted in the recovery of the starting material (96%). Irradiating a mixture of (6*R**,4*R**)-2-methylundec-7-yne-4,6-diol (58.3 mg, 0.294 mmol, 1.0 equiv), $W(CO)_6$ (52.0 mg, 0.148 mmol, 0.5 equiv), and DABCO (33.0 mg, 0.293 mmol, 1.0 equiv) in distilled and degassed THF (2.1 mL) for 16 h at 55 °C resulted in the recovery of the starting material (87%). No cyclization product was evident in the crude ^1H NMR spectra for either trial.

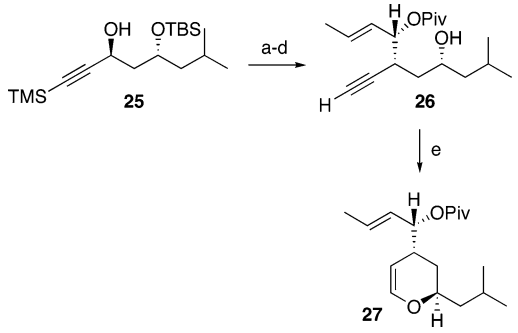
(28) (a) Marshall, J. A.; Grant, C. M. *J. Org. Chem.* **1999**, *64*, 8214. (b) Marshall, J. A.; Chobanian, H. R. *J. Org. Chem.* **2000**, *65*, 8357. (c) Marshall, J. A. *Chem. Rev.* **2000**, *100*, 3163. (d) Marshall, J. A.; Chobanian, H. R.; Yanik, M. M. *Org. Lett.* **2001**, *3*, 3369.

SCHEME 7[a]



[a] Reaction conditions: (a) MsCl, Et_3N, CH_2Cl_2 (95%); (b) crotonaldehyde, InI, $Pd(OAc)_2$, PPh_3, THF, HMPA; (c) Piv-Cl, DMAP, Et_3N; (d) TBAF, THF (49%, 3 steps); (e) $W(CO)_6$, *hν*, DABCO, THF (81%).

SCHEME 8[a]

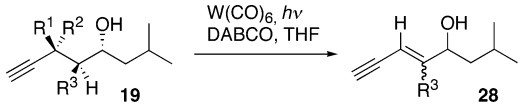


[a] Reaction conditions: (a) MsCl, DIEA, CH_2Cl_2 (95%); (b) crotonaldehyde, InI, $Pd(OAc)_2$, PPh_3, THF, HMPA; (c) Piv-Cl, DMAP, Et_3N; (d) HF·pyridine, pyridine, THF, then TBAF, THF (36%, 3 steps); (e) $W(CO)_6$, *hν*, DABCO, THF (70%).

compound provided dihydropyran **24** in 81% yield. Analogous conditions were used to convert the *anti*-diol derivative **25** into dihydropyran **27** (Scheme 8). After 14 h at 40 °C, dihydropyran **27** was formed in 40% yield and alkynol **26** was recovered in 55% yield. Even when substrate **26** was subjected to cyclization conditions for 23 h at 40 °C, TLC analysis indicated starting alkynol remained. Irradiation for an additional 12-h period at 60 °C finally consumed the starting alkynol and gave dihydropyran **27** in a slightly lower yield (70%) than diastereomer **24**. The products for the competing *exo*-cyclization pathway were not detected in the crude ^1H NMR in any of these trials, confirming that propargylic oxygen substituents display a remarkably different reactivity than carbon-substituted analogues. In addition to chelation effects, inherent conformational differences between the different substrates may also be contributing to determining the dominant reaction pathways.

Our model studies also revealed some limitations of the cycloisomerization methodology. The photoactivated $W(CO)_6$/DABCO/THF system proved to be incompatible with substrates that possess a leaving group at the propargylic carbon.[29] Esters at this site gave the volatile

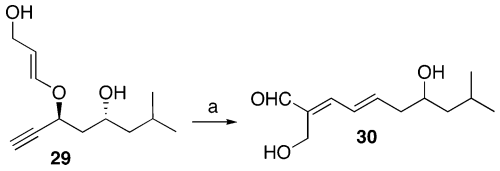
TABLE 2. Elimination as a Side Reaction in Cycloisomerization Reactions



entry	substrate	R^1 =	R^2 =	R^3 =	product	yield [%]
1	**19v**	OAc	H	Me	28	11
2	**19w**	H	OAc	Me	28	13
3	**19x**	$O_2CCH_2COCH_3$	H	H	28	25
4	**19y**	H	PhS	H		*a*
5	**19z**	*p*-$OC_6H_4CH_2OH$	H	H		*b*

[a] Starting material decomposed. [b] Starting material decomposed; ^1H NMR analysis of the crude reaction mixture showed 4-hydroxymethylphenol.

SCHEME 9[a]



[a] Reaction conditions: (a) $W(CO)_6$, *hν*, DABCO, THF, 4 h, 60 °C (65%).

enyne **28** in low yield as the only isolated product (Table 2, entries 1−3). Phenol and thiophenol substitution led to decomposition and recovery of the phenol (Table 2, entries 4 and 5). The low yields and decomposition noted for substrates **19v**−**z** represent a limitation of the photoactivated $W(CO)_6$/DABCO/THF system and may explain some of the lower yields in Table 1.[30] Propargylic alcohol derivatives have been used for the preparation of α,*β*-unsaturated Fischer carbenes, through a *β*-elimination of the intermediate Fischer carbene.[31] Interestingly, when vinyl ether **29** was subjected to the reaction conditions, dienal (2*E*,4*E*)-**30** was formed as the major isomer in 65% yield (Scheme 9).[32] Control experiments[33] indicated that photoactivated tungsten hexacarbonyl and DABCO are required for the rearrangement, suggesting a vinylidene intermediate.[34] The abbreviated reaction time also indicates that the rearrangement is preferred over cyclization, thus representing a mild entry into functionalized dienal systems.

We also briefly studied the further functionalization of the dihydropyran framework **21** through 1,2-Wittig rearrangements.[35] After cycloisomerization of diol **19b**,

(29) (a) For applications of propargylic leaving groups in the synthesis of furan systems using molybdenum hexacarbonyl, see: McDonald, F. E.; Gleason, M. M. *J. Am. Chem. Soc.* **1996**, *118*, 6648. (b) For similar results involving propargylic leaving groups in ruthenium-catalyzed isomerizations see: Trost, B. M.; Rhee, Y. H. *J. Am. Chem. Soc.* **2002**, *124*, 2528.

(30) Cutchins and McDonald recently reported low yields (30%) for a substrate bearing a *p*-methoxyphenylamine at the propargylic position. See ref 12b.

(31) (a) Dötz, K. H.; Paetsch, D.; Le Bozec, H. *J. Organomet. Chem.* **1999**, *589*, 11.

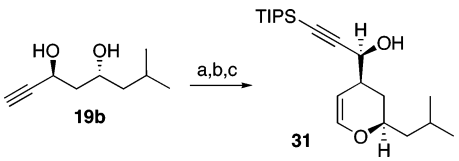
(32) (a) The yield includes approximately 6% of the (2*Z*,4*E*)-**30** isomer. (b) For $W(CO)_5$·THF-catalyzed cyclization of aromatic ene−yne systems see: Maeyama, K.; Iwasawa, N. *J. Org. Chem.* **1999**, *64*, 1344.

(33) Irradiating a solution of the propargyl vinyl ether in THF with $W(CO)_6$ does not give the product. Subsequent addition of DABCO to this photoactivated reaction mixture at room temperature leads to a rapid (1 h) formation of the unsaturated aldehyde. DABCO alone or irradiation with DABCO does not promote the rearrangement.

(34) A chromium(0) pentacarbonyl vinylidene intermediate has been proposed for the [3.3]-sigmatropic rearrangement of 1-acyloxy-α,*β*-unsaturated Fischer carbenes to 3-acyloxy-1-alkynes. Söderberg, B. C.; O'Neil, S. N.; Chisnell, A. C.; Liu, J. *Tetrahedron* **2000**, *56*, 5037.

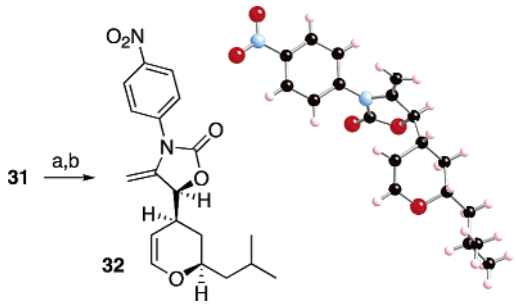
(35) Tomooka, K.; Yamamoto, H.; Nakai, T. *Liebigs Ann. Chem.* **1997**, 1275.

SCHEME 10[a]



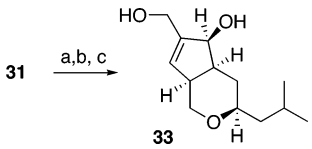
[a] Reaction conditions: (a) $W(CO)_6$, *hν*, DABCO, THF, 56 °C (53%); (b) 3-bromo-1-triisopropylsilanylprop-1-yne, *n*-Bu_4NHSO_4, 50% NaOH, toluene (94%); (c) *n*-BuLi, TMEDA, THF, (78%).

SCHEME 11[a]



[a] Reaction conditions: (a) 4-nitrophenylisocyanate, DBU, CH_2Cl_2, rt (88%); (b) TBAF, THF (47%).

SCHEME 12[a]



[a] Reaction conditions: (a) TBAF, THF (70%); (b) bromomethyldimethylchlorosilane, imidazole, DMF (49%); (c) Bu_3SnH, AIBN, PhH then KF, $KHCO_3$, H_2O_2, MeOH/THF (1:1) (20%).

alkylation[36] of the dihydropyran intermediate **21b** with 3-bromo-1-triisopropylsilanylprop-1-yne[37] and deprotonation with *n*-BuLi and TMEDA in THF gave **31,** the product of a stereoselective 1,2-Wittig rearrangement, in 78% yield (Scheme 10). For an unambiguous assignment of the relative configuration of this compound, **31** was exposed to 4-nitrophenylisocyanate in CH_2Cl_2 and catalytic DBU[38] to afford the corresponding 4-nitrophenylisocyanate in 88% yield (Scheme 11). Deprotection with TBAF in THF gave the oxazolidinone **32** in 47% yield.[39] Crystallization from pentane/CH_2Cl_2 provided crystals that were suitable for assigning the structure of the 1,2-Wittig product **31**.

During our investigations into the stereochemical assignment of the product from the 1,2-Wittig rearrangement, a radical cascade reaction afforded the interesting bicyclic structure **33** (Scheme 12). Deprotection of **31** with TBAF in THF gave the terminal acetylene in 70% yield. The propargylic alcohol was then derivatized with bromomethyldimethylchlorosilane in the presence of imidazole in 49% yield. Radical cyclization of the resulting bromodimethylsilane[40] followed by Tamao oxidation[41] provided compound **33** in 20% yield.[42] The formation of products **31**, **32**, and **33** demonstrates the ready access to complex carbo- and heterobicyclic scaffolds from alkynols **19** through use of the tungsten cycloisomerization methodology.

Conclusions

Our experimental results suggest that in the tungsten-catalyzed cyloisomerization reaction of alkynols, the ratio of *endo*- to *exo*-products for substrates substituted at the propargylic position is strongly substituent dependent. Most likely as a consequence of chelation to the metal complex, oxygen substitution at the propargylic carbon slows the rate of alkyne insertion and allows for dihydrofuran formation through *exo*-cyclization. In contrast, the use of bulky silyl ethers or carbon substituents leads to dihydropyrans through *endo*-cyclization. Substrates bearing leaving groups such as esters, phenols, or thiophenols at the propargylic site represent a limitation to the cycloisomerization methodology. Such substrates are not compatible with the experimental conditions, providing elimination rather than cyclization products. In addition, we have found that propargyl vinyl ethers will rearrange to give dienals instead of cyclizing to the corresponding glycals. While dihydrofurans **20** are difficult to functionalize further due to their chemical lability, 1,2-Wittig rearrangement products of dihydropyrans **21** are readily obtained and converted to interesting bicyclic building blocks for organic synthesis.

Experimental Section

General Details. All moisture-sensitive reactions were performed using syringe−septum techniques under an N_2 atmosphere and all glassware was dried in an oven at 140 °C for more than 4 h prior to use. THF and ethyl ether were distilled from sodium/benzophenone ketyl. Methylene choride and toluene were filtered through activated alumina prior to use. $W(CO)_6$ was purchased from Acros or Strem. DABCO was sublimed under vacuum.

General Procedure for the Tungsten-Catalyzed Cycloisomerization of Alkynols. Substrate **19c** (59.0 mg, 0.350 mmol, 1.0 equiv) was transferred as a solution in freshly distilled THF (2.5 mL + 2.5 mL wash) into a flame-dried reaction flask. The sample was concentrated on the rotary-evaporator and dried under high vacuum (<1.0 mmHg) for more than 1 h. Freshly distilled and degassed THF (5.0 mL, liquid nitrogen freeze−pump−thaw, 3 cycles) was added via cannula. After the addition of $W(CO)_6$ (61.0 mg, 0.170 mmol, 0.5 equiv) and sublimed DABCO (83.0 mg, 0.740 mmol, 2.1 equiv) under a positive stream of nitrogen, the mixture were irradiated under nitrogen by a medium-pressure mercury lamp with a Pyrex filter for 14 h at an oil bath temperature of 56 °C to give a yellow solution. After 14 h, TLC analysis indicated

(36) (a) Liang, J.; Hoard, D. W.; Van Khau, V.; Martinelli, M. J.; Moher, E. D.; Moore, R. E.; Tius, M. A. *J. Org. Chem.* **1999**, *64*, 1459. (b) Freedman, H. H.; Dubois, R. A. *Tetrahedron Lett.* **1975**, *16*, 3251.

(37) Jones, G. B.; Wright, J. M.; Plourde, G. W., II; Hynd, G.; Huber, R. S.; Mathews, J. E. *J. Am. Chem. Soc.* **2000**, *122*, 1937.

(38) Nicolaou, K. C.; Baran, P. S.; Zhong, Y.-L.; Barluenga, S.; Hunt, K. W.; Kranich, R.; Vega, J. A. *J. Am. Chem. Soc.* **2002**, *124*, 2233.

(39) For a similar transformation that afforded a 4-methylenetetrahydro-1,3-oxazine-2-one, see: Tamaru, Y.; Kimura, M.; Tanaka, S.; Kure, S.; Yoshida, Z. *Bull. Chem. Soc. Jpn.* **1994**, *67*, 2838.

(40) (a) Bogen, S.; Gulea, M.; Fensterbank, L.; Malacria, M. *J. Org. Chem.* **1999**, *64*, 4920. (b) Journet, M.; Malacria, M. *J. Org. Chem.* **1992**, *57*, 3085. (c) Gómez, A. M.; López, J. C.; Fraser-Reid, B. *J. Org. Chem.* **1995**, *60*, 3859. (d) Crimmins, M. T.; O'Mahony, R. *J. Org. Chem.* **1989**, *54*, 1157.

(41) (a) Tamao, K.; Ishida, N.; Tanaka, T.; Kumada, M. *Organometallics* **1983**, *2*, 1694. (b) Tamao, K.; Ishida, N.; Kumada, M. *J. Org. Chem.* **1983**, *48*, 2120.

(42) The assignment of the relative configuration of this compound is based on the COSY/NOESY ^1H NMR analysis of the bis(3,5-dinitrobenzoyl) derivative. See the Supporting Information.

that the starting material had been consumed and the sample was concentrated. The resulting residue was diluted with ethyl ether and filtered through a plug of SiO_2 (2 cm in a pasteur pipet, ethyl ether wash). The combined filtrate was concentrated and analyzed by ^1H and ^{13}C. The product ratios were determined by integration of the vinyl proton signals in the ^1H NMR spectra of the crude reaction mixture and indicated a product ratio of **20c**:**21c** of 1:1. Purification by chromatography on SiO_2 (100:1 to 95:5, hexanes/Et_3N) gave an inseparable mixture of the title compounds (29.0 mg, 49%) as a colorless, unstable solid.[43] **20c**: ^1H NMR (CD_2Cl_2) δ 4.17 (s, 1H), 3.96 (t, 1H, J = 1.6 Hz); ^{13}C NMR (CD_2Cl_2) δ 83.1, 79.0, 47.7, 43.6, 25.6, 23.9, 22.1, 14.1. **21c**: ^1H NMR (CD_2Cl_2) δ 6.36 (d, 1 H, J = 6.1 Hz), 4.71 (dd, 1H, J = 6.1, 2.2 Hz); ^{13}C NMR (CD_2Cl_2) δ 145.2, 105.7, 78.1, 69.5, 41.8, 41.7, 24.5, 21.6, 24.4, 14.8.

(3*R,5*R**)-5-Isobutyl-2-methylenetetrahydrofuran-3-ol (20a).** According to the general procedure, **19a** (49.0 mg, 0.310 mmol, 1.0 equiv), tungsten hexacarbonyl (56.0 mg, 0.160 mmol, 0.5 equiv), and DABCO (70.0 mg, 0.630 mmol, 2.0 equiv) in freshly distilled and degassed THF (5.0 mL) were irradiated for 14 h at 56 °C to give a yellow solution that was filtered through a plug of SiO_2 (ethyl ether wash) and the filtrate was concentrated. Due to the instability of **20a**, the crude reaction mixture was used to acquire spectral data:[43] ^1H NMR δ 4.53−4.47 (m, 2 H), 4.23 (s, 1 H), 3.99 (s, 1 H), 2.03 (ddd, 1 H, J = 12.9, 5.1, 2.0 Hz), 1.80−1.52 (m, 3 H), 1.31 (ddd, 1 H, J = 13.4, 7.7, 5.4 Hz), 0.92 (d, 3 H, J = 6.6 Hz), 0.91 (d, 3 H, J = 6.7 Hz); ^{13}C NMR δ 166.0, 81.3, 79.6, 71.7, 44.6, 40.9, 25.4, 23.2, 22.6.

(2*R,4*S**)-2-Isobutyl-3,4-dihydro-2*H*-pyran-4-ol (21b).** According to the general procedure, **19b** (198.8 mg, 1.272 mmol, 1.0 equiv), tungsten hexacarbonyl (112 mg, 0.318 mmol, 0.25 equiv), and DABCO (143.0 mg, 1.268 mmol, 1.0 equiv) in freshly distilled and degassed THF (12.0 mL) were irradiated for 24 h at 50 °C to give a yellow solution. Purification by chromatography on SiO_2 (95:5:1 to 80:20:1, hexanes/ethyl ether/Et_3N) gave **21b** (102.2 mg, 51%) as a colorless oil: ^1H NMR δ 6.35 (d, 1 H, J = 6.0 Hz), 4.72 (dt, 1 H, J = 6.2, 1.9 Hz), 4.44 (br s, 1 H), 4.03−3.93 (m, 1 H), 2.13 (qt, 1 H, J = 6.7, 1.8 Hz), 1.87−1.72 (m, 1 H), 1.66−1.51 (m, 2 H), 1.27 (ddd, 1 H, J = 13.3, 8.4, 4.6 Hz), 0.91 (app d, 6 H, J = 6.6 Hz); ^{13}C NMR δ 145.5, 105.5, 73.4, 63.4, 44.4, 38.9, 24.4, 23.4, 22.3; IR (neat) 3346, 3062, 2956, 2923, 2871, 2871, 1643, 1468, 1382, 1369, 1230, 1107, 1037 cm^{-1}; MS (EI) *m*/*z* (rel intensity) 156 (M^+, 13), 141 ([M − CH_3]$^+$, 3), 138 ([M − H_2O]$^+$, 3), 123 ([M − CH_3 − H_2O]$^+$, 3), 99 (26), 95 (15), 81 (25), 73 (100), 71 (39), 70 (38), 69 (38), 56 (42); HRMS (EI) *m*/*z* calcd for $C_9H_{16}O_2$ 156.1150, found 156.1151.

(3*R,4*R**,5*R**)-5-Isobutyl-4-methyl-2-methylenetetrahydrofuran-3-ol (20d).** According to the general procedure, **19d** (41.0 mg, 0.240 mmol, 1.0 equiv), $W(CO)_6$ (42.0 mg, 0.120 mmol, 0.5 equiv), and DABCO (56.0 mg, 0.500 mmol, 2.0 equiv) in freshly distilled and degassed THF (5.0 mL) were irradiated for 14 h at 56 °C. Purification by chromatography on SiO_2 (80:20:1, hexanes/ethyl ether/Et_3N) gave **20d** (20.0 mg, 49%) as a colorless, unstable solid. Due to the instability of **20d**, the crude reaction mixture was used to acquire spectral data: ^1H NMR δ 4.28 (d, 1 H, J = 5.2 Hz), 4.20 (s, 1 H), 3.98 (s, 1 H), 4.01−3.94 (m, 1 H), 1.88−1.68 (m, 2 H), 1.45−1.25 (m, 2 H), 0.98 (d, 3 H, J = 6.8 Hz), 0.90 (d, 3 H, J = 6.6 Hz), 0.88 (d, 3 H, J = 6.4 Hz); ^{13}C NMR δ 165.8, 84.3, 81.5, 73.5, 44.0, 43.2, 25.4, 23.7, 22.0, 9.9.

(3*S,5*R**)-5-Isobutyl-4,4-dimethyl-2-methylene-tetrahydro-furan-3-ol (20e) and (2*R**,4*R**)-2-Isobutyl-3,3-dimethyl-3,4-dihydro-2*H*-pyran-4-ol (21e).** According to the general procedure, **19e** (27.5 mg, 0.149 mmol, 1.0 equiv), tungsten hexacarbonyl (26.0 mg, 0.074 mmol, 0.5 equiv), and DABCO (34.0 mg, 0.301 mmol, 2.0 equiv) in freshly distilled and degassed THF (1.5 mL) were irradiated for 14 h at 55 °C to give a dark red solution. ^1H NMR analysis of the crude reaction mixture indicated a ratio of **20e**:**21e** of 2:1. Purification by chromatography on SiO_2 (80:20:1, hexanes/ethyl ether/Et_3N) gave a mixture of **20e** and **21e** (13.6 mg, 50%) as a colorless oil.[43] **20e**: ^1H NMR δ 4.25 (t, 1 H, J = 2.0 Hz), 4.21 (dt, 1 H, J = 9.5, 2.0 Hz), 4.01 (t, 1 H, J = 2.0 Hz), 3.79 (dd, 1 H, J = 10.2, 2.2 Hz); ^{13}C NMR δ 164.1, 84.2, 79.9, 79.3, 43.3, 38.2, 13.5. **21e**: ^1H NMR δ 6.32 (dd, 1 H, J = 6.0, 1.6 Hz), 4.62 (dd, 1 H, J = 6.0, 2.0 Hz), 3.97 (dt, 1 H, J = 8.5, 1.8 Hz), 3.62 (dd, 1 H, J = 10.8, 2.0 Hz); ^{13}C NMR δ 145.0, 104.3, 80.9, 72.3, 37.3, 35.7, 13.0.

(3*R,5*R**)-5-Isobutyl-4,4-dimethyl-2-methylenetetrahydrofuran-3-ol (20f).** According to the general procedure, **19f** (21.2 mg, 0.115 mmol, 1.0 equiv), tungsten hexacarbonyl (20.2 mg, 0.057 mmol, 0.5 equiv), and DABCO (26.0 mg, 0.230 mmol, 2.0 equiv) in freshly distilled and degassed THF (1.5 mL) were irradiated for 14 h at 55 °C to give a dark red solution. Purification by chromatography on SiO_2 (90:10:1, hexanes/ethyl ether/Et_3N) gave **20f** (9.4 mg, 44%) as a colorless oil: ^1H NMR δ 4.30 (d, 1 H, J = 1.5 Hz), 4.12 (d, 1 H, J = 2.1 Hz), 4.08 (d, 1 H, J = 1.3 Hz), 3.98 (d, 1 H, J = 3.7 Hz), 1.89−1.75 (m, 1 H), 1.53 (d, 1 H, J = 3.8 Hz), 1.44 (ddd, 1 H, J = 14.1, 10.6, 4.7 Hz), 1.13 (ddd, 1 H, J = 14.1, 9.2, 2.2 Hz), 1.02 (s, 3 H), 0.96 (d, 3 H, J = 6.7 Hz), 0.93 (d, 3 H, J = 6.6 Hz), 0.84 (s, 3 H); ^{13}C NMR δ 165.0, 85.6, 82.7, 80.1, 43.8, 38.2, 25.7, 24.0, 21.9, 19.9, 18.3; IR (neat) 3418, 2957, 2934, 2872, 1939, 1717, 1677, 1468, 1384, 1369, 1082 cm^{-1}; MS (EI) *m*/*z* (rel intensity) 184 (M^+, 12), 153 ([M − CH_3O]$^+$, 7), 125 (5), 121 (10), 111 (30), 98 (16), 85 (30), 69 (100), 57 (42); HRMS (EI) *m*/*z* calcd for $C_{11}H_{20}O_2$ 184.1463, found 184.1465.

(3*S,4*S**,5*R**)-5-isobutyl-4-methyl-2-methylenetetrahydrofuran-3-ol (20g) and (2*R**,3*S**,4*R**)-2-Isobutyl-3-methyl-3,4-dihydro-2*H*-pyran-4-ol (21g).** According to the general procedure, **19g** (36.3 mg, 0.213 mmol, 1.0 equiv), $W(CO)_6$ (37.5 mg, 0.107 mmol, 0.5 equiv), and DABCO (48.0 mg, 0.425 mmol, 2.0 equiv) in freshly distilled and degassed THF (2.0 mL) were irradiated for 12 h at 60 °C. ^1H NMR analysis of the crude reaction mixture indicated a ratio of **20g**:**21g** of 1:2. Purification by chromatography on SiO_2 (85:15:1, hexanes/ethyl ether/Et_3N) gave a mixture of **20g** and **21g** (14.1 mg, 39%) as a colorless, crystalline solid that decomposed upon standing. The crude reaction mixture was used to acquire spectral data.[43] **20g**: ^1H NMR δ 4.69 (d, 1 H, J = 6.45 Hz), 4.26 (s, 1 H); ^{13}C NMR δ 164.3, 79.7, 79.6, 74.1, 39.8, 39.5, 25.1, 23.5, 22.4, 6.5. **21g**: ^1H NMR δ 6.30 (dd, 1 H, J = 6.1, 1.3 Hz), 4.63−4.47 (m, 2 H), 4.01−3.94 (m, 1H); ^{13}C NMR δ 145.0, 103.6, 76.5, 66.6, 40.7, 35.9, 24.7, 23.3, 22.4, 5.7.

(3*R*,4*S*,5*R*)-5-Isobutyl-4-methyl-2-methylenetetrahydrofuran-3-ol (20h). According to the general procedure, **19h** (33.0 mg, 0.194 mmol, 1.0 equiv), tungsten hexacarbonyl (34.1 mg, 0.097 mmol, 0.5 equiv), and DABCO (43.8 mg, 0.388 mmol, 2.0 equiv) in freshly distilled and degassed THF (2.0 mL) were irradiated for 12 h at 60 °C to give a yellow-orange solution. Purification by chromatography on SiO_2 (80:20:1, hexanes/ethyl ether/Et_3N) gave **20h** (15.0 mg, 46%) as a colorless oil: $[\alpha]_D$ +48.6 (*c* 0.84, CH_2Cl_2, 22 °C); ^1H NMR δ 4.54 (app dt, 1 H, J = 9.5, 4.9 Hz), 4.31 (s, 1 H), 4.18 (app t, 1 H, J = 3.0 Hz), 4.08 (d, 1 H, J = 1.6 Hz), 2.21−2.11 (m, 1 H), 1.83−1.70 (m, 1 H), 1.69 (d, 1 H, J = 3.6 Hz), 1.51 (ddd, 1 H, J = 15.0, 9.2, 5.8 Hz), 1.30−1.22 (m, 1 H), 0.95 (d, 3 H, J = 6.7 Hz), 0.94 (d, 3 H, J = 6.6 Hz), 0.87 (d, 3 H, J = 7.2 Hz); ^{13}C NMR δ 164.8, 82.5, 81.2, 78.7, 43.1, 39.1, 25.4, 23.6, 22.4, 11.3; IR (neat) 3383, 2958, 2934, 2872, 1676, 1638, 1467, 1383, 1369, 1023, 984, 814 cm^{-1}; MS (EI) *m*/*z* (rel intensity) 170 (M^+, 35), 153 ([M − OH]$^+$, 14), 139 ([M − CH_3O]$^+$, 10), 128 ([M − C_3H_6]$^+$, 8), 113 (16), 109 (30), 97 (63), 85 (34), 69 (78), 55 (100); HRMS (EI) *m*/*z* calcd for $C_{10}H_{18}O_2$ 170.1307, found 170.1314.

(2*R,4*R**)-2-Isobutyl-4-(*tert*-butyldiphenylsilanyloxy)-3,4-dihydro-2*H*-pyran (21i).** According to the general procedure, **19i** (55.0 mg, 0.140 mmol, 1.0 equiv), tungsten

(43) ^1H and ^{13}C NMR signals for mixtures are tentatively assigned and based on correlations with spectra of structurally related compounds. For cases where the assignment is ambiguous, only diagnostic signals are listed.

hexacarbonyl (25.0 mg, 0.070 mmol, 0.5 equiv), and DABCO (32.0 mg, 0.290 mmol, 2.1 equiv) in freshly distilled and degassed THF (2.5 mL) were irradiated for 18 h at 56 °C to give a yellow solution. ^{1}H NMR analysis of the crude reaction mixture indicated a ratio of *endo*:*exo* isomers of 30:1. Purification by chromatography on SiO_2 (100:0:1 to 98:2:1, hexanes/ethyl ether/Et_3N) gave a mixture of **21i** and the *exo*-cyclization product (8.0 mg, 15%) as a colorless solid. **21i**: ^{1}H NMR δ 7.71−7.65 (m, 4 H), 7.43−7.35 (m, 6 H), 6.39 (d, 1 H, J = 6.1 Hz), 4.66 (dt, 1 H, J = 1.8, 6.0 Hz), 4.22−4.10 (m, 2 H), 1.84−1.74 (m, 2 H), 1.63−1.54 (m, 1 H), 1.42 (ddd, 1 H, J = 14.0, 11.9, 3.7 Hz), 1.29 (ddd, 1 H, J = 13.5, 7.7, 5.5 Hz), 1.06 (s, 9 H), 0.97 (d, 3 H, J = 6.6 Hz), 0.96 (d, 3 H, J = 6.6 Hz); ^{13}C NMR δ 146.4, 136.1, 136.0, 134.7, 134.6, 129.8, 127.8, 127.7, 103.6, 69.9, 61.6, 44.4, 38.2, 27.2, 24.6, 23.2, 22.7, 19.3; IR (neat) 3069, 2958, 2929, 2893, 2858, 1961, 1888, 1821, 1720, 1640, 1469, 1427, 1243, 1108, 1084, 1054, 821, 797, 737, 702 cm^{-1}; MS (EI) *m*/*z* (rel intensity) 394 (M^+, 15), 337 ([M − C_4H_9]$^+$, 52), 253 (82), 199 (100), 161 (16), 105 (16), 81 (31); HRMS (EI) *m*/*z* calcd for $C_{25}H_{34}O_2Si$ 394.2328, found 394.2324.

(3*R,5*R**)-5-Isobutyl-3-*tert*-butoxy-2-methylenetetrahydrofuran (20j) and (2*R**,4*R**)-2-Isobutyl-4-*tert*-butoxy-3,4-dihydro-2*H*-pyran (21j).** According to the general procedure, **19j** (19.0 mg, 0.089 mmol, 1.0 equiv), tungsten hexacarbonyl (15.7 mg, 0.045 mmol, 0.5 equiv), and DABCO (20.0 mg, 0.178 mmol, 2.0 equiv) in freshly distilled and degassed THF (1.8 mL) were irradiated for 14 h at 56 °C to give a yellow solution. ^{1}H NMR analysis of the crude reaction mixture indicated a ratio of **20j**:**21j** of 1:4. Attempted purification by chromatography on SiO_2 (100:0:1 to 96:4:1, hexanes/ethyl ether/Et_3N) led to decomposition, so the spectral data are for the crude sample.[43] **20j:** ^{1}H NMR δ 4.30 (s, 1H), 3.97 (s, 1 H). **21j:** ^{1}H NMR δ 6.46 (d, 1 H, J = 6.1 Hz), 4.77 (td, 1 H, J = 6.5, 1.5 Hz); ^{13}C NMR δ 146.5, 103.5, 73.9, 70.1, 59.7, 44.6, 38.3, 28.7, 24.6, 23.5, 22.4.

(3*R,5*R**)-3-Benzyloxy-5-isobutyl-2-methylenetetrahydrofuran (20k) and (2*R**,4*R**)-4-Benzyloxy-2-isobutyl-3,4-dihydro-2*H*-pyran (21k).** According to the general procedure, **19k** (26.0 mg, 0.110 mmol, 1.0 equiv), tungsten hexacarbonyl (19.0 mg, 0.050 mmol, 0.5 equiv), and DABCO (24.6 mg, 0.220 mmol, 2.0 equiv) in freshly distilled and degassed THF (2.2 mL) were irradiated for 14 h at 56 °C to give a yellow solution. ^{1}H NMR analysis of the crude reaction mixture indicated a ratio of **20k**:**21k** of 6:1. Purification by chromatography on SiO_2 (100:1 to 100:2, hexanes/Et_3N) gave an inseparable mixture of the title compounds (14.1 mg, 54%) as a colorless oil.[43] **20k**: ^{1}H NMR δ 4.71, 4.48 (AB, 2 H, J = 11.8 Hz), 4.41 (t, 1 H, J = 0.8 Hz), 4.27 (d, 1 H, J = 4.8 Hz), 4.03 (d, 1 H, J = 1.5 Hz), 2.21 (d, 1 H, J = 13.1, 4.9 Hz); ^{13}C NMR δ 161.3, 83.9. **21k**: ^{1}H NMR δ 6.54 (d, 1 H, J = 6.1 Hz), 4.99−4.95 (m, 1 H), 4.61, 4.53 (AB, 2 H, J = 12.1 Hz), 4.08−3.99 (m, 1 H), 3.86−3.83 (m, 1 H); ^{13}C NMR δ 147.7, 100.4.

(2*R,4*S**)-4-Benzyloxy-2-isobutyl-3,4-dihydro-2*H*-pyran (21*l*).** According to the general procedure, **19*l*** (54.0 mg, 0.220 mmol, 1.0 equiv), tungsten hexacarbonyl (38.0 mg, 0.110 mmol, 0.5 equiv), and DABCO (50.0 mg, 0.450 mmol, 2.0 equiv) in freshly distilled and degassed THF (4.4 mL) were irradiated for 18 h at 56 °C to give a yellow solution. Purification by chromatography on SiO_2 (2 columns, 99:1, hexanes/Et_3N then hexanes to 96:4, hexanes/ethyl ether) gave **21*l*** (36.2 mg, 67%) as a colorless oil: ^{1}H NMR δ 7.36−7.26 (m, 5 H), 6.40 (dd, 1 H, J = 6.3, 1.1 Hz), 4.86 (dt, 1 H, J = 6.3, 1.9 Hz), 4.57 (s, 2 H), 4.27−4.21 (m, 1 H), 4.04−4.39 (m, 1 H), 2.13 (qt, 1 H, J = 6.6, 1.7 Hz), 1.87−1.60 (m, 3 H), 1.28 (ddd, 1 H, J = 13.9, 8.8, 3.8 Hz), 0.92 (d, 3 H, J = 6.7 Hz), 0.92 (d, 3 H, J = 6.5 Hz); ^{13}C NMR δ 145.8, 138.8, 128.6, 127.8, 127.7, 102.7, 73.2, 70.0, 69.7, 44.5, 35.2, 24.4, 23.4, 22.3; IR (neat) 3089, 3063, 3030, 2956, 2924, 2869, 1644, 1467, 1454, 732, 696 cm^{-1}; MS (EI) *m*/*z* (rel intensity) 246 (M^+, 15), 203 ([M − C_3H_7]$^+$, 8), 155 ([M − $C_6H_5CH_2$]$^+$, 17), 140 ([M − C_6H_5 − CH_3]$^+$, 11), 107 (15), 91 (100), 81 (56), 69 (25); HRMS (EI) *m*/*z* calcd for $C_6H_{22}O_2$ 246.1620, found 246.1633.

(3*R,5*R**)-5-Isobutyl-3-methoxy-2-methylenetetrahydrofuran (20m) and (2*R**,4*R**)-2-Isobutyl-4-methoxy-3,4-dihydro-2*H*-pyran (21m).** According to the general procedure, **19m** (22.0 mg, 0.128 mmol, 1.0 equiv), tungsten hexacarbonyl (22.5 mg, 0.064 mmol, 0.5 equiv), and DABCO (28.7 mg, 0.256 mmol, 2.0 equiv) in freshly distilled and degassed THF (2.6 mL) were irradiated for 14 h at 56 °C to give a yellow solution. ^{1}H NMR analysis of the crude reaction mixture indicated a ratio of **20m**:**21m** of 8:1. Attempted purification by chromatography on SiO_2 (100:1 to 100:2, hexanes/Et_3N) led to decomposition so spectral data are for the crude sample.[43] **20m**: ^{1}H NMR δ 4.54−4.47 (m, 1 H), 4.37 (s, 1 H), 4.06 (d, 1 H, J = 5.2 Hz), 4.00 (s, 1 H), 3.35 (s, 3H), 2.15 (dd, 1 H, J = 13.1, 4.9 Hz); ^{13}C NMR δ 161.2, 83.7, 80.9, 79.9, 56.1, 44.9, 39.3, 25.6, 23.3, 22.9. **21m**: ^{1}H NMR δ 6.52 (d, 1 H, J = 6.1 Hz), 4.97 (td, 1 H, J = 6.5, 1.7 Hz), 3.34 (s, 3 H); ^{13}C NMR δ 147.6, 100.2, 70.2, 68.9, 55.3, 44.6, 34.5, 24.6, 23.5, 22.5.

(2*R,4*S**)-2-Isobutyl-4-[3-(triisopropylsilanyl)prop-2-ynoxy]-3,4-dihydro-2*H*-pyran (21n).** According to the general procedure, **19n** (52.5 mg, 0.150 mmol, 1.0 equiv), tungsten hexacarbonyl (26.4 mg, 0.075 mmol, 0.5 equiv), and DABCO (33.9 mg, 0.301 mmol, 2.0 equiv) in freshly distilled and degassed THF (3.0 mL) were irradiated for 12 h at 40 °C to give an orange-red solution. Purification by chromatography on SiO_2 (100:0:1 to 95:5:1, hexanes/ethyl ether/Et_3N) gave **21n** (24.0 mg, 46%) as a colorless oil: ^{1}H NMR δ 6.38 (d, 1 H, J = 6.2 Hz), 4.80 (app dt, 1 H, J = 6.3, 1.9 Hz), 4.45−4.40 (m, 1 H), 4.24(s, 2 H), 4.03−3.94 (m, 1 H), 2.16 (app qt, 1 H, J = 6.5, 1.8 Hz), 1.85−1.58 (m, 3 H), 1.29 (ddd, 1 H, J = 13.3, 8.2, 4.8 Hz), 1.20−1.00 (m, 22 H), 0.91 (app d, 6 H, J = 6.6 Hz); ^{13}C NMR δ 145.9, 104.0, 102.5, 87.6, 73.2, 69.1, 56.3, 44.3, 34.9, 24.4, 23.3, 22.4, 18.8, 11.4; IR (neat) 3065, 2956, 2893, 2866, 2170, 1644, 1465, 1383, 1366, 1349, 1232, 1075 cm^{-1}; MS (EI) *m*/*z* (rel intensity) 350 (M^+, 20), 307 ([M − C_3H_7]$^+$, 5), 223 (9), 169 (100), 155 (7), 141 (28), 113 (30); HRMS (EI) *m*/*z* calcd for $C_{21}H_{38}O_2Si$ 350.2641, found 350.2628.

(3*R,5*R**)-5-Isobutyl-3-[3-(triisopropylsilanyl)prop-2-ynoxy]-2-methylenetetrahydrofuran (20o) and (2*R**,4*R**)-2-Isobutyl-4-[3-(triisopropylsilanyl)prop-2-ynoxy]-3,4-dihydro-2*H*-pyran (21o).** According to the general procedure, **19o** (87.0 mg, 0.248 mmol, 1.0 equiv), tungsten hexacarbonyl (43.6 mg, 0.124 mmol, 0.5 equiv), and DABCO (56.0 mg, 0.496 mmol, 2.0 equiv) in freshly distilled and degassed THF (5.0 mL) were irradiated for 7 h at room temperature to give a yellow solution. ^{1}H NMR analysis of the crude reaction mixture indicated a ratio of **20o**:**21o** of 8:1. Purification by chromatography on SiO_2 (100:0:1 to 97.5:2.5:1, hexanes/ethyl ether/Et_3N) gave an inseparable mixture of the title compounds (21.5 mg, 25%) as a colorless oil.[43] **20o**: ^{1}H NMR δ 4.59 (d, 1 H, J = 5.1 Hz), 4.56−4.47 (m, 1 H), 4.39 (s, 1 H), 4.30, 4.29 (AB, 2 H, J = 16.1 Hz), 4.08 (s, 1 H), 2.21−2.15 (m, 1H); ^{13}C NMR δ 160.3, 103.2, 88.2, 84.2, 80.0, 76.7, 55.8, 44.7, 39.3, 25.5, 23.3, 22.7, 18.8, 11.4. **21o**: ^{1}H NMR δ 6.53 (d, 1 H, J = 6.1 Hz), 4.96 (t, 1 H, J = 5.0 Hz).

(2*R,3*R**,4*R**)-4-(*tert*-Butyldiphenylsilanyloxy)-2-isobutyl-3-methyl-3,4-dihydro-2*H*-pyran (21p).** According to the general procedure, **19p** (100.0 mg, 0.250 mmol, 1.0 equiv), tungsten hexacarbonyl (26.0 mg, 0.070 mmol, 0.3 equiv), and DABCO (55.0 mg, 0.490 mmol, 2.0 equiv) in freshly distilled and degassed THF (3.0 mL) were irradiated for 14 h at 56 °C. Purification by chromatography on SiO_2 (100:0:1 to 95:5:1, hexanes/CH_2Cl_2/diethylamine) gave **21p** (25.0 mg, 25%) as a colorless, amorphous solid: ^{1}H NMR (CD_2Cl_2) δ 7.71−7.68 (m, 4 H), 7.42−7.36 (m, 6 H), 6.24 (d, 1 H, J = 6.1 Hz), 4.46 (dd, 1 H, J = 5.9, 5.1 Hz), 4.02 (dd, 1 H, J = 5.1, 3.7 Hz), 3.97 (app dt, 1 H, J = 9.8, 3.2 Hz), 1.93−1.80 (m, 1 H), 1.64−1.54 (m, 1 H), 1.44 (ddd, 1 H, J = 14.0, 9.9, 4.3 Hz), 1.32 (ddd, 1 H, J = 13.0, 9.7, 3.2 Hz), 1.05 (s, 9 H), 1.00 (d, 3 H, J = 7.0 Hz), 0.94 (d, 3 H, J = 6.6 Hz), 0.94 (d, 3 H, J = 6.7 Hz); ^{13}C NMR (CD_2Cl_2) δ 145.5, 136.7, 136.5, 135.5, 134.8, 130.1, 129.9, 128.1, 127.8, 104.0, 74.5, 66.2, 41.9, 39.2, 27.4, 24.7, 24.2, 21.8, 19.9,

13.8; IR (neat) 3070, 2957, 2931, 2894, 2857, 1645, 1472, 1427, 1242, 1111, 1085, 1019, 701 cm^{-1}; MS (EI) *m/z* (rel intensity) 407 ([M − H]$^+$, 22), 393 ([M − CH_3]$^+$, 28), 379 ([M − C_2H_5]$^+$, 12), 365 ([M − C_3H_7]$^+$, 15), 351 ([M − C_4H_9]$^+$, 26), 295 (6), 265 (57), 253 (100), 199 (100), 95 (58), 77 (30), 69 (18); HRMS (EI) *m/z* calcd for $C_{26}H_{35}O_2Si$ (M − H) 407.2406, found 407.2410.

(2*R,4*S**)-2-Isobutyl-3,3-dimethyl-3,4-dihydro-4-triisopropylsilanoxy-2*H*-pyran (21q).** According to the general procedure, **19q** (28.0 mg, 0.082 mmol), $W(CO)_6$ (15.0 mg, 0.043 mmol, 0.5 equiv), and DABCO (19.0 mg, 0.168 mmol, 2.1 equiv) in THF (1.0 mL) were irradiated for 12 h at 60 °C to give a yellow solution. Purification by chromatography on SiO_2 (100:0:1 to 100:2:1, hexanes/ethyl ether/Et_3N) gave **19q** (11.9 mg, 43%) and a mixture of **20q** and **21q** (13.8 mg, 49%) as a colorless oil in a ratio of **20q**:**21q** of 1:4. Characteristic signals for **20q**:[43] ^{1}H NMR δ 4.26 (d, 1 H, J = 1.5 Hz), 4.16 (dd, 1 H, J = 10.5, 2.2 Hz), 4.07 (s, 1H), 4.02 (d, 1 H, J = 1.5 Hz). Purification of the mixture by chromatography on SiO_2 (hexanes) gave **21q** (9.2 mg, 33%) as a colorless oil: ^{1}H NMR δ 6.33 (d, 1 H, J = 6.0 Hz), 4.81 (app t, 1 H, J = 5.7 Hz), 3.89 (dd, 1 H, J = 10.9, 2.0 Hz), 3.62 (d, 1 H, J = 5.3 Hz), 1.93−1.79 (m, 1 H), 1.50 (ddd, 1 H, J = 14.5, 10.9, 3.8 Hz), 1.26−1.01 (m, 22 H), 0.94 (s, 3 H), 0.90 (d, 3 H, J = 6.5 Hz), 0.77 (s, 3 H); ^{13}C NMR δ 145.0, 102.9, 75.8, 71.1, 37.6, 37.3, 24.8, 24.3, 22.6, 21.5, 18.9, 18.5, 13.2; IR (neat) 3062, 2959, 2894, 2867, 2722, 1846, 1645, 1466, 1386, 1367, 1241, 1088, 1059 cm^{-1}; MS (EI) *m/z* (rel intensity) 325 ([M − CH_3]$^+$, 7), 297 ([M − C_3H_7]$^+$, 13), 229 (7), 211 (10), 185 (23), 169 (5), 131 (16), 115 (10), 103 (17), 75 (65), 69 (47), 61 (100); HRMS (EI) *m/z* calcd for $C_{17}H_{33}O_2Si$ (M − C_3H_7) 297.2250, found 297.2242.

(3*R,5*R**)-2-Isobutyl-4-[3-(triisopropylsilanyl)prop-2-ynoxy]-3,3-dimethyl-5-methylenetetrahydrofuran (20s).** According to the general procedure, **19s** (21.2 mg, 0.056 mmol, 1.0 equiv), $W(CO)_6$ (11.0 mg, 0.031 mmol, 0.5 equiv), and DABCO (14.0 mg, 0.124 mmol, 2.2 equiv) in freshly distilled and degassed THF (1.0 mL) were irradiated for 18 h at 55 °C to afford a dark red solution. Purification by chromatography on SiO_2 (100:1, hexanes/Et_3N) gave **20s** (6.7 mg, 32%) as a colorless oil: ^{1}H NMR δ 4.38 (d, 1 H, J = 1.3 Hz), 4.29 (s, 2 H), 4.10 (dd, 1 H, J = 10.4, 2.0 Hz), 4.05 (d, 1 H, J = 1.3 Hz), 3.97 (s, 1 H), 1.87−1.73 (m, 1 H), 1.48−1.38 (m, 2 H), 1.12−1.04 (m, 21 H), 1.01 (s, 3 H), 0.96 (d, 3 H, J = 6.7 Hz), 0.92 (d, 3 H, J = 6.6 Hz), 0.85 (s, 3 H); ^{13}C NMR δ 159.8, 103.6, 88.1, 85.7, 84.7, 84.1, 55.6, 43.8, 37.9, 25.8, 24.0, 22.1, 20.0, 18.8, 18.1, 11.4; IR (neat) 3109, 2958, 2945, 2866, 2171, 1673, 1640, 1466, 1384, 1369, 1354, 1074 cm^{-1}; MS (EI) *m/z* (rel intensity) 378 (M$^+$, 29), 363([M − CH_3]$^+$, 9), 335 ([M − C_3H_7]$^+$, 67), 249 (9), 223 (19), 153 (100), 111 (34), 69 (50); HRMS (EI) *m/z* calcd for $C_{23}H_{42}O_2Si$ 378.2954, found 378.2957.

(3*R,5*R**)-3-Benzyloxy-5-isobutyl-4,4-dimethyl-2-methylenetetrahydrofuran (20u).** According to the general procedure, **19u** (46.5 mg, 0.169 mmol, 1.0 equiv), $W(CO)_6$ (30.0 mg, 0.085 mmol, 0.5 equiv), and DABCO (38.0 mg, 0.337 mmol, 2.0 equiv) in freshly distilled and degassed THF (1.0 mL) were irradiated for 16 h at 55 °C to give a dark red solution. Purification by chromatography on SiO_2 (100:1, hexanes/Et_3N) gave **20u** (28.3 mg, 61%) as a yellow oil: ^{1}H NMR δ 7.36−7.25 (m, 5 H), 4.78, 4.45 (AB, 2 H, J = 12.3 Hz), 4.43 (s, 1 H), 4.22 (dd, 1 H, J = 10.4, 1.9 Hz), 4.01 (s, 1 H), 3.61 (s, 1 H), 1.91−1.77 (m, 1 H), 1.46 (ddd, 1 H, J = 14.4, 10.5, 4.75 Hz), 1.15 (ddd, 1 H, J = 11.1, 7.2, 1.9 Hz), 1.10 (s, 3 H), 0.98 (d, 3 H, J = 6.7 Hz), 0.94 (d, 3 H, J = 6.6 Hz), 0.85 (s, 3 H); ^{13}C NMR δ 160.6, 138.8, 128.5, 127.7, 127.6, 86.2, 85.7, 84.6, 69.8, 44.2, 38.0, 25.8, 24.0, 22.1, 20.0, 18.2; IR (neat) 3112, 3089, 3065, 3031, 2958, 2928, 2872, 1943, 1807, 1673, 1644, 1467, 1454, 1385, 1365, 1081, 1001, 739, 693 cm^{-1}; MS (EI) *m/z* (rel intensity) 274 (M$^+$, 8), 259 ([M − CH_3]$^+$, 1), 193 (10), 183 ([M − $C_6H_5CH_2$]$^+$, 9), 168 ([M − $C_6H_5CH_2$ − CH_3]$^+$, 8), 153 (78), 91 (100), 73 (24), 69 (37), 61 (30), 59 (24); HRMS (EI) *m/z* calcd for $C_{18}H_{26}O_2$ 274.1933, found 274.1932.

(2*R,4*S**)-2-Isobutyl-4-[(1*S**)-1-pivaloylbut-2-enyl]-3,4-dihydro-2*H*-pyran (24).** According to the general procedure, **23** (10.9 mg, 0.037 mmol, 1.0 equiv), tungsten hexacarbonyl (6.0 mg, 0.02 mmol, 0.5 equiv), and DABCO (8.0 mg, 0.07 mmol, 1.9 equiv) in freshly distilled and degassed THF (1.0 mL) were irradiated for 14 h at 55 °C to give a yellow solution. Purification by chromatography on SiO_2 (99:1:1, hexanes/ethyl ether/Et_3N) gave **24** (8.8 mg, 81%) as a colorless oil: ^{1}H NMR δ 6.38 (dd, 1 H, J = 6.2, 2.1 Hz), 5.77−5.66 (m, 1 H), 5.37 (ddd, 1 H, J = 15.3, 7.0, 1.6 Hz), 4.95 (app t, 1 H, J = 7.2 Hz), 4.57 (app dt, 1 H, J = 6.2, 1.6 Hz), 3.90−3.82 (m, 1 H), 2.59−2.50 (m, 1 H), 1.84−1.74 (m, 2 H), 1.70 (app dt, 3 H, J = 6.5, 0.7 Hz), 1.55 (ddd, 1 H, J = 14.1, 8.5, 5.7 Hz), 1.33−1.18 (m, 1 H), 1.21 (s, 9 H), 0.91 (d, 6 H, J = 6.6 Hz); ^{13}C NMR δ 177.9, 145.0, 129.9, 127.7, 100.9, 77.1, 73.5, 45.1, 39.2, 36.3, 32.0, 27.4, 24.4, 23.5, 22.4, 18.1; IR (neat) 3063, 2957, 2925, 2871, 1730, 1645, 1480, 1467, 1159 cm^{-1}; MS (CI) *m/z* (rel intensity) 193 ([M − $C_5H_9O_2$]$^+$, 12), 177 ([M − $C_5H_9O_3$]$^+$, 6), 163 ([M − $C_6H_{11}O_3$]$^+$, 6), 135 (6), 129 (14), 89 (23), 73 (100), 61 (37); HRMS (EI) *m/z* calcd for $C_{13}H_{20}O$ (M − $C_5H_{10}O_2$) 192.1514, found 192.1516.

(2*R,4*R**)-2-Isobutyl-4-[(1*R**)-1-pivaloylbut-2-en-1-yl]-3,4-dihydro-2*H*-pyran (27).** According to the general procedure, **26** (18.0 mg, 0.061 mmol, 1.0 equiv), tungsten hexacarbonyl (11.0 mg, 0.031 mmol, 0.5 equiv), and DABCO (14.0 mg, 0.124 mmol, 2.0 equiv) in freshly distilled and degassed THF (1.5 mL) were irradiated for 23 h at 40 °C, then for 12 h at 60 °C to give a yellow solution. Purification by chromatography on SiO_2 (100:0:1 to 90:10:1, hexanes/ethyl ether/Et_3N) gave **27** (12.6 mg, 70%) as a colorless oil: ^{1}H NMR δ 6.38 (dd, 1 H, J = 6.5, 1.5 Hz), 5.77−5.66 (m, 1 H), 5.36 (dd, 1 H, J = 15.3, 7.3 Hz), 5.01 (app t, 1 H, J = 7.6 Hz), 4.65 (dd, 1 H, J = 6.1, 3.9 Hz), 3.91 (app ddt, 1 H, J = 10.1, 8.4, 5.3 Hz), 2.38−2.24 (m, 1 H), 1.84−1.71 (m, 2 H), 1.70 (d, 3 H, J = 6.5 Hz), 1.62−1.49 (m, 2 H), 1.25−1.19 (m, 1 H), 1.20 (s, 9 H), 0.92 (d, 3 H, J = 6.4 Hz), 0.91 (d, 3 H, J = 6.6 Hz); ^{13}C NMR δ 177.8, 144.6, 130.3, 128.2, 100.4, 78.1, 70.8, 43.8, 39.1, 33.3, 29.9, 27.4, 24.7, 23.3, 22.6, 18.1; IR (neat) 3063, 2957, 2929, 2871, 1730, 1672, 1645, 1480, 1467, 1157 cm^{-1}; MS (EI) *m/z* (rel intensity) 294 (M$^+$, 0.1), 237 ([M − C_4H_9]$^+$, 2), 209 (5), 193 ([M − $C_5H_9O_2$]$^+$, 9), 192 ([M − $C_5H_{10}O_2$]$^+$, 14), 139 (33), 121 (8), 57 (100); HRMS (EI) *m/z* calcd for $C_{13}H_{20}O$ (M − $C_5H_{10}O_2$) 192.1514, found 192.1511.

7-Hydroxy-2-hydroxymethyl-9-methyldeca-2,4-dienal (30). To a solution of (3*S**,5*R**)-7-methyl-3-[3-hydroxy-1-propenyloxy]-5-(triethylsilanyloxy)-1-(trimethylsilanyl)oct-1-yne (54.7 mg, 0.137 mmol, 1.0 equiv) in THF (5.0 mL) was added a solution of TBAF (1.0 M in THF, 0.43 mL, 0.43 mmol, 3.1 equiv). After 2 h at room temperature, the solvent was removed in vacuo and the residue was partitioned between ethyl ether and water. The aqueous layer was extracted with ethyl ether and the combined organic layers were washed with brine, dried (Na_2SO_4), filtered, and concentrated to give a yellow oil. The crude oil was dried under high vacuum (<1.0 mmHg) overnight, diluted with THF (2.5 mL), and added to a mixture of $W(CO)_6$ (24.0 mg, 0.068 mmol, 0.5 equiv) and DABCO (31.0 mg, 0.276 mmol, 2.0 equiv). Irradiation for 4 h at 56 °C followed by concentration and purification by chromatography on SiO_2 (40:60, hexanes/ethyl acetate) gave (2*E*,4*E*)-**30** and (2*Z*,4*E*)-**30** in a ratio of 15:1 (18.8 mg, 65%, 2 steps) as a yellow oil. (2*E*,4*E*)-**30**: ^{1}H NMR δ 9.45 (s, 1 H), 6.92 (d, 1 H, J = 11.3 Hz), 6.70 (ddt, 1 H, J = 14.8, 11.3, 1.2 Hz), 6.41 (app dt,1 H, J = 14.8, 7.4 Hz), 4.44 (s, 2 H), 3.90−3.80 (m, 1 H), 2.53 (br s, 1 H), 2.46−2.36 (m, 2 H), 1.80−1.76 (m, 1 H), 1.60 (br s, 1 H), 1.45 (ddd, 1 H, J = 13.9, 8.9, 5.4 Hz), 1.27 (ddd, 1 H, J = 13.8, 8.8, 4.2 Hz), 0.94 (d, 3 H, J = 5.1 Hz), 0.92 (d, 3 H, J = 5.1 Hz); ^{13}C NMR δ 195.7, 150.6, 144.6, 138.1, 127.8, 69.2, 56.0, 46.7, 42.1, 24.8, 23.6, 22.2; IR (neat) 3377, 3038, 2955, 2925, 2869, 2711, 1672, 1633, 1017 cm^{-1}; MS (EI) *m/z* (rel intensity) 194 ([M − H_2O]$^+$, 52), 176 ([M − 2 H_2O]$^+$, 7), 133 ([M − 2 H_2O − C_3H_7]$^+$, 6), 126 ([M − C_6H_{14}]$^+$, 41), 108 (100), 107 (52), 80 (66), 79 (95), 69 (52), 57 (21); HRMS (EI) *m/z* calcd for $C_{12}H_{18}O_3$ (M − H_2O) 194.1309, found 194.1308.

(2*R,4*S**)-2-Isobutyl-3,4-dihydro-4-[(1*S**)-3-(triisopropylsilanyl)-1-hydroxyprop-2-yn-1-yl]-2*H*-pyran (31).** To a solution of **21n** (154.5 mg, 0.441 mmol, 1.0 equiv) in THF (4.0 mL) at −78 °C under N_2 was added TMEDA (150 μL, 0.994 mmol, 2.3 equiv) followed by *n*-BuLi (1.2 M in hexanes, 0.85 mL, 0.960 mmol, 2.2 equiv). The resulting black reaction mixture was stirred for 20 min, quenched with saturated aqueous NH_4Cl (3.0 mL), and warmed to room temperature. The orange-colored mixture was diluted with water and extracted with ethyl ether. The combined organic layers were washed with brine, dried (Na_2SO_4), filtered, and concentrated to give an orange oil. Purification by chromatography on SiO_2 (95:5:1, hexanes/ethyl ether/Et_3N) afforded **31** (120.1 mg, 78%) as a pale yellow oil: ^{1}H NMR δ 6.46 (dd, 1 H, *J* = 6.2, 2.1 Hz), 4.76 (dt, 1 H, *J* = 1.8, 6.2 Hz), 4.18 (t, 1 H, *J* = 5.5 Hz), 3.94−3.86 (m, 1 H), 2.65−2.54 (m, 1 H), 1.95−1.74 (m, 3 H), 1.62−1.51 (m, 2 H), 1.28 (ddd, 1 H, *J* = 13.3, 8.1, 5.0 Hz), 1.06 (s, 21 H), 0.92 (d, 3 H, *J* = 6.6 Hz), 0.91 (d, 3 H, *J* = 6.6 Hz); ^{13}C NMR δ 146.3, 107.4, 99.9, 86.6, 73.6, 66.1, 45.0, 39.2, 31.7, 24.4, 23.3, 22.5, 18.8, 11.3; IR (neat) 3373, 3061, 2957, 2944, 2866, 2169, 1646, 1464, 1383, 1368, 1240, 1052 cm^{-1}; MS (EI) *m*/*z* (rel intensity) 349 ([M − H]$^+$, 1), 307 ([M − C_3H_7]$^+$, 8), 207 (7), 203 (11), 139 (100), 121 (9), 83 (41), 75 (33), 69 (19), 59 (25); HRMS (EI) *m*/*z* calcd for $C_{18}H_{31}O_2Si$ (M − C_3H_7) 307.2093, found 307.2092.

(5*S)-5-[(2*R**,4*S**)-2-Isobutyl-3,4-dihydro-2*H*-pyran-4-yl]-4-methylene-3-(4-nitrophenyl)oxazolidin-2-one (32).** To a solution of (2*R**,4*S**)-2-isobutyl-3,4-dihydro-4-[(1*S**)-3-(triisopropylsilanyl)-1-[(4-nitrophenyl)carbamoyloxy]-prop-2-yn-1-yl]-2*H*-pyran (70.1 mg, 0.136 mmol, 1.0 equiv) in THF (5.0 mL) was added TBAF (1.0 M in THF, 0.15 mL, 0.15 mmol, 1.1 equiv). The reaction mixture instantly turned yellow and then slowly became dark red over 30 min. Saturated aqueous NH_4Cl was added and the mixture was extracted with CH_2Cl_2. The combined organic layers were dried (Na_2SO_4), filtered, and concentrated to give an orange solid. Purification by chromatography on SiO_2 (75:25:0.5 to 60:40:0.5, hexanes/ethyl ether/Et_3N) gave **32** (22.9 mg, 47%) as a pale yellow amorphous solid that crystallized upon standing. Crystals suitable for X-ray diffraction were formed by slow evaporation of a pentane/methylene chloride solution: Mp 121.8−122.5 °C (pentane/methylene chloride); ^{1}H NMR δ 8.35 (app dt, 2 H, *J* = 9.1, 2.1 Hz), 7.60 (app dt, 2 H, *J* = 9.1, 2.1 Hz), 6.53 (dd, 1 H, *J* = 6.2, 2.1 Hz), 5.10 (app dt, 1 H, *J* = 4.0, 2.0) Hz), 4.56 (dt, 1 H, *J* = 6.2, 1.8 Hz), 4.47 (dd, 1 H, *J* = 3.2, 2.3 Hz), 4.33 (dd, 1 H, *J* = 3.2, 1.8 Hz), 3.96 (dddd, 1 H, *J* = 10.6, 8.5, 4.6, 1.6 Hz), 2.96−2.87 (m, 1 H), 1.96 (app ddt, 1 H, *J* = 13.0, 6.0, 1.7 Hz), 1.89−1.78 (m, 1 H), 1.75−1.57 (m, 2 H), 1.32 (ddd, 1 H, *J* = 13.8, 8.3, 4.6 Hz), 0.94 (d, 6 H, *J* = 6.6 Hz); ^{13}C NMR δ 154.6, 147.9, 146.9, 142.4, 139.7, 127.3, 125.2, 96.9, 84.9, 80.3, 73.5, 44.9, 37.5, 30.5, 24.4, 23.4, 22.4; IR (neat) 3112, 3083, 3054, 2956, 2928, 2870, 1777, 1647, 1597, 1525, 1501, 1401, 1341, 854 cm^{-1}; MS (EI) *m*/*z* (rel intensity) 358 (M$^+$, 71), 343 ([M − CH_3]$^+$, 5), 329 (11), 328 (50), 315 ([M − C_3H_7]$^+$, 16), 301 ([M − C_4H_9]$^+$, 35), 139 (100); HRMS (EI) *m*/*z* calcd for $C_{19}H_{22}N_2O_5$ 358.1529, found 358.1530.

(3*R,5*S**,4a*S**,7a*S**)-6-Hydroxymethyl-3-isobutyl-1,3,4,-4a,5,7a-hexahydro-cyclopenta[*c*]pyran-5-ol (33).** To a solution of (2*R**,4*S**)-2-isobutyl-3,4-dihydro-4-[(1*S**)-1-hydroxyprop-2-yn-1-yl]-2*H*-pyran (17.8 mg, 0.092 mmol, 1.0 equiv) and imidazole (19.0 mg, 0.279 mmol, 3.0 equiv) in DMF (1.0 mL) at room temperature under N_2 was added bromomethylchlorodimethylsilane (20.0 μL, 0.147 mmol, 1.6 equiv). After 10 min, saturated, aqueous NH_4Cl and water were added and the mixture was extracted with ethyl ether. The combined organic layers were washed with brine, dried (Na_2SO_4), filtrated, and concentrated to give an oily residue. Purification by chromatography on SiO_2 (100:1 pentane/Et_3N) gave a colorless oil (15.6 mg, 49%) that was diluted with benzene (0.5 mL). A solution of AIBN (3.25 mg, 0.020 mmol, 0.45 equiv) in benzene (0.5 mL) was added. The reaction mixture was heated to reflux under N_2. Additional AIBN (3.25 mg, 0.020 mmol, 0.45 equiv) and Bu_3SnH (50 μL, 0.19 mmol, 4.1 equiv) in benzene (1.5 mL) were added portionwise over 6 h. After a total of 8 h, the mixture was cooled to room temperature and concentrated. To the resulting residue was added MeOH (1.5 mL), THF (1.5 mL), KF (30.0 mg, 0.516 mmol, 11.5 equiv), $KHCO_3$ (45.0 mg, 0.450 mmol, 10.0 equiv), and H_2O_2 (30% in H_2O, 1.0 mL, 29 mmol, 650 equiv). The white suspension was heated at reflux for 2 h, stirred at 35 °C overnight (10 h), and filtered through Celite (ethyl ether wash). The filtrate was concentrated and the residue was partitioned between ethyl ether and brine. The aqueous layer was backwashed with ethyl ether. The combined organic layers were dried (Na_2SO_4), filtered, and concentrated to give a colorless solid. Purification by chromatography on SiO_2 (50:50, hexanes/ethyl acetate to ethyl acetate) gave **33** (2.0 mg, 20%) as a colorless, amorphous solid: ^{1}H NMR δ 5.65 (s, 1 H), 4.96 (br s, 1 H), 4.33 (s, 2 H), 4.07 (d, 1 H, *J* = 11.7 Hz), 3.65 (dd, 1 H, *J* = 12.1, 4.0 Hz), 3.27−3.19 (m, 1 H), 2.69 (app dq, 1 H, *J* = 12.0, 6.1 Hz), 2.44 (br s, 1 H), 2.34 (br s, 1 H), 1.98 (br s, 1 H), 1.85−1.71 (m, 1 H), 1.53−1.25 (m, 3 H), 1.17 (ddd, 1 H, *J* = 13.2, 8.3, 4.7 Hz), 0.88 (d, 6 H, *J* = 6.6 Hz); MS (EI) *m*/*z* (rel intensity) 226 (M$^+$, 0.1), 208 ([M − H_2O]$^+$, 12), 190 ([M − 2 H_2O]$^+$, 33), 179 ([M − C_2H_5 − H_2O]$^+$, 19), 169 ([M − C_4H_9]$^+$, 6), 151 ([M − C_4H_9 − H_2O]$^+$, 9), 133 (9), 121 (16), 104 (100), 91 (53), 61 (52); HRMS (EI) *m*/*z* calcd for $C_{13}H_{20}O_2$ (M − H_2O) 208.1463, found 208.1458.

Acknowledgment. This work was supported in part by NIH (GM-55433) and Merck Research Laboratories. We would like to thank Professor Craig S. Wilcox for use of a photoreactor, Dr. Steven J. Geib for X-ray crystallography, and Dr. Fu-Tyan Lin for NMR analyses.

Supporting Information Available: Syntheses of **19**, **21n**, **22**, **23**, **25**, **28**, (2*R**,4*S**)-2-isobutyl-3,4-dihydro-4-[(1*S**)-3-(triisopropylsilanyl)-1-[(4-nitrophenyl)carbamoyloxy]prop-2-yn-1-yl]-2*H*-pyran, (2*R**,4*S**)-2-isobutyl-3,4-dihydro-4-[(1*S**)-1-hydroxyprop-2-yn-1-yl]-2*H*-pyran, and (3*R**,5*S**,4a*S**,7a*S**)-6-(3,5-dinitrobenzoyloxymethyl)-5-(3,5-dinitrobenzoyloxy)-3-isobutyl-1,3,4,4a,5,7a-hexahydrocyclopenta[*c*]pyran; ^{1}H and ^{13}C NMR spectra of all new compounds. This material is available free of charge via the Internet at http://pubs.acs.org.

JO034813S