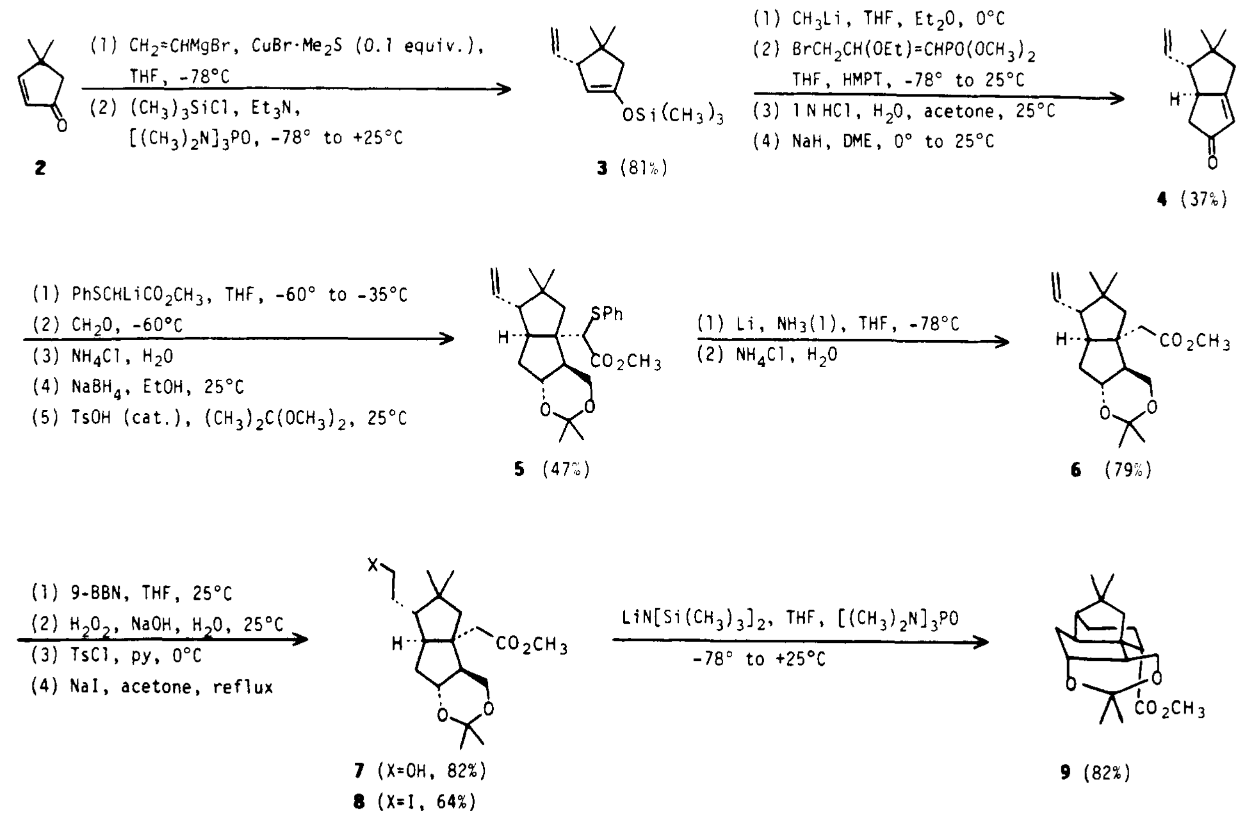
Scheme I



behavior of the earlier intermediates, the structure of this nicely crystalline dihydroxy acid was determined by single-crystal X-ray diffraction[13] which firmly established the structure as depicted by **11**. Treatment of the diol with acetic anhydride in pyridine produces selectively the primary acetate **12** which upon reaction with pyridinium chlorochromate[14] undergoes both oxidation of the remaining alcohol function and elimination of acetic acid to provide the α-methylene ketone **13** which was the final precursor of quadrone in the Danishefsky synthesis.[3] Comparison of ^{1}H NMR spectra of our sample and the earlier workers' material indicated their identity. Indeed, when **13** is placed in a flask at ca. 200 °C under nitrogen for 5–10 min, quadrone (**1**) is obtained directly. The synthetic material is identical with an authentic sample according to ^{1}H NMR, TLC, and GLC data.

In summary, we have completed a rather direct, regioselective synthesis of quadrone which is accomplished with excellent stereochemical control over four of the five chiral centers of the natural product and which serves as an important application of our approach to the construction of lactone ring systems. Further work is under way to introduce the fifth chiral center with the correct configuration and determine the absolute configuration[15] of quadrone by circular dichroism and X-ray studies of optically active derivatives of **11**. The details of this work will be published subsequently in a full paper.

Acknowledgment. We express our appreciation to Dr. R. L. Ranieri (W. R. Grace & Co.) for providing an authentic sample of quadrone, Professor S. Danishefsky and K. Vaughan (Yale University) for supplying NMR spectra of compound **13**, Professor E. Piers (University of British Columbia) for informing us of the experimental details of his annulation procedure,[7] and Professor J. W. Lauher (SUNY) for his assistance with the X-ray diffraction study. We also acknowledge financial support received from the National Institutes of Health, DHEW (Grant CA20701 and CA22741).

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[13] Compound **11** crystallizes from a mixture of acetone and pentane as triclinic prisms belonging to the space group $P\bar{1}$ with $a = 6.102$ (2), $b = 7.439$ (3), $c = 15.63$ (1) Å; $\alpha = 88.21$ (6), $\beta = 84.76$ (6), $\gamma = 76.67$ (3)°; $Z = 2$. The data set was collected on an Enraf-Nonius CAD4A diffractometer by using Mo Kα X radiation in the range $0 < 2\Theta \leq 40°$. The structure was solved by using the Multan direct method programs and refined to unweighted and weighted R values of 0.088 and 0.100, respectively, for the 172 variables and 493 observations with $F_0 \geq 3\sigma(F_0)$. The computations were performed on a PDP 1145 computer by using the Enraf-Nonius Structure Determination Package developed by Okaya and Frenz. See: Okaya, Y. In "Computing in Crystallography"; Schenk, H., Olthof-Hazekamp, R., van Koningsveld, H., Bassi, G. C., Eds.; Delft University Press: The Netherlands, 1978; pp 153-165. Frenz, B. A. *Ibid.*, pp 64-71.

[14] Corey, E. J.; Suggs, J. W. *Tetrahedron Lett.* **1975**, 2647-2650.

[15] The absolute configuration of quadrone was not determined in the original structural studies of the natural material, although X-ray diffraction was used to assign the structure.[1]

Evidence for Migratory Insertion of a Methylidene Ligand into a Transition Metal–Methyl Bond

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Received March 30, 1981

Recent evidence suggests that insertion of surface-bound methylidene groups into transition metal–alkyl linkages may be the key chain growth step in Fischer–Tropsch reactions,[1] and it has been believed for some time that similar insertions are involved in the formation of polymethylene from diazomethane in the presence of some organometallic complexes.[2] However, only one example has been reported of a stoichiometric reaction of a complex containing an alkylidene ligand, lacking stabilizing heteroatomic substituents, which appears to involve insertion of the alkylidene ligand into an adjacent transition metal–alkyl bond.[3]

[†] Undergraduate research participant.

[1] (a) Brady, R. C.; Pettit, R. *J. Am. Chem. Soc.* **1980**, *102*, 6181. (b) Ibid. **1981**, *103*, 1287.

[2] Mango, F. D.; Dvoretzky, I. *J. Am. Chem. Soc.* **1966**, *88*, 1654.

[3] Sharp, P. R.; Schrock, R. R. *J. Organomet. Chem.* **1979**, *171*, 43.

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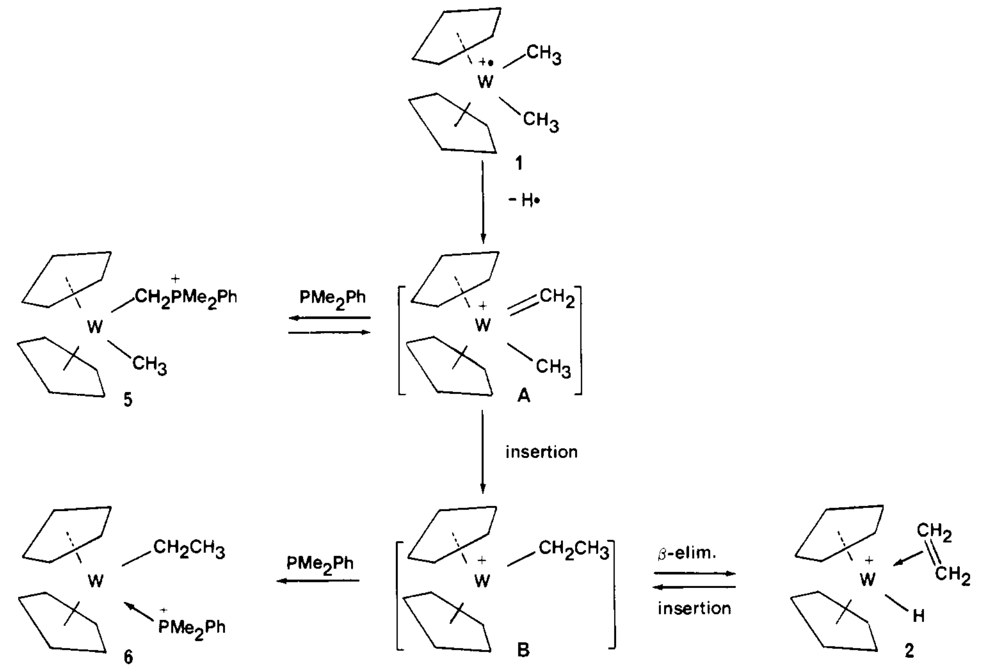
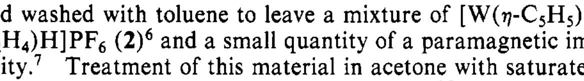
Scheme I



We wish to report experiments which provide evidence for the occurrence of such an insertion in a transient tungsten–methylidenemethyl complex and which also indicate that this reaction becomes highly favorable when the alkylidene center is electrophilic. This supports the analogy suggested between alkylidene insertion and migratory insertion within a carbonyl–alkyl complex (eq 1).[3]



(1)

Continuous addition over 4.5 h of a 2.5 mM solution of [W(η-C_5H_5)$_2$(CH_3)$_2$]PF_6 (**1**)[4] in tetrahydrofuran (THF) to 1.0 mol equiv of a 14 mM solution of 4-(triphenylmethyl)-1-(diphenylmethylidene)-2,5-cyclohexadiene (the dimer of the trityl radical)[5] initially gave a cloudy yellow solution. Over a further 20-h duration the solution decolorized, and a brown solid precipitated. The solvent was then removed under vacuum, and the remaining solid washed with toluene to leave a mixture of [W(η-C_5H_5)$_2$(C_2H_4)H]PF_6 (**2**)[6] and a small quantity of a paramagnetic impurity.[7] Treatment of this material in acetone with saturated aqueous KOH gave [W(η-C_5H_5)$_2$(C_2H_4)] (**3**),[6,8] contaminated with ca. 2% [W(η-C_5H_5)$_2$(CH_3)$_2$] (**4**),[6,8,9] in 96% isolated yield based on **1**. Triphenylmethane was recovered from the toluene washings.

The formation of **2** (eq 2) can best be explained by a reaction

$$[\mathrm{W}(\eta\text{-}\mathrm{C_5H_5})_2(\mathrm{CH_3})_2]\mathrm{PF_6} \xrightarrow{\mathrm{Ph_3C\cdot}} [\mathrm{W}(\eta\text{-}\mathrm{C_5H_5})_2(\mathrm{C_2H_4})\mathrm{H}]\mathrm{PF_6} \xrightarrow{-\mathrm{H^+}} [\mathrm{W}(\eta\text{-}\mathrm{C_5H_5})_2(\mathrm{C_2H_4})] \quad (2)$$

sequence (Scheme I) beginning with hydrogen-atom abstraction from the 17e paramagnetic complex **1** to give a diamagnetic 18e intermediate methylidenemethyl cation (A). Insertion of the methylidene ligand into the tungsten–methyl bond would then give a coordinatively unsaturated 16e tungsten ethyl cation (B), which could form the observed product **2** by β-elimination of ethylene.

Evidence supporting the intermediacy of the methylidene complex A is provided by the isolation of [W(η-C_5H_5)$_2$(CH_2PMe_2Ph)CH_3]PF_6 (**5**)[10] (in 79% recrystallized yield) when the reaction is attempted in the presence of 1 equiv of PMe_2Ph (eq 3 and Scheme I). This trapping reaction is reminiscent of

$$[\mathrm{W}(\eta\text{-}\mathrm{C_5H_5})_2(\mathrm{CH_3})_2]\mathrm{PF_6} \xrightarrow{\mathrm{PMe_2Ph/Ph_3C\cdot}} \underset{\mathbf{5}}{[\mathrm{W}(\eta\text{-}\mathrm{C_5H_5})_2(\mathrm{CH_2PMe_2Ph})\mathrm{CH_3}]\mathrm{PF_6}} \quad (3)$$

that observed when [W(η-C_5H_5)$_2$(L)CH_3]PF_6 complexes (L = C_2H_4, SEt_2, or PPh_3) are treated with PMe_2Ph to give [W(η-C_5H_5)$_2$(CH_2PMe_2Ph)H]PF_6, a reaction which provided evidence for an intermediate methylidene–hydride complex, [W(η-C_5H_5)$_2$(CH_2)H]$^+$, in reactions of these species.[11] The reaction of the phosphine with A appears to be reversible, and on prolonged heating **5** forms **2** together with free PMe_2Ph and [W(η-C_5H_5)$_2$(PMe_2Ph)C_2H_5]PF_6 (**6**), isomeric with **5**. Formation of both **2** and **6** provides further evidence for the conversion of A to B. Both **2** and **6** are present until **5** has been consumed, after which the free PMe_2Ph continues to react slowly with **2** to give eventually 86% conversion of the tungsten species to **6**[12,13] (eq 4

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(4) Cooper, N. J.; Green, M. L. H.; Mahtab, R. *J. Chem. Soc., Dalton Trans.* **1979**, 1557.

(5) (a) Copenhauer, J. W.; Roy, M. F.; Marvel, C. S. *J. Am. Chem. Soc.* **1935**, *57*, 1311. (b) McBride, J. M. *Tetrahedron* **1974**, *30*, 2009 and references therein.

(6) Benfield, F. W. S.; Green, M. L. H. *J. Chem. Soc., Dalton Trans.* **1974**, 1324.

(7) ^{1}H NMR spectra showed that no other diamagnetic species were present, and IR spectra gave no evidence for the presence of species other than **2**.

(8) ^{1}H NMR and mass spectra. The relative yields of **3** and **4** are based on the ^{1}H NMR spectrum.

(9) Although **1** is reduced to **4** under these conditions, we do not believe that the formation of **4** indicates that the product **2** is simply contaminated with unreacted **1** for the following reasons: (a) The observed yield of **4** is relatively insensitive to the quantity of trityl radical used in the first reaction, and we have been unable to find conditions under which **4** is not formed. (b) The yield of **4** is very sensitive to other variations in the reaction conditions, for example, inverse addition during the reaction with **1** gives a product mixture, after KOH treatment, containing 20% of **4**. These observations suggest that intermediate A can react with **1** to give a paramagnetic, and probably binuclear, side product which yields **4** under the deprotonation conditions. The nature of this side product is under continuing investigation.

(10) ^{1}H NMR (acetone-d_6) δ 8.24–7.59 (m, 5 H, C_6H_5), 4.83 (s, 10 H, $2C_5H_5$), 2.27 (d, J_{H-P} = 13.1 Hz, 6 H, $P(CH_3)_2$), 1.13 (d, J_{H-P} = 13.1 Hz, (satellites J_{W-H} = 7.2 Hz), 2 H, WCH_2P), –0.03 (d, J_{H-P} = 1.5 Hz, (satellites J_{W-H} = 5.2 Hz), 3 H, WCH_3). Anal. Calcd for $C_{20}H_{26}P_2F_6W$: C, 38.36; H, 4.18. Found: C, 38.27; H, 4.26.

(11) (a) Cooper, N. J.; Green, M. L. H. *J. Chem. Soc., Dalton Trans.* **1979**, 1121. (b) Canestrari, M.; Green, M. L. H. *J. Chem. Soc., Chem. Commun.* **1979**, 913.

(12) The reaction was carried out in a sealed tube and monitored by ^{1}H NMR spectroscopy.

and Scheme I).

$$[W(\eta\text{-}C_5H_5)_2(CH_2PMe_2Ph)CH_3]PF_6 \xrightarrow[75\ ^\circ C]{12\ days} \underset{6}{[W(\eta\text{-}C_5H_5)_2(PMe_2Ph)(C_2H_5)]PF_6} \quad (4)$$

Evidence in support of the intramolecular nature of the reaction converting **1** into **2** was obtained from isotopic labeling studies. A 1:1 mixture of **1** and $[W(\eta\text{-}C_5H_5)_2(CD_3)_2]PF_6$ (**1**-d_6) was treated with 1 mol equiv of the trityl radical dimer in THF to give an 85% yield of the crude ethylene hydride cation. A 1:3 mixture of Ph_3CD and Ph_3CH, as determined by mass spectroscopy, was also recovered from the reaction mixture; the isolated alkane corresponded to an 83% recovery of the starting trityl dimer, and it is presumed that the excess $Ph_3C\cdot$ abstracts hydrogen atoms from the solvent or the walls of the vessel. The isotopic composition of the ethylene ligand was determined by deprotonation of the product in acetone with aqueous KOH and examination of the mass spectrum of the mixture of **3**-d_n complexes obtained. This indicated that the product was mainly **3**-d_0 (46%) and **3**-d_4 (42%), together with small quantities of **3**-d_1 (4%) and **3**-d_3 (8%). Since the isotopic envelope of the $[W(\eta\text{-}C_5H_5)_2]^+$ fragmentation peak indicates that no deuterium has been incorporated into the cyclopentadienyl ligands, we can assume that these figures give the isotopic composition of the ethylene ligand directly.

The observation that **3**-d_1 and **3**-d_3 were formed led us initially to question the significance of this labeling experiment, but we have been able to demonstrate that scrambling occurs after the formation of **2**. When a 1:1 mixture of **2**-d_0 and **2**-d_5 (prepared from **4**-d_6) was stirred in THF for 24 h and the cation subsequently deprotonated under the same conditions as in the labeling study, the recovered **3** was demonstrated by mass spectroscopy to contain an identical mixture of **3**-d_n species to that obtained in the labeling study. Scrambling does not occur during the deprotonation as demonstrated by deprotonation of a 1:1 mixture of **2**-d_0 and **2**-d_5 to give a 1:1 mixture of **3**-d_0 and **3**-d_4. A reasonable interpretation of these experiments involves a facile exchange of the metal-bound hydride and deuteride between **2**-d_0 and **2**-d_5 (eq 5), followed by

$$[W(\eta\text{-}C_5H_5)_2(CH_2CH_2)H]^+ + [W(\eta\text{-}C_5H_5)_2(CD_2CD_2)D]^+ \rightleftarrows [W(\eta\text{-}C_5H_5)_2(CH_2CH_2)D]^+ + [W(\eta\text{-}C_5H_5)_2(CD_2CD_2)H]^+ \quad (5)$$

an ethylene insertion/elimination sequence, probably solvent promoted, which exchanges H and D within **2**-d_1 and **2**-d_4[14] (e.g., eq 6).

$$[W(\eta\text{-}C_5H_5)_2(CD_2CD_2)H]^+ \xrightarrow{S} [W(\eta\text{-}C_5H_5)_2(S)CD_2CD_2H]^+ \xrightarrow{-S} [W(\eta\text{-}C_5H_5)_2(CD_2CDH)D]^+ \quad (6)$$

It is now clear that the particular mixture of **3**-d_n complexes obtained in the labeling experiment must imply that **2** was originally formed as a 1:1 mixture of **2**-d_0 and **2**-d_5, and we can conclude that the formation of **2** must involve an intramolecular carbon–carbon bond forming step such as the migratory insertion shown in Scheme I.

The facile intramolecular methylidene insertion in A stands in marked contrast to the intermolecular thermal decomposition of $[Ta(\eta\text{-}C_5H_5)_2(CH_2)CH_3]$ (**7**),[15] isoelectronic with A, to give $[Ta(\eta\text{-}C_5H_5)_2(C_2H_4)CH_3]$, and we suggest that this difference can be attributed to electronic differences at the unsaturated carbon center. The methylidene ligand in A is electrophilic while that in **7** is known to be nucleophilic, and the electrophilicity of the unsaturated carbon in A presumably facilitates migration of the methyl group with its bonding pair.[3] This is consistent with the recent observation of alkyl migrations in niobium–carbene complexes, closely related to **7**, in which zirconoxy substituents render the unsaturated carbons electrophilic.[16]

Acknowledgment. We thank the donors of the Petroleum Research Fund, administered by the American Chemical Society, the Exxon Educational Foundation, and the National Science Foundation (Grant CHE80-16162) for their support of this research.

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[13] ^1H NMR (acetone-d_6) δ 7.89–7.39 (m, 5 H, C_6H_5), 5.18 (d, J_{H-P} = 2.2 Hz, 10 H, $2C_5H_5$), 2.07 (d, J_{H-P} = 9.6 Hz, 6 H, $P(CH_3)_2$), 1.37 (t of d, J = 5.8 Hz, J_{H-P} = 1 Hz, 3 H, CH_3CH_2), 1.11 (q of d, J = 5.8 Hz, J_{H-P} = 1.5 Hz, 2 H, CH_3CH_2). Anal. Calcd for $C_{20}H_{26}P_2F_6W$: C, 38.36; H, 4.18. Found: C, 38.38; H, 4.21.

[14] This mechanism explains why 50% of the **3** formed is **3**-d_0 + **3**-d_1 and 50% is **3**-d_3 + **3**-d_4. The formation of twice as much **3**-d_3 as **3**-d_1 implies a kinetic isotope effect in the ethylene insertion reaction.

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Role of Solvent in the Mechanism of Amine Oxide Thermolysis Elucidated by the Temperature Dependence of a Kinetic Isotope Effect

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Received February 23, 1981

Thermolysis of normal sulfoxides, e.g., $C_6H_{11}CHDCH_2X$ (**1**, X = SOC_6H_5), forms terminal olefins via a cis elimination[1-3] characterized by a temperature dependence of k_H/k_D over a (at least) 100 °C temperature range.[4] In keeping with a cyclic transition state, $[\Delta E_a]_D{}^H$ was equal to the zero-point energy difference $[\Delta E_0]_D{}^H = 1.15$ kcal/mol and $A_H/A_D = 0.76$, the latter value being within the range 0.75–1.2[5] established for linear H transfer. On the other hand, under nearly identical experimental conditions [diglyme solvent, a temperature range of 120 °C, and a substrate structure of **1** (X = $ONMe_2$)], isotope effect;[4] $k_H/k_D = A_H/A_D = 2.209 \pm 0.007$. These results, and a number of others previously reported,[7] comprise the supporting evidence for the postulate that in a reaction process with a single rate-determining step,[8] a bent (transition state) $TS^\ddagger$ involving nonlinear H transfer is characterized by a temperature independent isotope effect; i.e., $[\Delta E_a]_D^H$ approaches zero and k_H/k_D approaches A_H/A_D. In this report we wish to rationalize the temperature dependence of k_H/k_D as a criterion for identifying a bent $TS^\ddagger$ of H transfer and demonstrate the sensitivity of this criterion for distinguishing the changes in $TS^\ddagger$ structure which can attend any alteration in reaction conditions, for example, a change in the nature of the solvent.

Virtual Temperature Independence of k_H/k_D and the Unusual Magnitudes of A_H/A_D of the Bent $TS^\ddagger$. The representation in Figure 1 is intended to show that for linear transfer between the

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