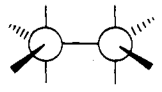
of triply bonded $Os_2^{6+}$ complexes, for which one-electron reductions occur at potentials in the range −0.20 to +0.60 V.[4c,13]

An analysis of the X-ray data for $Os_2Cl_4(Ph_2PC_6H_4)_2$ established the identity of the compound and revealed that the molecule has a unique geometry with $C_2$ symmetry.[14] The compound crystallizes in the chiral space group $C222_1$ with 4 molecules/unit cell, each of which resides on a crystallographic $C_2$ axis.[15] The 2-fold axis is aligned perpendicular to the Os–Os bond vector, and it bisects the two cis-bridging $o\text{-}(Ph_2P)C_6H_4^-$ groups.

As can be clearly seen in the ORTEP drawing of the molecule in Figure 1, there are two types of chloride ligands on each Os atom; Cl(2) is in an apical position defined by the nearly linear (176.0 (1)°) chain Cl(2)–Os(1)–P(1), and Cl(1) resides in the equatorial plane containing Os(1), Os(1)′, and C(2). This arrangement defines a distorted trigonal bipyramid (tbp) (see angles in Figure 1 caption), which is not an uncommon geometry for metal centers in a binuclear complex. However, the orientations of the two separate tbp units about each Os atom in this case are not parallel to one another in the usual way (a) but instead are perpendicular as in (b).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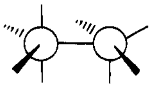
b

We know of no precedent for this arrangement of ligands for an $M_2L_8$ compound. The reasons that the molecule prefers to adopt this unusual geometry are presumed to be steric in nature, due to the constraints imposed upon the structure by the cis ortho-metalated $PPh_3$ groups. Although it is feasible from an electronic point of view, the molecule cannot alleviate steric repulsions across the Os–Os bond by a rotation about the Os≡Os bond axis because the C–P bridging groups are much too rigid. As a consequence, the chloride ligands stagger themselves in another way that involves Cl(1) becoming "swept back" from the center of the molecule toward the axial site (Os(1)′–Os(1)–Cl(1) = 143.02°). This leaves Cl(2) to occupy an apical position for an overall stable arrangement of ligands that minimizes unfavorable steric interactions.

The Os–Os bond length of 2.231 (1) Å in $Os_2Cl_4(Ph_2PC_6H_4)_2$ is very short, the shortest one reported for an Os≡Os complex other than those in the $[Os_2X_8]^{2-}$ anions (X = Cl or Br).[4d] The magnetic properties of the new compound have not been investigated yet, but it is expected to possess a diamagnetic ground state, by analogy to the parent compound $Os_2(O_2CCH_3)_2(Ph_2PC_6H_4)_2Cl_2$, which also has an unusually short Os–Os distance.

This study was undertaken in order to explore the possibility of preparing new classes of binuclear osmium compounds containing a metal-to-metal triple bond. Our isolation of $Os_2Cl_4(Ph_2PC_6H_4)_2$ represents a significant contribution to Os≡Os chemistry. It is the first example of a neutral $Os_2L_8$ compound, and it possesses a hitherto unknown $M_2L_8$ geometry. Furthermore, it constitutes another example of a multiply bonded complex with ortho-metalated ligands, of which there are only a few examples in the literature.[6,16] We are continuing to work toward a better understanding of the syntheses and reactivities of these elusive classes of $M_2$ compounds. A more detailed account of these results will be submitted.

**Acknowledgment.** We thank the National Science Foundation for support.

**Supplementary Material Available:** Tables of crystallographic parameters, atomic positional parameters and equivalent isotropic displacement parameters, bond distances and angles, and anisotropic thermal parameters (5 pages); a table of observed and calculated structure factors (7 pages). Ordering information is given on any current masthead page.

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(15) The complex crystallizes in the orthorhombic space group $C222_1$ with $a$ = 16.083 (1) Å, $b$ = 17.280 (7) Å, $c$ = 12.173 (2) Å, $V$ = 3383 (3) $Å^3$, $Z$ = 4, $d_{calcd}$ = 2.051 g/$cm^3$, and $\mu$(Mo K$\alpha$) = 79.53 $cm^{-1}$. An Enraf-Nonius CAD-4 diffractometer was used to gather 1571 unique data at 22 °C using the $\omega$-scan technique. The data were corrected for Lorentz and polarization effects, and azimuthal scans ($\psi$-scans) of nine reflections having an Eulerian angle $\chi$ near 90° were used as a basis for an empirical absorption correction. The position of the unique Os atom was derived from a three-dimensional Patterson map, and all other atoms were located in subsequent difference maps. Refinement of 199 parameters using 1414 reflections with $F_o^2 > 3\sigma(F_o^2)$ produced residuals of $R$ = 0.024 and $R_w$ = 0.032. The quality-of-fit index is 0.948, and the largest shift/esd = 0.15.

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# Intramolecular Formal Iron-Catalyzed Ene Reactions: New and Highly Stereoselective Iron-Catalyzed Carbocyclizations of Triene Ethers

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New catalytic transition-metal-mediated carbon–carbon bond-forming reactions have found exceptional utility in organic synthesis.[1,2] Of particular note are the applications of organotransition-metal chemistry to the problem of constructing carbocyclic rings.[3] We have recently reported the *intermolecular* L·Fe(0)-catalyzed formal ene reactions of 1,3-dienes with allylic ethers.[4] These reactions complement the known thermal, Lewis acid catalyzed, and magnesium ene reactions and expand the utility of 1,3-dienes as enophilic substrates in the ene reaction.[5] We now wish to report that acyclic triene ethers will undergo new iron-catalyzed carbocyclization reactions at ambient temperature with high cis or trans simple diastereoselectivity and with high

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(4) Takacs, J. M.; Anderson, L. G.; Madhavan, G. V. B.; Creswell, M. W.; Seely, F. L.; Devroy, W. F. *Organometallics* **1986**, *5*, 2395–2398.

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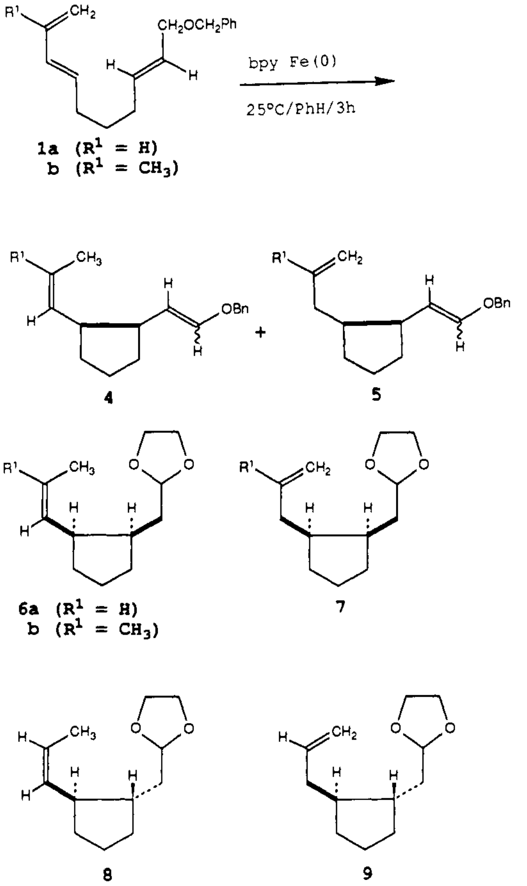
stereoinduction by a resident noncoordinating chiral center.[6,7]

The (2*E*, 7*E*)-2,7,9-decatriene ethers **1** and **2** are readily synthesized starting from δ-valerolactones.[8,9] Treatment of the *E*,*E*-triene ether **1a** ($R^1$ = H) with 10–15 mol % of the bpy·Fe(0) catalyst (benzene, 25 °C, 3–8 h) effects a remarkably facile cyclization to yield a mixture of four isomeric 1,2-disubstituted cyclopentanes (eq 1).[10] Two of the isomers formed are of no consequence and result from the fact that compounds **4** and **5** are each formed as a 60:40 cis–trans mixture of enol–ether isomers. The crude reaction mixture can be directly subjected to acetalization conditions ($HOCH_2CH_2OH$, TsOH, THF) to yield a 95:5 mixture of the cis-substituted cyclopentanes **6** and **7**, which are isolated in 82% overall yield. The major product **6a** ($R^1$ = H) is formed exclusively with the cis olefin geometry as the consequence of a stereospecific formal [4 + 4] ene reaction.[11] The carbon–carbon bond formation proceeds with exceptionally high (>100:1) cis simple diastereoselection. Capillary gas chromatographic analysis of the crude reaction mixture shows that less than 0.2% of *trans*-cyclopentane isomers **8** or **9** is formed.



**1a** ($R^1$ = H)
**b** ($R^1$ = $CH_3$)

**4** **5**

**6a** ($R^1$ = H)
**b** ($R^1$ = $CH_3$)

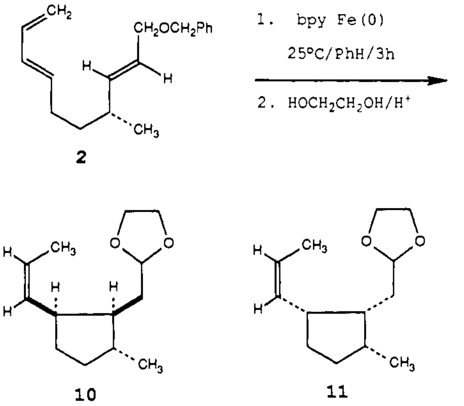
**7**

**8** **9**

(1)

The reaction selectivities observed in *bimolecular* iron-catalyzed reactions of 1,3-dienes are markedly influenced by the ligands coordinated to the iron catalyst and the diene substitution pattern but are relatively unaffected by the reaction medium.[4] In contrast, the regio- and stereoselectivity observed in the cyclization of **1a** is only modestly influenced by changing the ligand. For example, treatment of **1a** with the 1,10-phenanthrolene-modified catalyst phen·Fe(0) yields a mixture of all four cyclized products **6–9** in a 91:4:4:1 ratio. Similarly, further substitution on the diene moiety does not significantly affect the course of the cyclization. The 7-methyl substituted *E*,*E*-triene **1b** ($R^1$ = $CH_3$) smoothly cyclizes under the influence of the bpy·Fe(0) catalyst to yield **6b** ($R^1$ = $CH_3$; 66%) in greater than 93% isomeric purity. Changing the reaction solvent from benzene to a more strongly coordinating solvent such as THF, however, diverts the course of the reaction from the intramolecular ene pathway to predominantly (>95%) bimolecular diene-to-diene [4 + 4]- and [4 + 2]-cycloaddition pathways.

We have recently found that a remote coordinating ligand can be used to direct the stereochemical course of certain bimolecular iron-catalyzed ene couplings.[12] The 4-methyl-substituted *E*,*E*-triene **2** lacks a coordinating substituent yet undergoes iron-catalyzed carbocyclization with high stereoinduction enabling control of the relative stereochemistry between three contiguous asymmetric centers. Treatment of **2** with 15 mol % bpy·Fe(0) followed by acetalization yields a mixture of cyclopentanes in which isomer **10** comprises greater than 98% (62% overall, eq 2).[13]



**2**

**10** **11**

(2)

No other isomer accounts for more than 0.5% of the crude product mixture. Thus, the methyl-bearing stereocenter discriminates between the formation of diastereomers **10** and **11** with a minimum stereoinduction greater than 150:1.

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(6) A preliminary account of this work: Takacs, James M.; Anderson, Lawrence G. *Abstract of Papers*, 192nd National Meeting of the American Chemical Society, Anaheim, CA; American Chemical Society: Washington, DC; ORGN 46.

(7) Morrison, J. D. *Asymmetric Synthesis*; Academic: New York, 1984; Vol. 3, Part B, pp 111–212.

(8) (a) (2*E*,7*E*)-Decatrienes **1** and **2** were synthesized from δ-valerolactone and α-methyl-δ-valerolactone, respectively, via a five-step conversion to the (*E*)-1-(benzyloxy)hept-2-en-7-ol derivative [(1) Li[$(EtO)_2P(O)CHCO_2Et$]/1.0 DIBAL/THF/–78 °C/83%; (2) TBDMSCl/$Et_3N$/DMAP/$CH_2Cl_2$/99%; (3) 2.2 DIBAL/THF/0 °C/69%; (4) (a) BuLi/THF/–78 °C, (b) $PhCH_2Br$/THF/HMPA/25 °C, (c) MeOH/TsOH/66%] followed by PCC oxidation and olefination [(1) PCC/$CH_2Cl_2$/$NaHCO_3$; (2) Li[$CH_2{=}C(R')CHP(O)Ph_2$]/THF/HMPA/–78 to 25 °C/70%].[9] (b) (2*Z*,7*E*)-Undecatriene **3** was synthesized from propargyl alcohol via alkylation to 1-(benzyloxy)-7-(tetrahydropyranyl)hept-2-yn-7-ol [(1) (a) *n*-BuLi/THF/HMPA, (b) $THPO(CH_2)_4I$/–78 to 25 °C/73%; (2) (a) *n*-BuLi/THF/–78 °C, (b) $PhCH_2Br$/THF/HMPA/25 °C/82%] followed by semihydrogenation, deprotection, and then olefination as described above [(1) $H_2$(Pd–$BaSO_4$–$PbCO_3$/$CH_3OH$/79%; (2) MeOH/catalyst TsOH/85%; (3) PCC/$CH_2Cl_2$/$Na_2CO_3$; (4) Li[$CH_2{=}CHCHP(O)Ph_2$]/THF/HMPA/–78 to 25 °C/1 h/64%].

(9) (a) Takacs, J. M.; Helle, M. A.; Seely, F. L. *Tetrahedron Lett.* **1986**, *27*, 1257–1260. (b) Ukai, J.; Ikeda, Y.; Ikeda, N.; Yamamoto, H. *Tetrahedron Lett.* **1983**, *24*, 4029–4032.

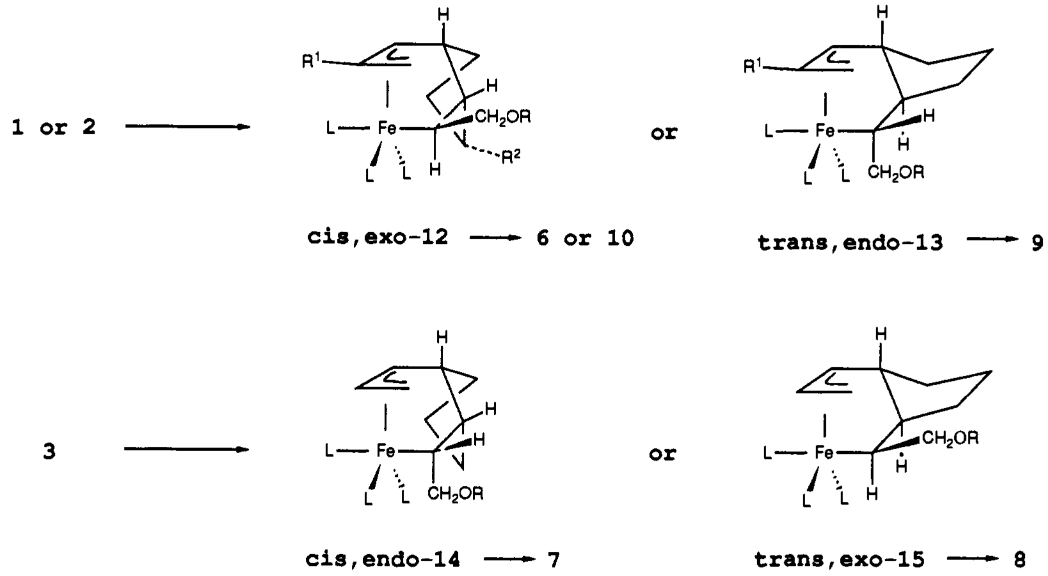
(10) A benzene solution (5–10 °C) of iron(III) acetylacetonate containing 1.1 equiv of 2,2′-bipyridine and 10 equiv of furan is reduced by 3.1 equiv of $Et_3Al$ to yield a solution of catalytically active "bpy·Fe(0)". This catalyst preparation is analogous to those that we have previously described: see ref 4. Furan is an unreactive diene that we employ to keep the bpy·Fe(0) catalyst soluble in the absence of substrate. The facile intramolecular reaction is surprising in light of our previous observations on the bpy·Fe(0)-catalyzed bimolecular cross-coupling reactions of certain monosubstituted 1,3-dienes and substituted allylic ethers. Those 1,3-dienes substituted in the 4-position (i.e., 1,3-octadiene or 1-cyclohexyl-1,3-butadiene) fail to undergo coupling to allyl benzyl ether under our normal reaction conditions (bpy·Fe(0), PhH, 25 °C, 12 h). Similarly, *trans*-2-butenyl benzyl ether is unreactive toward coupling to isoprene under these conditions.

(11) The stereochemical assignments are based upon ozonolysis of **6a** [(1)$O_3$/$CH_2Cl_2$/–78 °C; (2) $Me_2S$] and base-catalyzed epimerization (*i*-$Pr_2NEt$/DMF/100 °C) of the resulting product to the more stable *trans*-cyclopentane carboxaldehyde. Isomers **6** and **7** yield a single product after hydrogenation (5% Pd on C/$CH_2OH$/1 atm of $H_2$).

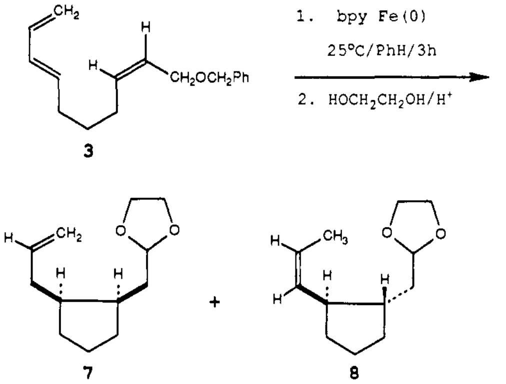
(12) Takacs, J. M.; Anderson, L. G.; Newsome, P. W. *J. Am. Chem. Soc.* in press.

(13) The stereochemical assignment of **10** was confirmed by conversion to the *trans*-1,3-dimethylcyclopentane derivative via the following sequence: (1) ozonolysis and reductive workup to the alcohol [(1) $O_3$/$CH_2Cl_2$/–78 °C; (2) $NaBH_4$/$CH_3OH$]; (2) tosylation (TsCl/Pyr/$CH_2Cl_2$); (3) lithium triethylborohydride reduction ($LiEt_3BH$/THF/0 °C).

**Scheme I.** Possible Diastereomeric Intermediates Formed in the Cyclizations of Trienes 1-3



On the basis of our previous mechanistic studies, we anticipated that changing the geometry of the olefin at the 2-position of triene **1** might enable us to exercise a degree of stereocontrol in the cyclization. Accordingly, the 2*Z*,7*E*-triene ether **3** was prepared starting from propargyl alcohol.[8] The bpy·Fe(0)-catalyzed carbocyclization yields after acetalization a 96:4 mixture of two isomeric cyclopentanes (eq 3). The major product **8** is again a formal [4 + 4] ene product but now is the isomer possessing the trans relative stereochemistry. The minor component is the cis [4 + 2] ene product **7**. Less than 0.2% of the cis [4 + 4] isomer **6** is produced. Thus either *cis*- or *trans*-cyclopentane derivatives can be prepared with high selectivity depending upon the choice of starting olefin geometry.



(3)

It has been previously noted that transannular-cyclization processes often proceed with higher stereo- and regioselectivity than simple cyclization processes.[14] The cyclizations of triene ethers **1-3** proceed via the transannular carbon-carbon bond-forming oxidative-coupling reaction of a chelated L·Fe(0)-(diene olefin) complex.[4] The unusual regio- and diastereoselectivity that we observe in the reactions of **1-3** can be accounted for by the selective formation of intermediates **12** ($R^1$, $R^2$ = H, $CH_3$) and **15**. These results suggest an apparent preference for pseudo-exo orientation of the benzyloxymethyl group during the five-membered ring formation (Scheme I). The stereoinduction observed in the cyclization of **2** can be rationalized by placing the methyl substituent ($R^2$) in the least sterically encumbered position in the intermediate *cis*, *exo*-**12**. Further mechanistic studies and synthetic applications of this new catalytic carbocyclization procedure are in progress.

**Acknowledgment.** We thank the National Institutes of Health (GM 34927), the donors of the Petroleum Research Fund, administered by the American Chemical Society, and the University of Utah Research Committee for generous support of this work. We thank Mark W. Creswell and Beckie E. Takacs for assistance in preparing the triene ethers. NMR spectra were obtained by using 300-mHz spectrometers purchased with funds provided by National Science Foundation and Department of Defense Instrumentation Grants.

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[14] Delongschamp, P. *Aldrichimica Acta* **1984**, *17*, 59-65.

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## Resonance Raman Spectra of Colchicinoids: Free and Bound to Tubulin

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Colchicine binds specifically and with high affinity to tubulin, the major protein subunit of microtubules. The colchicine-tubulin complex substoichiometrically inhibits normal assembly of tubulin into microtubules, resulting in interference with or cessation of normal microtubule-mediated processes, including cell motility, secretion, and growth.[1] The colchicine-tubulin interaction has been extensively investigated since its discovery by Taylor and co-workers in the mid 1960s;[2] however, an understanding of the interaction on a molecular level remains elusive. Two different mechanisms have been proposed to describe the colchicine-tubulin interaction. The first, focusing primarily on the kinetic and spectroscopic features of the association, proposes that a boat-boat interconversion in the colchicine C ring occurs upon binding to tubulin.[3] The second mechanism, based on thermodynamic data, describes colchicine binding in terms of the binding of a bifunctional ligand to two subsites of the protein, requiring protein but

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[1] For reviews of the colchicine-tubulin interaction, see: (a) Capraro, H. G.; Brossi, A. In *The Alkaloids*; Brossi, A., Ed.; Academic: New York, 1984; Vol. 23, pp 1-70. (b) Luduena, R. F. In *Microtubules*; Roberts, K., Hyams, J. S., Eds.; Academic: New York, 1979; pp 66-166.

[2] Weisenberg, R. C.; Borisy, G. G.; Taylor, E. W. *Biochemistry* **1968**, *7*, 4466 and references therein.

[3] Detrich, H. W., III; Williams, R. C., Jr.; Macdonald, T. L.; Wilson, L.; Puett, D. *Biochemistry* **1981**, *21*, 5999.