

in the synthesis of **2**. Attachment of the isoprenyl equivalents **5** and **6** was then accomplished in one operation¹² by treatment of the chloro ketone **8a** with 1 equiv of 1-lithio-2-methyl-1,3-butadiene (**9**)¹³ at $-78\text{ }^{\circ}\text{C}$ which effected 1,2-addition after which an excess of lithium isopropenyl acetylide (**10**) was added and the mixture was heated in order to induce pinacol rearrangement and subsequent alkynylidene addition to the transiently liberated carbonyl. Addition of LiAlH_4 to the resultant mixture (at $0\text{ }^{\circ}\text{C}$) proceeded with reduction of the alkyne and produced upon workup **3a** as a single isomer (57%). Similarly, chloro ketone **8b** was converted to a single bis-isoprenyl isomer (**3b**) in 61% yield (Scheme II).

At this point in the synthesis, all 20 carbons required for the cembrane skeleton were assembled in three operations and the stage was set for a test of the crucial macroexpansion step. Exposure of **3a** and **3b** separately to KH and 18-crown-6 ether in THF at room temperature for 2 h afforded upon workup crystalline ketone **2** (mp $62\text{--}62.5\text{ }^{\circ}\text{C}$; 48% and 55% yields, respectively) as the only 14-membered ring product. The stereochemistry of the olefinic units in **2** was established through two-dimensional homonuclear *J*-correlation spectroscopy (2D COSY NMR)¹⁴ and difference NOE experiments. The observed enhancements were found to correlate well with internuclear distances in the conformer of **2** (Figure 1) obtained by energy minimization using the MMPI force field.¹⁵

Completion of the synthesis from the cembranoid **2** proved to be straightforward, requiring only removal of the oxygen at C-5, selective hydrogenation of the C-13,C-14 double bond, and deprotection of the C-1 isopropenyl group. Since ketone **2** was found to slowly isomerize in solution, it was first reduced¹⁶ to the more stable alcohol **11** which was selectively hydrogenated over PtO_2 catalyst to give trienol **12**. Completion of the C-5 deoxygenation was then accomplished by conversion of **12** to its C-5 acetate and reduction of the latter to produce triene **13**. The stereo and positional integrity of the C-3,C-4 double bond was established by CMR and 2D COSY PMR spectroscopy and by ozonolysis of **13** which produced ketoaldehyde **14** identical with a sample obtained from ozonolysis of *O*-methyl terpineol. Finally, treatment of **13** with acetyl mesylate¹⁷ resulted in liberation of the C-1 isopropenyl group to provide (-)-(3*Z*)-cembrene A (**1**; mp $33\text{--}33.5\text{ }^{\circ}\text{C}$; $[\alpha]_D^{20} -128.3^{\circ}$ (MeOH, 0.63)).¹⁸ The ^1H and ^{13}C NMR and IR spectra of this sample were identical with those previously reported.^{3,19} Moreover, **1** obtained in this work and an authentic sample from the secretion of *Cubitermes umbratus*²⁰ exhibited the same retention times by capillary column (50 meter) gas chromatography using SE-54 and OV-1 stationary phases.

In summary, this study establishes a straightforward synthesis (eight steps) of (-)-(3*Z*)-cembrene A and, more generally, marks

a fundamentally new approach to the preparation of chiral cembranoids and macrocycles from common ring precursors. The availability of **2**, possessing the complete cembrane skeleton, in only four steps from commercially available starting materials provides a point of divergence for other syntheses of chiral members of this class. Further studies are in progress.

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Supplementary Material Available: Spectroscopic and analytical data for key compounds **2** and **11–13** along with tables on the correlation of NOE data and calculated (MMPI) internuclear distances and on the correlation of coupling constants and calculated (MMPI) dihedral angles for compound **2** (3 pages). Ordering information is given on any current masthead page.

Metalloketene Formation by Insertion of Carbon Suboxide into Tungsten and Rhenium Metal-Hydride Bonds

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Of the four stable oxides of carbon, only CO and CO_2 have received serious attention from chemists with regard to their reactivities with the transition metals. In light of the wealth of chemistry associated with these simple carbon oxides, we are investigating the organometallic chemistry of carbon suboxide, $\text{O}=\text{C}=\text{C}=\text{O}$.¹ Surprisingly, this aspect of C_3O_2 chemistry has been virtually neglected,² even though extensive studies of its organic and physical chemistries have shown it to be a remarkably reactive molecule.³ One research area holding particular interest for us concerns the interaction of C_3O_2 with other ligands coordinated to metal centers, especially hydrides. Since allenes⁴ and heterocumulenes (like carbon dioxide,⁵ isocyanates,⁶ and carbodiimides⁷) often participate in insertion reactions with metal hydrides, it seemed reasonable that similar insertions might occur with C_3O_2 to provide access to a new class of reactive ligands of the general type " HC_3O_2 ". Furthermore, the hydridic or protic nature of the particular metal hydride might determine whether the hydrogen is delivered to C-1 (favored for hydridic M-H species) or C-2 (favored for protic M-H complexes),⁸ thus giving

(12) For related work, see: Holt, D. A. *Tetrahedron Lett.* **1981**, 22, 2243 and ref 1b and 5.

(13) Prepared by reaction of *n*-BuLi with (*E*)-1-iodo-2-methyl-1,3-butadiene in THF or Et_2O at $-78\text{ }^{\circ}\text{C}$. This stereo- and regiochemically pure iodide was prepared by zirconium-catalyzed methylalumination of vinylacetylene according to the procedure of: Negishi, E.; Van Horn, D. E.; King, A. O.; Okukado, N. *Synthesis* **1979**, 501. The reaction of **9** with **8a** or **8b** resulted in 1,2 addition to the carbonyl and deprotonation. Enolate intermediates resulting from the latter process survived the subsequent reaction conditions and gave upon workup chloro ketones **8a,b** as a 1:3 mixture.

(14) For a recent and related use of this technique and lead references, see: Lynn, D. G.; Graden, D. W. *J. Am. Chem. Soc.* **1984**, *106*, 1119.

(15) For a review, see: Allinger, N. L.; Burkert, U. *ACS Monogr.* **1982**, *177*.

(16) Gemal, A. L.; Luche, J. L. *J. Am. Chem. Soc.* **1981**, *103*, 5454.

(17) Karger, M. H.; Mazur, Y. J. *Org. Chem.* **1971**, *36*, 532.

(18) An attempt to determine the sign of rotation of natural material produced a positive rotation, but due to the small sample size and its purity, the value was considered too uncertain for publication (Professor Weimer, personal communication, University of Iowa). When taken with our results, a positive rotation for the natural material would require that it have an *S* configuration.

(19) The originally reported data contained some ^{13}C NMR and ^1H NMR values which have since been corrected (reference 3b). We thank Professor Weimer (University of Iowa) for the proton and carbon NMR spectra of natural material.

(20) We thank Professor G. Prestwich (SUNY-Stony Brook) for this mixture.

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(2) Literature concerning the interactions of C_3O_2 with transition-metal complexes: (a) Kolomnikov, I. S.; Koreskov, Yu. D.; Lobeeva, T. S.; Vol'pin, M. E.; *Izv. Akad. Nauk SSSR, Ser. Khim.* **1972**, 1132. (b) Paiaro, G.; Pandolfo, L. *Angew. Chem., Int. Ed. Engl.* **1981**, *20*, 288. (c) Paiaro, G.; Pandolfo, L. *Ibid.* **1981**, *20*, 289. (d) Paiaro, G.; Pandolfo, L.; Segala, P. *Congr. Naz. Chim. Inorg., [Atti]*, *12th 1979*, 77. (e) Pandolfo, L.; Paiaro, G.; Valle, G.; Ganis, P. *Gazz. Chim. Ital.* **1985**, *115*, 59. (f) Pandolfo, L.; Paiaro, G.; Valle, G.; Ganis, P. *Ibid.* **1985**, *115*, 65. (g) Pandolfo, L.; Paiaro, G. *J. Mol. Catal.* **1984**, *27*, 343.

(3) For recent reviews describing the physical^{2a} and organic^{2b} chemistries of C_3O_2 , see: (a) "Gmelins Handbuch der Anorganischen Chemie"; Verlag-Chemie: Weinheim, 1970; Kohlenstoff, C, Section I, Syst. No. 14, pp 75 ff. (b) Kappe, T.; Jiegler, E. *Angew. Chem., Int. Ed. Engl.* **1974**, *13*, 491.

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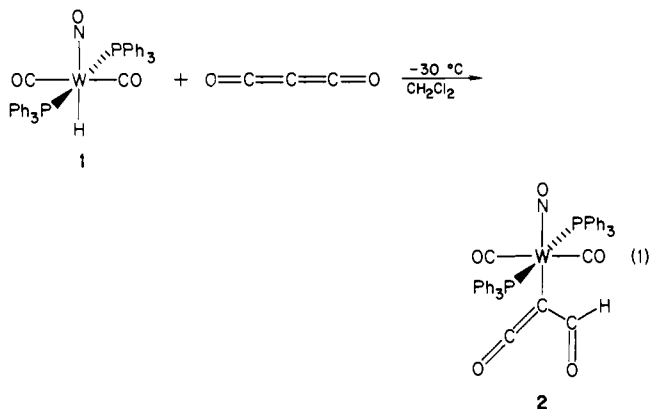
(5) (a) Palmer, D. A.; van Eldik, R. *Chem. Rev.* **1983**, *83*, 651. (b) Darensbourg, D. J.; Kudasoski, R. A. *Adv. Organomet. Chem.* **1983**, *22*, 129.

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access to a variety of ligand types.

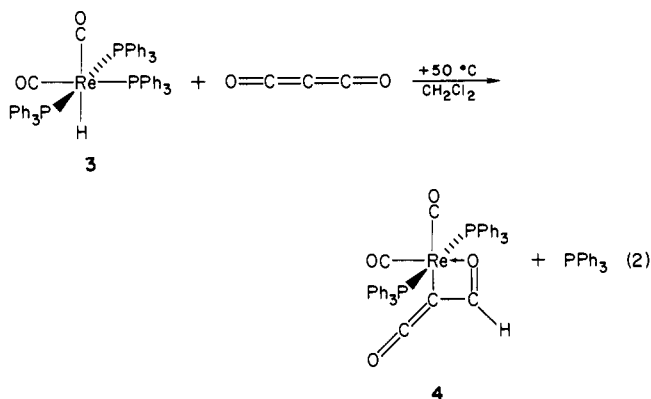
Carbon suboxide (1 equiv) reacts at $-30\text{ }^{\circ}\text{C}$ in a smooth, clean fashion with the tungsten(0) hydrido complex *trans,trans*- $\text{W}(\text{CO})_2(\text{NO})(\text{PPh}_3)_2$ (**1**)⁹ to afford the product of a formal 1,2-hydride insertion, *trans,trans*- $\text{W}\{\text{C}(\text{CHO})\text{CO}\}(\text{CO})_2(\text{NO})(\text{PPh}_3)_2$ (**2**), as red-orange, air-sensitive microcrystals in $\sim 70\%$ yield (eq 1).¹⁰ The formulation of **2** as a novel formylketenido complex



of tungsten follows from the characteristic infrared and multinuclear NMR spectra of **2** and the isotopomers **2-d** (prepared from $\text{W}(\text{CO})_2(\text{NO})(\text{PPh}_3)_2$ and C_3O_2) and **2-¹³C** (prepared from $\text{O}=\text{C}=\text{C}=\text{C}=\text{O}$ and **1**).¹¹ The newly formed ketenido ligand exhibits the expected infrared absorptions at 2068 cm^{-1} (ν_{CCO}) and $2744, 1605\text{ cm}^{-1}$ ($\nu_{\text{CH}}, \nu_{\text{CO}}$) for its ketene and aldehyde subunits, respectively.¹⁰ The ^1H NMR spectrum of **2** boasts a new singlet resonance at $\delta 8.82$, which is absent in the spectrum of **2-d**. Moreover, the magnitude of the coupling constant between the labeled carbon and the unique proton in **2-¹³C**, 23.4 Hz , is in the range observed for $^2J_{\text{CH}}$ in other common aldehydes.¹² Finally, the chemical shift value for the labeled carbon and the magnitudes of its coupling constants to tungsten and phosphorus in the ^{13}C NMR spectrum of **2-¹³C** ($\delta 45.8$; $^2J_{\text{CP}} = 5$, $^1J_{\text{CW}} = 50.1\text{ Hz}$) are in accord with the ligand being attached to tungsten through its central carbon atom and the proton residing on an adjacent carbon.^{10,13} The overall *trans, trans* geometry of the carbonyl and phosphine ligands in **1** is maintained in **2**, as judged by infrared and ^{31}P NMR spectrometry.¹⁰

The reaction between C_3O_2 and *cis,mer*- $\text{ReH}(\text{CO})_2(\text{PPh}_3)_3$ (**3**)¹⁴ follows a slightly different course than that described above for the isoelectronic tungsten system. Reaction between **3** and C_3O_2 occurs only at elevated ($50\text{ }^{\circ}\text{C}$) temperatures over a period of

several hours to give yellow *cis,trans*- $\text{Re}\{\text{C}(\text{CHO})\text{CO}\}(\text{CO})_2(\text{PPh}_3)_2$ (**4**, *cis* carbonyls, *trans* phosphines) and free triphenylphosphine (eq 2).¹⁰ It is noteworthy that insertion of C_3O_2 is



a much more facile reaction for **1** than for **3**, an observation consistent with a required precoordination of the suboxide to the metal centers before the H-transfer step. Since **1** possesses intrinsic coordinative unsaturation due to the amphoteric nature of its nitrosyl ligand, an *associative* mechanism involving bending of the nitrosyl followed by coordination of C_3O_2 then rapid H-transfer and nitrosyl straightening is a reasonable one; loss of a coordinated ligand is not required. An analogous pathway is precluded for **3**, thus *dissociation* of one of the PPh_3 ligands is a necessary prerequisite for C_3O_2 coordination and subsequent insertion. This scenario implies formation of a coordinatively unsaturated rhenium formylketenido complex, but the metal's electronic requirements can be satisfied simply by chelation of the ligand's otherwise pendent formyl carbonyl to give **4**.¹⁵

The infrared spectrum of **4** clearly shows ν_{CCO} as a very strong absorption at 2080 cm^{-1} , and the mutually *cis* stereochemistry of the carbonyls about rhenium is indicated by two very strong bands of equal intensity at 1933 and 1859 cm^{-1} ; a medium-intensity band corresponding to a ring CCO stretch (cf. the analogous OCO modes in formate complexes) is observed at 1516 cm^{-1} . The ^{31}P NMR spectrum of **4** consists of a single sharp resonance, defining a mutually *trans* disposition of the two phosphine ligands (required if the formylketenido ligand is chelating). Finally, the resonance for the unique proton in the ^1H NMR spectrum of **4** provides the key evidence in support of this chelating structure: *the resonance appears as the expected triplet* ($\delta 9.04$, $^4J_{\text{PH}} = 1.9\text{ Hz}$).¹⁶

We are currently investigating the reactions of carbon suboxide with other transition-metal hydrides, including some that have acidic character, to explore the scope of its insertion reactions.

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Supplementary Material Available: Detailed experimental, spectral, and physical data for **2** and **4** (1 page). Ordering information is given on any current masthead page.

(15) Under similar reaction conditions with $\text{ReH}(\text{CO})_3(\text{PPh}_3)_2$, which contains neither an easily dissociable ligand nor a nitrosyl ligand, only decomposition of carbon suboxide is observed (probably a thermal reaction) and the rhenium complex can be recovered from solution unchanged.

(16) This long-range P-H coupling is *very* characteristic of four-membered



planar metallacycles having phosphine ligands located "cis" to the ring plane (typical coupling values are $1.5\text{--}2.5\text{ Hz}$). Such complexes having PR_3 ligands in the plane of the metallacycle ("trans" to the chelate) exhibit larger coupling constants (ca. 6.5 Hz). Unidentate M-XCHY species do not show this long-range coupling (i.e., complex **2**).⁷

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(9) (a) Hillhouse, G. L.; Haymore, B. L. *J. Organomet. Chem.* **1978**, *162*, C23. (b) **1** is prepared by treating THF solutions of $[\text{W}(\text{CO})_5(\text{NO})(\text{PPh}_3)_2][\text{PF}_6]$ with NaBH_4 in the presence of PPh_3 . Hillhouse, G. L.; Haymore, B. L., manuscript in preparation.

(10) For **2** and **4**: synthetic details, NMR (^1H , ^{13}C , ^{31}P) and IR data, and elemental analyses are given in the supplementary material.

(11) Stable silyl-substituted vinyl ketenes are known,^{11a,b} as are those stabilized by coordination of the diene moiety to metal fragments.^{11c-8} The complexes reported herein, however, represent the first stable examples of formylketenido complexes of transition metals. (a) Dötz, K. H. *Angew. Chem., Int. Ed. Engl.* **1979**, *18*, 954. (b) Dötz, K. H.; Fügen-Köster, B. *Chem. Ber.* **1980**, *113*, 1449. (c) King, R. B. *Inorg. Chem.* **1963**, *2*, 642. (d) Mitsudo, T.-A.; Sasaki, T.; Watanabe, Y.; Takegami, Y.; Nishigaki, S.; Nakatsu, K. *J. Chem. Soc., Chem. Commun.* **1978**, 252. (e) Hill, A. E.; Hoffmann, H. M. R. *Ibid.* **1972**, 574. (f) Newton, M. G.; Pantaleo, N. S.; King, R. B.; Chu, C.-K. *Ibid.* **1979**, 10. (g) Binger, P.; Cetinkaya, B.; Krüger, C. *J. Organomet. Chem.* **1978**, *159*, 63.

(12) For example, $^2J_{\text{CH}} = 26.6\text{ Hz}$ in CH_3CHO . Levy, G. C.; Nelson, G. L. "Carbon-13 Nuclear Magnetic Resonance for Organic Chemists"; Wiley-Interscience: New York, 1972; pp 127-128.

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