atoms in the core $[Mn_3O_4]^{4+}$, using the spin coupling model without the zero-field splitting (zFS) effect, is noteworthy: J values are so large that the ground state is a real spin doublet. There is general agreement[12,14,15] on a $S = {}^1/_2$ origin of the multiline EPR signal observed for the S_2 state[11] of the OEC. A detailed study[13] showed that the g-anisotropy of this signal was very small and proved the $S = {}^1/_2$ nature of the state implied. Recently[16] it was demonstrated that anisotropy in the OEC signal arises from anisotropy in the hyperfine coupling. Our result strongly suggests that this OEC signal could be interpreted on the basis of spin coupling as suggested earlier by some authors[14,15] with anisotropic effects treated as perturbation only. We are working on simulations of the OEC signal along those lines.

A cubane-type structure of the OEC was proposed by Brudvig[12] and Christou;[2,3] a distorted cubane structure and a structure made of a manganese triangle linked to a manganese atom were proposed recently[9] for the S_1 state. Such a 3 + 1 structure of the copper cluster in ascorbate oxidase (which catalyzes the reverse reaction of OEC) was found through X-ray diffraction by Huber,[17] who also proposed that the OEC could have a 3 + 1 arrangement of the manganese atoms. Our result shows that manganese–oxo triangular units exist. We are investigating the possibility of assembling this $Mn(IV)_3$ entity with a Mn(III) ion.

Acknowledgment. M.C. has benefited from a grant from Spain and CNRS (France).

Supplementary Material Available: Tables of positional parameters for non-H and H atoms, anisotropic and isotropic thermal parameters, and main interatomic distances and angles for **1** (6 pages); table of observed and calculated structure factors for **1** (13 pages). Ordering information is given on any current masthead page.

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(12) de Paula, J. C.; Beck, W. F.; Brudvig, G. W. *J. Am. Chem. Soc.* **1986**, *108*, 4002–4009.

(13) Hansson, O.; Aasa, R.; Vanngard, T. *Biophys. J.* **1987**, *51*, 825–832.

(14) Dismukes, G. C.; Siderer, Y. *Proc. Natl. Acad. Sci. U.S.A.* **1981**, *78*, 274–278.

(15) Hansson, O.; Andrēasson, L.-E. *Biochim. Biophys. Acta* **1982**, *679*, 261–268.

(16) Haddy, A.; Aasa, R.; Andrēasson, L.-E. *Biochemistry* **1989**, *28*, 6954–6959.

(17) Huber, R. *Angew. Chem., Int. Ed. Engl.* **1989**, *28*, 848–869.

Diastereoselective Reduction of 9-Oxo-13-tetradecanolide and 10,10-Dimethyl-9-oxo-13-tetradecanolide

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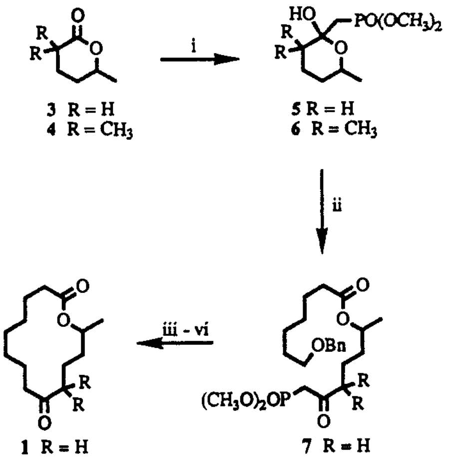
In 1981 Still and Galynker[1a] reported the stereoselective alkylations of a number of monosubstituted 8–12-membered-ring ketones and lactones. Invariably these reactions proceeded with high selectivity, to yield one of the two possible diastereomeric products. In order to rationalize the high diastereoselectivity of these reactions, Still and co-workers[1] used MM2 calculations.[2] The model that emerged from these studies[1] assumed that attack of a reagent from the more open face of the macrocycle gave rise to product ratios that were closely related to the conformational energies of the starting materials or intermediates (for an early transition state) or to the products themselves (for a late transition state).

Scheme I[a]



[a] (i) $CH_3PO(OCH_3)_2$, 2 equiv of BuLi, THF, −78 °C; (ii) $BnO(CH_2)_6COOH$, DCC, DMAP, DMF; (iii) H_2, 10% Pd/C, EtOH; (iv) DCC, DMSO, $Cl_2HCCOOH$; (v) K_2CO_3, 18-crown-6, toluene; (vi) H_2, 10% Pd/C, EtOH.

Table I. Reduction of 9-Oxo-13-tetradecanolide (**1**) with Various Reducing Agents

			stereoselectivity	
reducing agent	yield, %	temp, °C	**9** (R^*,S^*)	**10** (S^*,S^*)
$NaBH_4$	89	−78	50	50
K-Selectride	89	−78	78	22
L-Selectride	85	0	80	20
L-Selectride	93	−78	89	11
LS-Selectride	85	−78	90	10
predicted selectivity	(MM2)	−78	94	6
MAD	63	−78	30	70

More recently, a slightly different approach was used to rationalize the diastereoselective reactions of cyclodecenes. Vedejs and co-workers[3] eliminated the need for a full conformational analysis of the starting material or product by concentrating only on the immediate environment of the functional group. This local conformer approach has been very successful in rationalizing conformationally controlled epoxidations and osmylations.

We have been interested in studying the reactivity of 14-membered lactones[4] with the hope of developing a model[4c] to rationalize and eventually predict the stereoselective reactions in these ring systems. This communication reports our results on the reductions and conformational properties of 9-oxo-13-tetradecanolide (**1**) and 10,10-dimethyl-9-oxo-13-tetradecanolide (**2**).

Our starting materials for this study, macrolides **1** and **2**, were synthesized in 22% and 20% overall yields, respectively, starting from lactones **3**[5] and **4**, by the sequence outlined in Scheme I.[6] δ-Lactone **4** is available from 2,2-dimethyl-5-oxohexanoic acid[7] through sodium borohydride reduction.

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(1) (a) Still, W. C.; Galynker, I. *Tetrahedron* **1981**, *37*, 3981. (b) Still, W. C.; MacPherson, L. J.; Harada, T.; Callahan, J. F.; Rheingold, A. L. *Tetrahedron* **1984**, *40*, 2275. (c) Still, W. C. *Curr. Trends Org. Synth., Proc. Int. Conf. 4th* **1983**, 233.

(2) Burkert, U.; Allinger, N. L. *Molecular Mechanics*; ACS Monograph 177, American Chemical Society: Washington, DC, 1982.

(3) (a) Vedejs, E.; Gapinski, D. M. *J. Am. Chem. Soc.* **1983**, *105*, 5058. (b) Vedejs, E.; Dolphin, J. M.; Gapinski, D. M.; Mastalerz, H. *Curr. Trends Org. Synth., Proc. Int. Conf., 4th* **1983**, 221. (c) Vedejs, E.; Dent, W. H.; Gapinski, D. M.; McClure, C. K. *J. Am. Chem. Soc.* **1987**, *109*, 5437.

(4) (a) Neeland, E. G.; Ounsworth, J. P.; Sims, R. J.; Weiler, L. *Tetrahedron Lett.* **1987**, *28*, 35. (b) Ferreira, J. T. B.; Neeland, E. G.; Ounsworth, J. P.; Weiler, L. *Can. J. Chem.* **1987**, *65*, 2314. (c) Keller, T. H.; Neeland, E. G.; Rettig, S.; Trotter, J.; Weiler, L. *J. Am. Chem. Soc.* **1988**, *110*, 7858. (d) Keller, T. H. Ph.D. Thesis, University of British Columbia, June 1988.

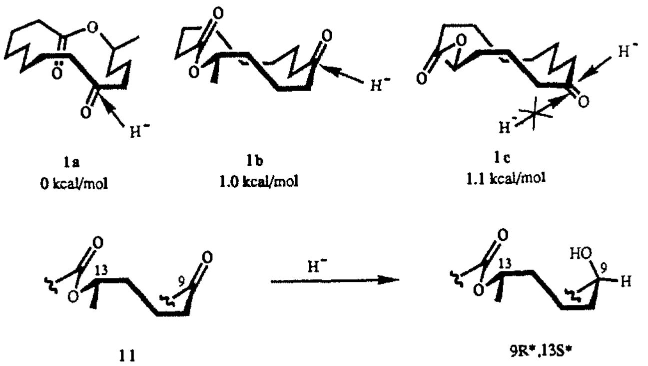
(5) Ansell, M. E.; Emmet, J. C.; Coombs, R. V. *J. Chem. Soc. C* **1968**, 217.

(6) All new compounds have been fully characterized spectroscopically and the elemental compositions established by microanalysis or high-resolution mass spectrometry.

(7) Cella, J. A. *Synth. Commun.* **1983**, *13*, 93.

0002-7863/90/1512-450$02.50/0

Scheme II

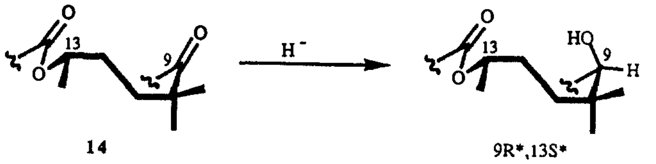


Treatment of macrolide **1** with sodium borohydride in methanol at −78 °C produced an equal mixture of diastereomeric alcohols **9** and **10** in 89% yield. The two isomers were easily separated by column chromatography, and the relative stereochemistry of the substituents was determined by X-ray crystallography of alcohol **10**.[8] On the assumption that sodium borohydride was too small to distinguish between the two diastereotopic faces of the keto group, we turned our attention to bulkier reducing agents. Reaction of **1** with potassium tri-*sec*-butylborohydride (K-Selectride) at −78 °C provided a 78:22 mixture of 9 and **10** in 89% yield. Similar reductions with lithium tri-*sec*-butylborohydride (L-Selectride) and lithium trisiamylborohydride (LS-Selectride) provided the two diastereomeric alcohols with even greater selectivity. Both reactions proceeded in excellent yield, furnishing **9** and **10** in ratios of 89:11 and 90:10, respectively (see Table I). Ketone **1** was also reduced with methylaluminum bis(2,6-di-*tert*-butyl-4-methylphenoxide) (MAD)[9] and isopropylmagnesium bromide at −78 °C, to give the alcohols **9** and **10** in a ratio of 30:70.

To rationalize these interesting results, we examined the low-energy conformations of the starting materials, since previous work by Wu and Houk[10] suggested that only early transition states can satisfactorily account for the selectivities observed in nucleophilic additions to cyclohexanones. The complexity of the ^{1}H NMR spectrum of **1** did not allow a detailed analysis of the coupling constants, and we therefore resigned ourselves to a conformational analysis using a combination of MM2 calculations and X-ray crystallography.[4c] The three lowest energy conformations for macrolide **1** (**1a–c**), together with their relative strain energies (MM2), are shown in Scheme II. Surprisingly, the global minimum is a [3344][4c,11] conformation **1a**, followed by the [3434][4c,11] conformations.[12]

Still and co-workers[1] have demonstrated that reagents approach the π-system of a macrocyclic compound largely, or perhaps exclusively, from the peripheral face. This can be expected to occur in conformations **1a** and **1b**, since the carbonyl group is perpendicular to the plane of the macrocyclic ring, and therefore the *re* face of the carbonyl group in **1a** and **1b** is blocked by the carbon atoms in the macrocyclic ring. A complication arises because conformation **1c** has the ketone in a corner position[4c,11] where the steric environment of the *si* and the *re* faces are almost identical, so that **1c** presumably would give rise to an equal mixture of the two diastereomeric alcohols. Nevertheless, peripheral attack on the local conformation **11**, common to the two lowest energy conformations **1a** and **1b**, clearly should produce the 9*S**,13*R** alcohol **9** predominantly.

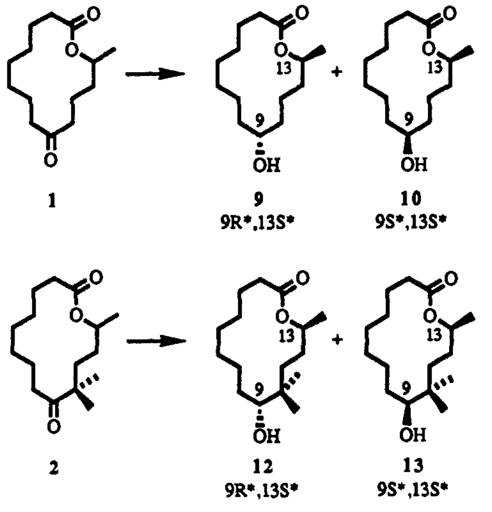
Scheme III



Still and co-workers[1] have also used Boltzmann distributions of the relevant conformations to predict the selectivity of a reaction. This approach is more complicated for the 14-membered macrolide under consideration, since it is difficult to estimate the reactivity of conformations with a ketone group in a corner position (e.g., **1c**). However, if exclusive peripheral attach is assumed for **1a** and **1b**, and equal attack on both faces of the carbonyl is allowed in **1c**, then a Boltzmann distribution of conformations **1a–c** leads to a predicted selectivity (at −78 °C) of **9**:**10** = 94:6. This is in good agreement with the diastereoselectivity observed in the reduction of **1** with LS-Selectride. This result indicates that sodium borohydride, as suspected, does not distinguish between the two faces of the keto group in **1a** and **1b**, while more bulky reducing agents react almost exclusively at the peripheral face of those two low-energy conformations and the stereochemistry can be reversed with the MAD reducing agents.

The stereoselectivity of the sodium borohydride reduction of **2** also was poor, yielding the two diastereomeric alcohols **12** and **13** in a ratio of 60:40. When **2** was treated with L-Selectride at −78 °C, no reduction product could be isolated even after several hours. However, when the temperature was raised to 0 °C, the reduction proceeded at an acceptable rate, to provide **12**[14] and **13** in a ratio of 89:11.

The conformational analysis of **2** is straightforward,[4d] since all conformations within 4 kcal/mol of the global minimum contain the same local conformation **14** (Scheme III). Peripheral attack of a reducing agent on **14** should lead predominantly to the formation of the (9*R**,13*S**)-10,10-dimethyl-9-hydroxy-13-tetradecanolide (**12**). The MM2 calculations therefore correctly predict the relative stereochemistry of the major isomer from the L-Selectride reduction.



In summary, we have shown that MM2 calculations can be successfully used to rationalize the outcome of stereoselective reactions in 14-membered macrolides. If a quantitative estimation of the product distribution is desired, a more rigorous conformational analysis is necessary.[12] However, our results suggest that many low-energy conformations of 14-membered rings share a common local conformation. The possibility of predicting the stereoselectivity of reactions in macrolides on the basis of a simple local conformation would be very attractive. We are currently

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[8] The crystallographic data for alcohol **10** has been published in ref 4c.

[9] Maruoka, K.; Itoh, T.; Sakurai, M.; Nonoshita, K.; Yamamoto, H. *J. Am. Chem. Soc.* **1988**, *110*, 3588.

[10] Wu, Y. D.; Houk, K. N. *J. Am. Chem. Soc.* **1987**, *109*, 908.

[11] Dale, J. *Acta Chem. Scand.* **1973**, *27*, 1115, 1130.

[12] Recently we have carried out a much more extensive search of the conformations of keto lactone **1** using a Monte Carlo method.[13] These calculations suggest that the keto lactone **1** has approximately 240 conformations within 4 kcal/mol of the lowest energy conformation, and 11 conformations within 1 kcal/mol of the lowest energy conformation. We are in the process of trying to deal with this added complexity from these calculations.

[13] Chang, G.; Guida, W. C.; Still, W. C. *J. Am. Chem. Soc.* **1989**, *111*, 4379.

[14] The relative stereochemistry of **12** was established by catalytic reduction (Pd/C, H_2, EtOH) of (9*R**,13*S**)-(7*E*)-10,10-dimethyl-9-hydroxy-7-tetradecen-13-olide.[4d]

extending this model to other 14-membered-ring compounds to determine the generality and predictive power of this approach.

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Disilene Complexes of Molybdenum and Tungsten

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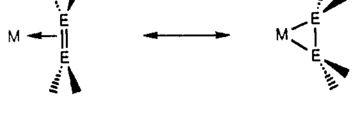
The stabilization afforded by coordination to transition metals has been exploited to prepare complexes of many reactive species that would otherwise have only brief lifetimes. Stable complexes of species such as carbon monosulfide,[1] benzynes,[2] and anti-Bredt olefins,[3] for example, have been isolated and characterized. Recently several researchers have explored the stabilization of unsaturated silicon species such as silenes ($R_2Si{=}CR'_2$)[4-6] and disilenes ($R_2Si{=}SiR_2$)[7] through the formation of transition-metal complexes. We now report the synthesis of molybdenum and tungsten complexes of a relatively unhindered disilene, Si_2Me_4, and the single-crystal X-ray structure determination of the tungsten complex.

The bonding of a disilene to a metal center can be expected to be similar to that of an organic olefin, which is best described by the Dewar-Chatt-Duncanson model.[8] In this model, synergistic σ and π interactions between the olefin p–π and π^* orbitals and metal orbitals of appropriate symmetry lead to a continuum of possible structures bounded by species containing formal sp^2 and sp^3 centers ("olefin complexes" and "metallacyclopropanes") as shown below.



The realization that the strong preference for sp^3 hybridization at silicon should lead to significant metallacyclic character in a disilene complex suggested to us that the synthesis of such complexes could be approached in the context of forming an MSi_2 ring, for example, by reductive dehalogenation of a precursor containing an X–M–Si–Si–X fragment. An analogous strategy has been used by Bennett and co-workers to synthesize a nickel benzyne complex.[2d] In the present work, synthesis of the group 6 metallocene derivatives $Cp_2M(Cl)(SiMe_2SiMe_2Cl)$ (M = Mo, W; Cp ≡ η^5-C_5H_5) was accomplished by treatment of $\{Cp_2MHLi\}_4$[9] with $ClSiMe_2SiMe_2Cl$,[10] followed by chlorination of the hydride with CCl_4 (eq 1). Reduction of $Cp_2M(Cl)(SiMe_2SiMe_2Cl)$ with Riecke magnesium in THF yields complexes with the stoichiometry $Cp_2M(SiMe_2)_2$ (M = Mo, **1a**, 67%; W, **1b**, 60%).[11]

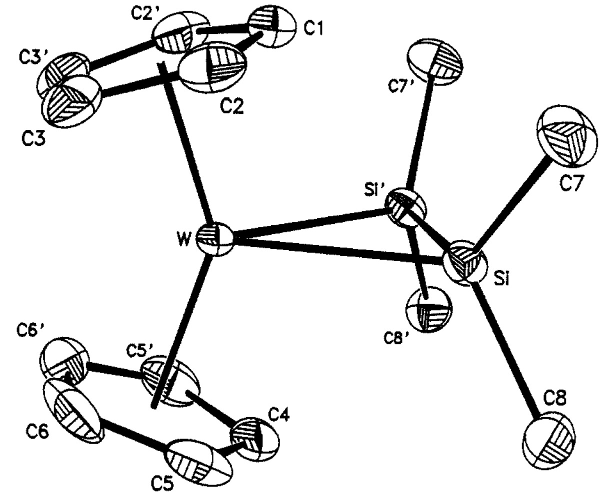
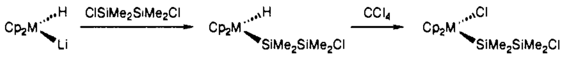
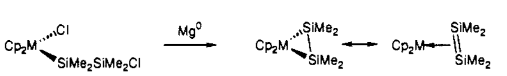


Figure 1. ORTEP drawing of $Cp_2W(SiMe_2)_2$ (**1b**) showing 30% probability thermal ellipsoids. Selected distances and angles: W–Si = 2.606 (2) Å; Si–Si′ = 2.260 (3) Å; Si–C7 = 1.889 (8) Å; Si–C8 = 1.898 (9) Å; Si–W–Si′ = 51.39 (6)°; W–Si–Si′ = 64.30 (7)°; Si–Si–C7 = 124.0 (3)°; Si′–Si–C8 = 120.3 (3)°.



$$Cp_2M\begin{smallmatrix}H\\ Li\end{smallmatrix} \xrightarrow{ClSiMe_2SiMe_2Cl} Cp_2M\begin{smallmatrix}H\\ SiMe_2SiMe_2Cl\end{smallmatrix} \xrightarrow{CCl_4} Cp_2M\begin{smallmatrix}Cl\\ SiMe_2SiMe_2Cl\end{smallmatrix} \qquad (1)$$



$$Cp_2M\begin{smallmatrix}Cl\\ SiMe_2SiMe_2Cl\end{smallmatrix} \xrightarrow{Mg^0} Cp_2M\begin{smallmatrix}SiMe_2\\ |\\ SiMe_2\end{smallmatrix} \longleftrightarrow Cp_2M\leftarrow\begin{smallmatrix}SiMe_2\\ \Vert\\ SiMe_2\end{smallmatrix} \qquad (2)$$

Compounds **1a** and **1b** exhibit nearly identical spectroscopic properties. The ^1H NMR spectra are quite simple, consisting of two singlets in a 5:6 ratio at ca. δ 3.9 and 0.6 attributed to Cp and SiMe protons, indicating highly symmetrical structures. A single resonance is observed in the ^{29}Si NMR (DEPT) spectra (**1a**, δ −20.3; **1b**, δ −48.1, $^1J_{^{183}W-^{29}Si}$ = 50.7 Hz). The one-bond W–Si coupling constant in **1b** is quite small compared to those for other tungsten silyl complexes such as $Cp_2W(H)(SiMe_2Cl)$ (117.6 Hz), $Cp_2W(H)(SiMe_3)$ (84.2 Hz), and $Cp_2W(Cl)(SiMe_2SiMe_2Cl)$ (83.0 Hz), indicating that the W–Si bonding in **1b** involves a high degree of p character on the Si_2 fragment and a relatively small contribution from the silicon s orbitals.

Recrystallization of the tungsten analogue from hydrocarbon solvents yielded well-formed prisms suitable for single-crystal X-ray diffraction studies. The molecular structure of **1b** and selected metrical data are presented in Figure 1.[12] The molecule sits on a crystallographic mirror plane, which contains the tungsten atom and bisects the Si–Si vector and each of the Cp rings. The geometry at tungsten is typical for a bent metallocene complex. The two silicon atoms subtend an angle of 51.39 (6)° at tungsten, and the Cp ring centroid–tungsten–Cp ring centroid angle is

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(1) See, for example: Broadhurst, P. V. *Polyhedron* **1985**, *4*, 1801.

(2) See, for example: (a) Buchwald, S. L.; Nielsen, R. B. *J. Am. Chem. Soc.* **1989**, *110*, 3171. (b) Erker, G. *Organometallics* **1985**, *4*, 1310. (c) Hartwig, J. F.; Andersen, R. A.; Bergman, R. G. *J. Am. Chem. Soc.* **1989**, *111*, 2717–2719. (d) Bennett, M. A.; Hambley, T. W.; Roberts, N. K.; Robertson, G. B. *Organometallics* **1985**, *4*, 1992–2000.

(3) Godleski, S. A.; Gundlach, K. B.; Valpey, R. S. *Organometallics* **1985**, *4*, 296–302.

(4) Campion, B. K.; Heyn, R.; Tilley, T. D. *J. Am. Chem. Soc.* **1988**, *110*, 7558–7560.

(5) (a) Randolf, C. L.; Wrighton, M. S. *Organometallics* **1987**, *6*, 365. (b) Lewis, C.; Wrighton, M. S. *J. Am. Chem. Soc.* **1983**, *105*, 7768.

(6) Berry, D. H.; Procopio, L. J. *J. Am. Chem. Soc.* **1989**, *111*, 4099–4100.

(7) (a) West, R. *Angew. Chem., Int. Ed. Engl.* **1987**, *26*, 1201–1211. (b) Pham, E. K.; West, R. *J. Am. Chem. Soc.* **1989**, *111*, 7667–7668.

(8) (a) Dewar, M. J. S. *Bull. Soc. Chim. Fr.* **1951**, *18*, C71. (b) Chatt, J.; Duncanson, L. A. *J. Chem. Soc.* **1953**, 2939.

(9) (a) Francis, B. R.; Green, M. L. H.; Luong-Thi, T.; Moser, G. A. *J. Chem. Soc., Dalton Trans.* **1976**, 1339–1345. (b) Bullock, R. M.; Headford, C. E. L.; Hennessy, K. M.; Kegley, S. E.; Norton, J. R. *J. Am. Chem. Soc.* **1989**, *111*, 3897.

(10) Ishikawa, M.; Kumada, M.; Sakurai, H. *J. Organomet. Chem.* **1970**, *23*, 63–69.

(11) Satisfactory elemental analyses were obtained for all new compounds. Experimental details are included in the supplementary material.

(12) A crystal of **1b** ($C_{14}H_{22}Si_2W$, fw 430.35) measuring 0.32 × 0.30 × 0.23 mm enclosed in a glass capillary was mounted on an Enraf-Nonius CAD-4 diffractometer, and cell parameters were determined: monoclinic space group $P2/1m$ ($Z = 2$), with $\beta = 116.22$ (1)°, $a = 7.713$ (1) Å, $b = 13.178$ (2) Å, $c = 8.211$ (1) Å. A total of 1781 unique reflections were measured ($4° \le 2\theta \le 55°$), of which 1665 with $I > 3\sigma$ were used in the refinement (82 variables). Final agreement factors: $R_1 = 0.032$, $R_2 = 0.049$, and goodness-of-fit = 1.555. Full details of data collection and refinement are included in the supplementary material.

0002-7863/90/1512-452$02.50/0