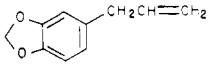
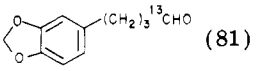
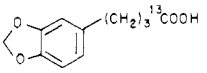
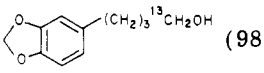
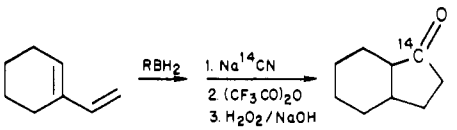
Table VIII
Synthesis of Carbon-13-Labeled Aldehydes, Acids, and Alcohols

alkene	aldehyde (% yield)	acid (% yield)	alcohol (% yield)
$H_3C(CH_2)_6CH=CH_2$	$H_3C(CH_2)_8{}^{13}CHO$ (86)	$H_3C(CH_2)_8{}^{13}COOH$ (94)	$H_3C(CH_2)_8{}^{13}CH_2OH$ (91)
	 (84)	 (93)	 (89)
	 (81)	 (84)	 (98)
p-$MeC_6H_4SCH_2C(CH_3)=CH_2$	p-$MeC_6H_4SCH_2$-$CH(CH_3)CH_2{}^{13}CHO$ (83)	p-$MeC_6H_4SCH_2$-$CH(CH_3)CH_2{}^{13}COOH$ (89)	p-$MeC_6H_4SCH_2$-$CH(CH_3)CH_2{}^{13}CH_2OH$ (90)
$HO(CH_2)_9CH=CH_2$	$HO(CH_2)_{11}{}^{13}CHO$ (85)	$HO(CH_2)_{11}{}^{13}COOH$ (98)	$HO(CH_2)_{11}{}^{13}CH_2OH$ (93)

preliminary studies we used the reaction to incorporate carbon-13 and carbon-14.[62]



We are investigating the use of the cyanidation reaction to synthesize carbon-11 labeled estrone as a potential breast-tumor imaging agent.

(62) Kabalka, G. W. *Synth. Commun.* **1980**, *10*, 93.
(63) Kabalka, G. W.; Finn, R. D.; Wolff, A. P., unpublished results.

Conclusions

Although we have succeeded in developing new routes for isotope incorporation via organoborane reactions, much remains to be done. The growing need for labeled compounds of increased complexity will continue to challenge organic chemists. It is clear that organoboranes and other organometallic reagents will play an ever increasing role in this area of research.

I gratefully acknowledge financial support from the U.S. Department of Energy, National Institutes of Health, and Research Corporation. I also thank my students and research associates for their contributions to our research efforts.

cis-Alkyl- and *cis*-Acylrhodium and -iridium Hydrides: Model Intermediates in Homogeneous Catalysis

DAVID MILSTEIN

Central Research & Development Department, E. I. du Pont de Nemours & Company, Experimental Station, Wilmington, Delaware 19898

Received September 1, 1983 (Revised Manuscript Received February 14, 1984)

Although homogeneous catalysis by transition-metal complexes has made significant contributions to industrial and laboratory processes,[1] the mechanistic detail of some of these processes still remains to be resolved. Much of our current mechanistic understanding is based on studies of model compounds, such as *cis*-alkyl- and *cis*-acylmetal hydrides, which are thought to be involved in some very useful transition-metal-catalyzed processes. These reactions, which form or break C–H bonds, include olefin hydrogenation, olefin hydroformylation, and aldehyde decarbonylation, all catalyzed by Rh(I) (Scheme I).

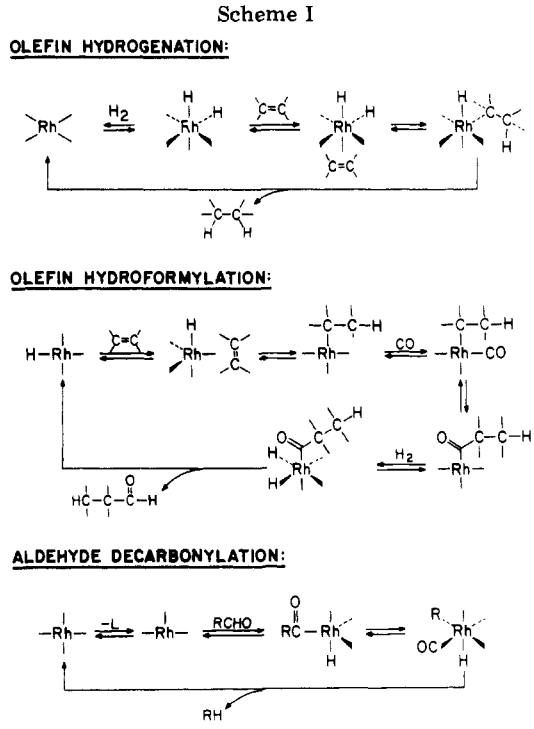
Relatively little is known about the reactivity of *cis*-alkyl- and *cis*-acylmetal hydrides. For example, intramolecular reductive elimination of an aldehyde from a metal complex, which has been proposed as the product-forming step in the cobalt-catalyzed[2] and rhodium-catalyzed[3] olefin hydroformylation reactions, has not been directly observed until very recently[4] for any well-characterized metal system. This lack of studies is perhaps a result of the relative rarity of *cis*-alkyl- and *cis*-acylmetal hydride complexes, which may be attributed to instability. Indeed, *cis*-hydridoalkyl complexes have been observed to decompose at low temperatures.[5] On the other hand, very stable *cis*-hydridoalkyliridium complexes have been recently isolated, raising the question whether this stability is thermodynamic or kinetic in nature.[6-10]

David Milstein was born in Ulm, Germany, and received his Ph.D. (Summa cum Laude) with J. Blum at the Hebrew University of Jerusalem in 1976, while concurrently serving as a Research Chemist at the Nuclear Research Center in Negev, Israel. Following postdoctoral work with J. K. Stille at Colorado State University, he joined the Central Research and Development Department of the Du Pont Co., where he is presently a Group Leader. His research interests are mostly in the areas of synthetic and mechanistic organometallic chemistry and homogeneous catalysis.

(1) G. W. Parshall, "Homogeneous Catalysis", Wiley, New York, 1980.
(2) R. F. Heck and D. S. Breslow, *J. Am. Chem. Soc.*, **83**, 4023 (1961).
(3) (a) G. Yagupsky, C. K. Brown, and G. Wilkinson, *J. Chem. Soc. A*, 2753 (1970); (b) C. K. Brown and G. Wilkinson, *J. Chem. Soc. A*, 2753 (1970).
(4) D. Milstein, *Organometallics*, 1, 1549 (1982).
(5) J. Halpern, *Acc. Chem. Res.*, **15**, 332 (1982).
(6) D. L. Thorn, *Organometallics*, 1, 197 (1982).
(7) T. H. Tulip and D. L. Thorn, *J. Am. Chem. Soc.*, **103**, 2448 (1981).
(8) A. H. Janowicz and R. G. Bergman, *J. Am. Chem. Soc.*, **104**, 352 (1982).
(9) B. Longato and W. Bresadola, *Inorg. Chem.*, **21**, 168 (1982).
(10) D. Milstein and J. C. Calabrese, *J. Am. Chem. Soc.*, **104**, 3773 (1982).

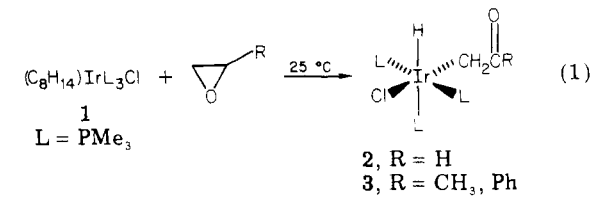
0001-4842/84/0117-0221$01.50/0

Scheme I



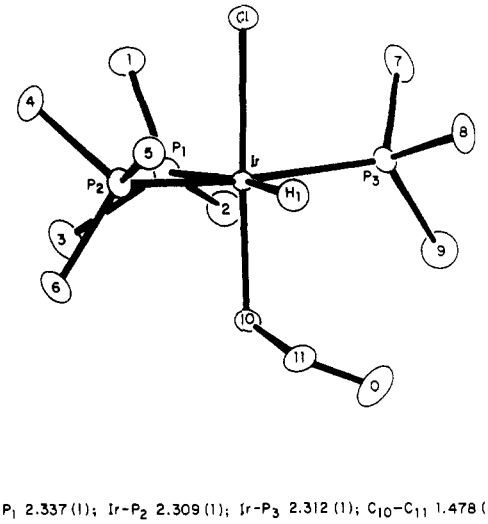
cis-Alkyliridium Hydrides via Oxidative Addition of Ir(I) to Epoxides

cis-Hydridoalkylrhodium, -ruthenium, and -palladium complexes have been postulated as intermediates in epoxide isomerization[11,12] and dimerization[13] reactions homogeneously catalyzed by these metals, but direct evidence for this was not available. Aiming at isolation of such complexes, $(C_8H_{14})Ir(PMe_3)_3Cl$ (1; C_8H_{14} = cyclooctene) was reacted with epoxides, resulting in quantitative yields of *cis*-hydridoalkyl complexes (eq 1).[10]



(1)

The reaction is regioselective, leading only to products in which the metal is attached to the least substituted carbon. The complexes are quite thermally stable—no reductive elimination is observed upon extended heating at 100 °C. The crystal structure of **2** (Figure 1) reveals that the Ir–P bond trans to the hydride in this octahedral complex is approximately 0.03 Å longer than the Ir–P bonds cis to it, thus reflecting a considerable trans effect of the hydride ligand. This structural feature, which has been observed in other hydridoiridium complexes as well,[14] will become important in our subsequent discussion of the reductive elimination process. Complex **2** can be decarbonylated by heating with $Rh(PMe_3)_3Cl$ at 100 °C to yield the stable cis complex *mer*-$Ir(H)(CH_3)(PMe_3)_3Cl$. The high thermal



Ir-P1 2.337 (1); Ir-P2 2.309 (1); Ir-P3 2.312 (1); C10-C11 1.478 (8) Å

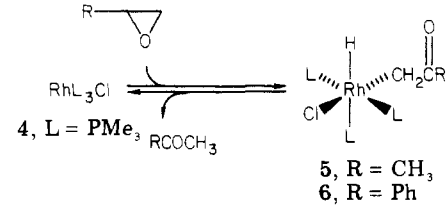
Figure 1. Molecular structure of *cis*-$HIr(CH_2CHO)(PMe_3)_3Cl$.

stability of these *cis*-hydridoalkyliridium complexes is contrary to the general belief that intramolecular *cis*-alkyl–hydride reductive elimination reactions tend to be very rapid[5] and has been recently observed with other *cis*-hydridoalkyliridium(III) complexes as well.[6-8]

cis-Alkyl and *cis*-Acyl Hydride Complexes from Rh-Catalyzed Epoxide Isomerization

As one would expect, extension of studies from Ir to Rh brings about a transition from useful models to actual catalysis. This catalysis, however, is unusual in the sense that it allows for intermediate isolation, thus providing both direct mechanistic information and a useful route to the hitherto inaccessible, relatively stable *cis*-hydridoalkylrhodium complexes.

Upon reaction of $Rh(PMe_3)_3Cl$ (**4**) with epoxides, slow catalytic isomerization of the epoxides to ketones takes place at 25 °C and the Rh(I) complex is converted into a *cis*-hydridoalkylrhodium(III) complex that can be easily isolated (eq 2).[15]



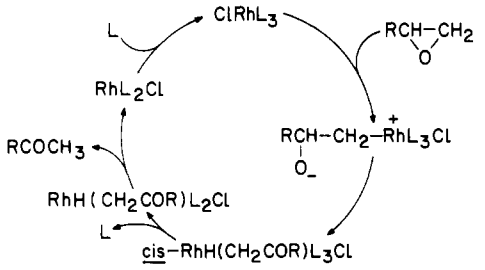
(2)

With ethylene oxide, the *cis*-hydridoacyl complex *mer*-$RhH(COCH_3)(PMe_3)_3Cl$ is formed while catalytic isomerization to acetaldehyde takes place.[15] The expected complex $RhH(CH_2CHO)(PMe_3)_3Cl$, analogous to the Ir complex **2**, is probably initially formed but reductively eliminates acetaldehyde, which then reacts to yield the observed product.

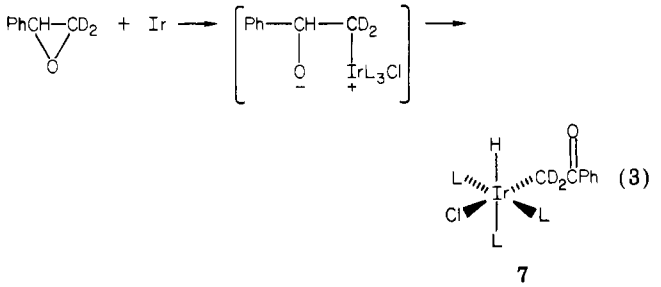
Mechanistically, formation of the hydridoalkylrhodium and -iridium complexes seems to proceed through oxidative addition of the metal to the least hindered C–O bond[16] followed by β-H elimination. Support for this mechanism includes formation of **7** as the sole

(11) D. Milstein, O. Buchman, and J. Blum, *J. Org. Chem.*, **42**, 2299 (1977).
(12) M. Suzuki, Y. Oda, and R. Noyori, *J. Am. Chem. Soc.*, **101**, 1623 (1979).
(13) J. Blum, B. Zinger, D. Milstein, and O. Buchman, *J. Org. Chem.*, **43**, 2961 (1978).
(14) G. B. Robertson and P. A. Tucker, *J. Am. Chem. Soc.*, **104**, 317 (1982).
(15) D. Milstein, *J. Am. Chem. Soc.*, **104**, 5227 (1982).
(16) Tetracyanoethylene oxide undergoes oxidative addition to group 8 metal complexes to form metallooxetanes: (a) R. Schlodder, J. A. Ibers, M. Lenarda, and M. Graziani, *J. Am. Chem. Soc.*, **96**, 6893 (1974); (b) M. Lenarda, R. Ros, O. Traverso, W. D. Pitts, W. H. Baddley, and M. Graziani, *Inorg. Chem.*, **16**, 3178 (1977).

Scheme II



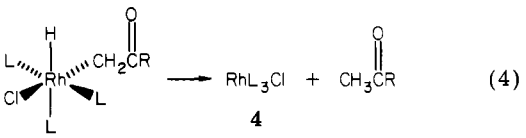
product of the reaction of β,β-dideuteriostyrene oxide and 1 (eq 3).[10]



(3)

7

Complexes **5** and **6** undergo slow reductive elimination under ambient conditions, yielding acetone and acetophenone, respectively, and regenerating the starting Rh(I) complex **4** (eq 4), thus completing the catalytic cycle for the epoxide isomerization reaction.



(4)

5, 6

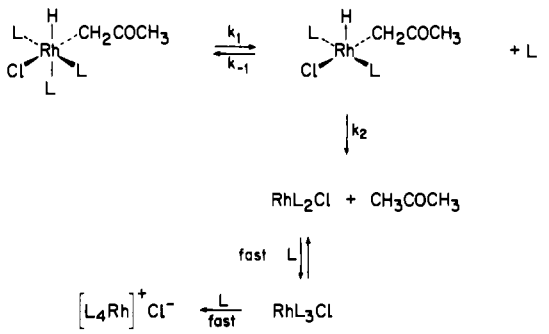
Isolation of the complexes **5** and **6** as the major Rh species in the catalytic reaction undoubtedly points out that the overall reductive elimination process (4) is rate determining in the catalytic cycle. Since this process proceeds by a prior slow PMe_3 dissociation from **5**[15] (vide infra), this phosphine dissociation step is rate determining in the catalytic isomerization process. This mechanism of epoxide isomerization catalyzed by **4** is thus plausibly presented by Scheme II.

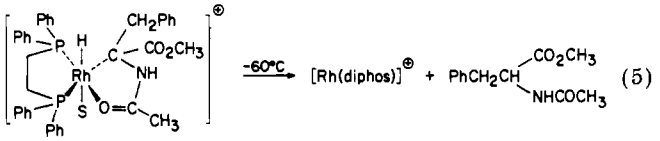
Mechanism of Alkyl–Hydride Reductive Elimination from Rh(III)

Directly observed reductive elimination processes of *cis*-alkylmetal hydrides are not common. *cis*-$OsH(CH_3)(CO)_4$ undergoes *intermolecular* methane elimination,[17] whereas *cis*-hydridoalkylplatinum complexes reductively eliminate in an intramolecular fashion.[18]

Of particular interest to us is alkyl–hydride reductive elimination from Rh, since rhodium complexes catalyze a number of synthetically important reactions thought to involve formation of C–H bonds via this step. An unstable *cis*-hydridoalkylrhodium complex **8** was recently intercepted at −78 °C in the hydrogenation of methyl (*Z*)-α-acetamidocinnamate catalyzed by Rh(diphos)$(CH_3OH)_2^+$.[19] Upon warming above −60 °C, **8** underwent reductive elimination (eq 5), which followed first-order kinetics. Reductive elimination from other unstable *cis*-hydridoalkylrhodium complexes observed very recently at low temperatures also follows first-order kinetics.[20]

Scheme III





(5)

8, S = CH_3OH, CH_3CN

The first isolated, relatively stable *cis*-hydridoalkylrhodium complexes[15] **5** and **6** proved to be especially amenable for the mechanistic studies of the alkyl–hydride reductive elimination reaction (eq 4). This reaction is intramolecular, since decomposition of a solution containing equimolar amounts of **5** and the cis complex *mer*-$RhD(CD_2COCD_3)(PMe_3)_3Cl$ yielded a 1:1 mixture of CH_3COCH_3 and CD_3COCD_3 with no crossover products obtained.[15] The rate of disappearance of **5** follows first-order kinetics and is unaffected by variations in the initial concentration of **5**. Activation parameters obtained from a linear Arrhenius plot of k_{obsd} (31 °C) are as follows: E_a = 25.6 kcal/mol, $\Delta H^\ddagger$ = 25.0 kcal/mol, $\Delta G^\ddagger$ = 23.4 kcal/mol, $\Delta S^\ddagger$ = 5.3 eu. The rate of the reductive elimination process is retarded by added PMe_3 and the stoichiometry is altered to that of eq 6. Still, disappearance of **5** obeys first-order kinetics.

$$5 + PMe_3 \rightarrow CH_3COCH_3 + Rh(PMe_3)_4^+Cl^- \quad (6)$$

Significantly, $1/k_{obsd}$ varies linearly with the concentration of added PMe_3. Also, a significant increase in the disappearance rate of **5** is observed in the presence of the "phosphine sponge" $Rh(acac)(C_2H_4)_2$. Kinetic measurements of the reductive elimination of the cis complex *mer*-$RhD(CD_2COCD_3)(PMe_3)_3Cl$ have yielded a small kinetic isotope effect k^H_{obsd}/k^D_{obsd} = 1.3 at 31 °C. This evidence indicates that the reductive elimination of **5** occurs by a *dissociative* mechanism, involving a rate-determining loss of PMe_3, as outlined in Scheme III. The actual reductive elimination step is practically irreversible: no reaction between acetone and **4** takes place at 31 °C even over periods of weeks.

Using the steady-state approximation for the concentration of the pentacoordinate Rh(III) intermediate, the rate law 7 is obtained, indicating that $1/k_{obsd}$ is a

$$\frac{-d[5]}{dt} = \frac{k_1k_2[4]}{k_{-1}[PMe_3] + k_2} = k_{obsd}[5] \quad (7)$$

(17) (a) S. J. Okrasinski and J. R. Norton, *J. Am. Chem. Soc.*, **99**, 295 (1977); (b) J. R. Norton, *Acc. Chem. Res.*, **12**, 139 (1979).
(18) L. Abis, A. Sen, and J. Halpern, *J. Am. Chem. Soc.*, **100**, 2915 (1978).
(19) A. S. C. Chan and J. Halpern, *J. Am. Chem. Soc.*, **102**, 838 (1980).
(20) W. D. Jones and F. J. Feher, *Organometallics*, **2**, 562 (1983).

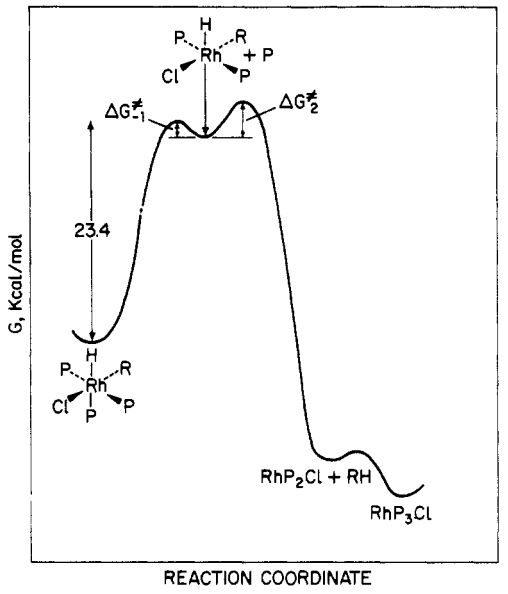
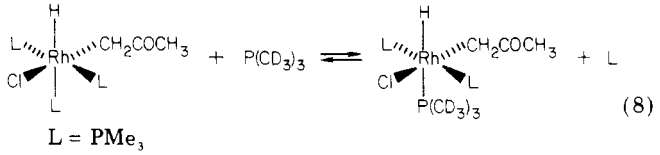


Figure 2. Free energy profile for alkyl–hydride reductive elimination from **5**; $\Delta G_2^{\ddagger} = \Delta G_{-1}^{\ddagger} + 0.3$ when $[PMe_3] = 1$ M.

linear function of $[PMe_3]$. From the linear plot follows $k_1 = 1.02 \times 10^{-4}$ s^{-1}, corresponding to $\Delta G^{\ddagger}$ (31 °C) = 23.3 kcal/mol and $k_{-1}/k_2 = 1.83$ mol^{-1}, indicating that the rate of the reductive elimination step is comparable to that of the reassociation process.

The PMe_3 ligand trans to the hydride in **5** is the one expected to dissociate, as a result of the strong trans effect exerted by the hydride ligand, as evidenced in the crystal structure of the analogous *cis*-$IrH(CH_2CHO)(PMe_3)_3Cl$ (vide supra). In order to directly demonstrate the reversible phosphine dissociation process and to determine which ligand dissociates, **5** was partially decomposed at 32 °C in the presence of excess $P(CD_3)_3$.[21] The recovered hydridoalkyl complex indeed contained this ligand, which incorporated exclusively trans to the hydride, thus establishing the equilibrium 8. *mer*-$RhH_2(PPh_3)_3Cl$ also dissociates the trans-hydride phosphine, as evidenced by NMR, the dissociation rate being ~400 s^{-1} at 30 °C,[22] more than 6 orders of magnitude larger than the rate of dissociation of PMe_3 from **5**. This indicates that the PMe_3 ligands in the hydridoalkylrhodium complexes are very tightly bound, and since the reductive elimination process is dissociative, the result is a relatively large activation barrier for this process. In other words, the stability of the trimethylphosphine *cis*-hydridoalkylrhodium complexes is kinetic in nature and the overall irreversible reductive elimination process is thermodynamically favorable (Figure 2). Ligand dissociation from Ir(III) complexes is expected to be even more difficult than from Rh(III), resulting in the reluctance of *cis*-hydridoalkyliridium PMe_3 complexes to undergo reductive elimination. Substituting PMe_3 by larger cone angle ligands (e.g., PPh_3) reduces the kinetic barrier.



(8)

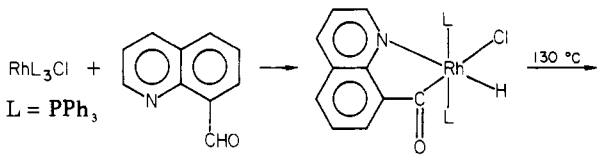
By microscopic reversibility, $RC(=O)CH_2$–H oxidative addition to **4** is thermodynamically unfavorable,[23] in agreement with conclusions based on the Pt system.[18] This process can be estimated to be endothermic by approximately 10 kcal/mol, taking into account estimates of $D_{M-H} \sim 60$ kcal/mol, $D_{M-alkyl} \sim 20$–30 kcal/mol[24] vs. $D_{CH_3COCH_2-H} = 98$ kcal/mol.

Dissociative intramolecular alkyl–hydride reductive elimination is unprecedented. However, ligand dissociation prior to *dialkyl* reductive elimination of 16-electron d^8 square-planar Pd[25] and Au[26] complexes is well-established. Also, oxidative addition of H_2 to Rh(I) is promoted by ligand dissociation,[27] and by microscopic reversibility, reductive elimination of H_2 from Rh(III) should also be dissociative. Theoretical studies[28] concluded that the reductive elimination barrier is controlled by an antisymmetric b_2 orbital, which depends on the energy of the metal levels and is lower in energy in the more coordinatively unsaturated complex. Thus, reductive elimination of a 4-coordinate d^8 complex or a 6-coordinate d^6 complex are difficult, whereas the 3- and 5-coordinate complexes have an open channel for reductive elimination. Our results are in accord with these theoretical findings. In a somewhat more intuitive and oversimplified way, one can view ligand dissociation as both effectively reducing the electron density on the metal and resulting in a less stable stereochemical configuration, thus allowing for an easier reductive pathway.

Aldehyde Oxidative Addition, Reductive Elimination, and Decarbonylation

Rh-catalyzed processes using aldehydes as substrates (e.g., decarbonylation,[29] hydroacylation,[30,31] hydrogenation,[32] hydrosilylation,[33] and hydroformylation[34] of aldehydes) may involve oxidative addition of the aldehyde to a Rh(I) complex. The first direct demonstration of such a reaction (eq 9) yielded the chelation stabilized *cis*-hydridoacylrhodium complex **9**. Similar use of the chelate stabilization principle has led to

(21) D. Milstein, unpublished results.
(22) P. Meakin, J. P. Jesson, and C. A. Tolman, *J. Am. Chem. Soc.*, **94**, 3240 (1972).
(23) $RC(=O)CH_2$–H oxidative addition to *unstable*, reactive intermediates has been observed: S. D. Ittel, C. A. Tolman, A. D. English, and J. P. Jesson, *J. Am. Chem. Soc.*, **100**, 7577 (1978).
(24) J. Halpern, *Acc. Chem. Res.*, **15**, 238 (1982).
(25) (a) A. Gillie and J. K. Stille, *J. Am. Chem. Soc.*, **102**, 4933 (1980); (b) F. Ozawa, T. Ito, Y. Nakamura, and A. Yamamoto, *Bull. Chem. Soc. Jpn.*, **54**, 1868 (1981).
(26) S. Komiya, T. A. Albright, R. Hoffmann, and J. K. Kochi, *J. Am. Chem. Soc.*, **98**, 7255 (1976).
(27) J. Halpern and C. S. Wong, *J. Chem. Soc., Chem. Commun.*, 629 (1973).
(28) (a) K. Tatsumi, R. Hoffmann, A. Yamamoto, and J. K. Stille, *Bull. Chem. Soc. Jpn.*, **54**, 1957 (1981); (b) R. Hoffmann in "Frontiers of Chemistry", K. J. Laidler, Ed., Pergamon Press, New York, 1982, pp 247–263.
(29) (a) J. Tsuji in "Organic Syntheses via Metal Carbonyls", I. Wender and P. Pino, Eds., Wiley, 1977, Vol. 2, p 595; (b) D. H. Doughty and L. H. Pignolet, *J. Am. Chem. Soc.*, **100**, 7083 (1978); (c) H. M. Walborsky and L. E. Allen, *ibid.*, **93**, 5465 (1971); (d) R. E. Ireland and G. Pfister, *Tetrahedron Lett.*, 2145 (1969).
(30) (a) J. W. Suggs, *J. Am. Chem. Soc.*, **100**, 640 (1978); (b) R. C. Larock, K. Oertle, and G. F. Potter, *ibid.*, **102**, 190 (1980); (c) R. C. Campbell, Jr., C. F. Lochow, K. P. Vora, and R. G. Miller, *ibid.*, **102**, 5824 (1980); (d) K. Sakai, J. Ido, O. Oda, and N. Nakamura, *Tetrahedron Lett.*, 1287 (1972).
(31) (a) K. P. Vora, C. F. Lochow, and R. G. Miller, *J. Organometal. Chem.*, **192**, 257 (1980); (b) P. Isnard, B. Denise, R. P. A. Sneeden, J. M. Cognion, and P. Durnal, *ibid.*, **240**, 285 (1982).
(32) T. Mizoroki, *Bull. Chem. Soc. Jpn.*, **50**, 2148 (1977).
(33) I. Ojima, M. Nihonyanagi, T. Kogure, and M. Kumagai, *J. Organometal. Chem.*, **94**, 449 (1975).
(34) (a) A. Spencer, *J. Organometal. Chem.*, **194**, 113 (1980); (b) A. S. C. Chan, W. E. Carroll, and D. E. Willis, *J. Mol. Catal.*, **19**, 377 (1983).

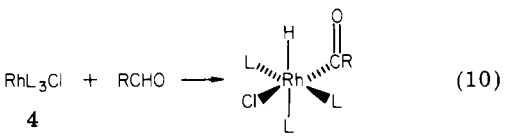


9

quinoline + $Rh(CO)L_2Cl$ (9)

synthesis of *cis*-hydridoacyliridium complexes.[35] Upon heating, **9** undergoes decarbonylation (eq 9), thus providing a model for Rh-catalyzed aldehyde decarbonylation,[29] a reaction appearing in various natural product syntheses and providing a method for stereospecific introduction of an angular methyl group[29d] and specific deuteration.[29c]

A *cis*-hydridoacylrhodium not stabilized by chelation was isolated from $Rh(PMe_3)_3Cl$ (**4**) catalyzed ethylene oxide isomerization[15] (vide supra). In a more general approach, it was found that simple aldehydes undergo facile cis oxidative addition to **4** at 25 °C, affording a series of stable *cis*-hydridoacylrhodium complexes in high yields (eq 10).[4] Reaction 10 proceeds at a con-



(10)

10

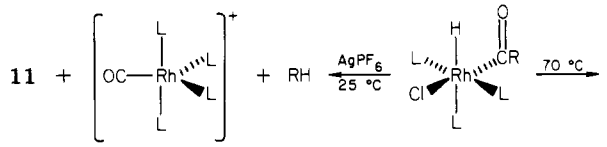
L = PMe_3; R = CH_3, $CH_3(CH_2)_2$, Ph, 4-C_6H_4F, OMe

veniently measurable rate at 0 °C and is first order in the aldehyde (R = $CH_3(CH_2)_2$) and in the Rh complex **4** (eq 11) with $k_{obsd} = 6 \times 10^{-4}$ s^{-1} mol^{-1}, corresponding

$$d[\mathbf{10}]/dt = k_{obsd}[CH_3(CH_2)_2CHO][\mathbf{4}] \quad (11)$$

to $\Delta G^{\ddagger} = 20$ kcal/mol.[21] *cis*-Hydridoacyliridium PMe_3 complexes can be obtained similarly from oxidative addition of aldehydes to $(C_8H_{14})Ir(PMe_3)_3Cl$ or $Ir(PMe_3)_4Cl$.[6,10]

Upon heating above 60 °C in C_6D_6, complexes **10** undergo migratory deinsertion followed by reductive elimination to yield RH and $Rh(PMe_3)_2(CO)Cl$ (**11**), resulting in overall aldehyde decarbonylation.[4] This process is accelerated considerably if an empty coordination site is provided: abstraction of the halide with Ag^+ brings about spontaneous decarbonylation (eq 12). This provides a model for the Rh-catalyzed aldehyde decarbonylation reaction unrestricted by chelation requirements.



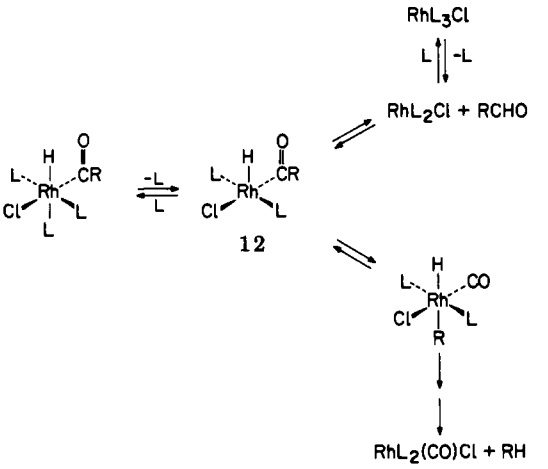
RH + **11** + L (12)

Significantly, in addition to the alkane, small amounts of the aldehydes were also obtained, as a result of reversible reductive elimination competing with the overall irreversible decarbonylation process (eq 13).

$$\mathbf{4} + RCHO \rightleftarrows \mathbf{10} \rightarrow RH + \mathbf{11} \quad (13)$$

Indeed, if the product aldehyde is efficiently removed as formed, the acyl–hydride reductive elimination process becomes the major one.[4] This is the first direct observation of aldehyde reductive elimination from a well-characterized hydridoacylmetal complex,[36] a process that has been postulated as the product-forming step in hydroformylation reactions.[2,3]

Scheme IV



The acyl–hydride reductive elimination process is *intramolecular*, as demonstrated by crossover experiments utilizing *cis*-$HRh(COCH_3)(PMe_3)_3Cl$ and *cis*-$DRh(COCD_3)(PMe_3)_3Cl$.[4] Decomposition of **10** (R = CH_3) follows first-order kinetics, k_{obsd} (70 °C) = 3.51×10^{-5} s^{-1}, $\Delta H^{\ddagger} = 28.5$ kcal/mol, $\Delta G^{\ddagger} = 27.1$ kcal/mol, $\Delta S^{\ddagger} = 4.1$ eu.[21] As with the hydridoalkyl complexes, the rate is accelerated by the addition of $Rh(acac)(C_2H_4)_2$ and retarded by added PMe_3, without significantly affecting the relative rates of the reductive elimination and decarbonylation processes.[4]

It is concluded that both the reductive elimination and decarbonylation processes proceed from a common coordinatively unsaturated complex **12**, formation of which is rate determining (Scheme IV). Since the alkyl–hydride reductive elimination step in the decarbonylation process is irreversible whereas the acyl–hydride reductive elimination is reversible, the decarbonylation process usually predominates. However, if the equilibrium is interrupted by removal of either of the products, the acyl–hydride reductive elimination prevails. This may take place in the olefin hydroformylation by reaction of the Rh(I) complex with olefin, CO, and hydrogen.

A free energy profile for the acyl–hydride reductive elimination process is presented in Figure 3. As in the alkyl–hydride reductive elimination (Figure 2), a high barrier for phosphine dissociation results in kinetic stability of the *cis*-hydridoacyl PMe_3 complexes. However, the acyl–hydride reductive elimination is also *thermodynamically* unfavored. By microscopic reversibility, we conclude that the thermodynamically favored oxidative addition process proceeds by predissociation of RhL_3Cl to the 14-electron species RhL_2Cl. This is the same conclusion reached in a kinetic study of the oxidative addition of aldehydes to $Rh(PPh_3)_3Cl$,[37] indicating that *dissociative* acyl–hydride reductive elimination from Rh(III) is not restricted to PMe_3

(35) E. F. Landvatter and T. B. Rauchfuss, *Organometallics*, 1, 506 (1982).

(36) The intermediacy of an unstable hydridoacyliridium complex in the acidification reaction of $Ir(COEt)(CO)_2(PPh_3)_2$ to yield propionaldehyde was suggested on the basis of IR of the mixture.[3a]

(37) J. Halpern in "Organotransition Metal Chemistry", Y. Ishi and M. Tsutsui, Eds., Plenum Press, 1975, p 109.

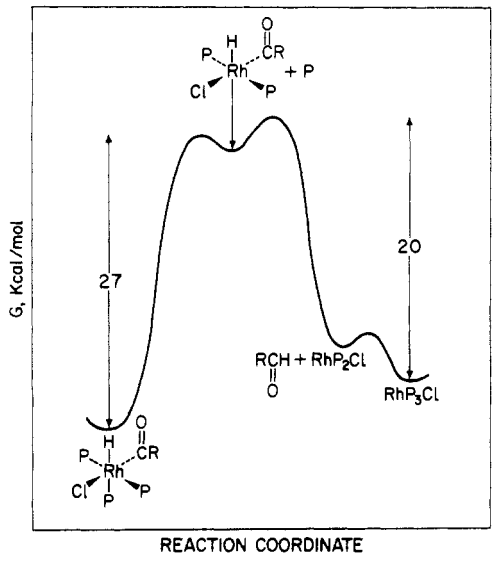
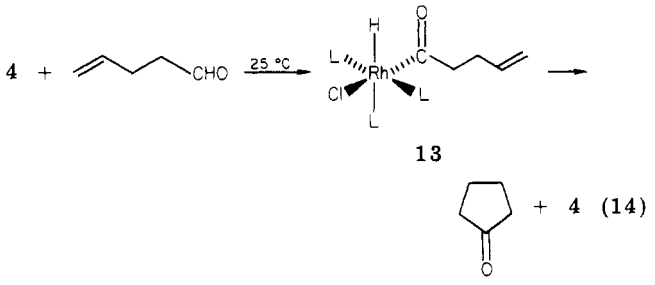


Figure 3. Free energy profile for acyl–hydride reductive elimination from **10** (R = CH_3).

complexes and is probably quite a general phenomenon.

Hydroacylation

In addition to the two general elimination modes of *cis*-hydridoacylrhodium(III) complexes, namely, acyl–hydride reductive elimination and decarbonylation, a third one is possible when the acyl group contains olefinic unsaturation. Thus, oxidative addition of 4-pentenal to $Rh(PMe_3)_3Cl$ (**4**) gives the complex **13** in high yield. Upon heating at 50 °C, **13** decomposes ($t_{1/2} \approx 1$ h), forming cyclopentanone and regenerating **4** (eq 14).[38] Process 14, which results in the net addition of



(14)

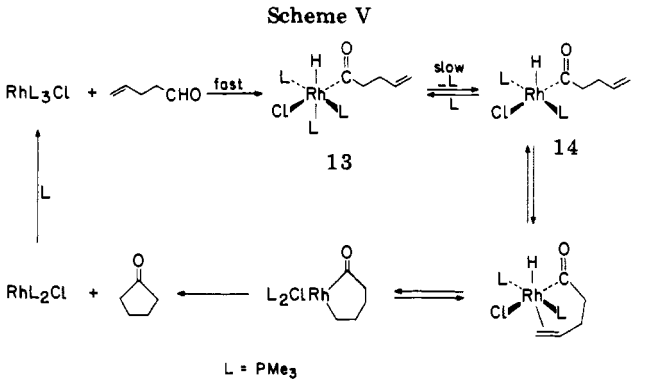
the formyl C–H bond to the double bond, is termed "intramolecular hydroacylation".[30,38] Since **4** is being regenerated, reaction 14 forms the basis for a catalytic cycle. Indeed, **4** catalyzes the cyclization of 4-pentenal to cyclopentanone at about 50 °C.[38]

Intramolecular hydroacylation of olefinic aldehydes to cyclopentanones promoted by Rh(I) triarylphosphine complexes is a useful synthetic process,[30b-d] providing a new approach for the preparation of prostaglandin precursors, although for catalytic activity ethylene presence is required. A complex analogous to **13** has indeed been postulated as a key intermediate in this process,[30b,c] although not observed.

As expected, the hydroacylation process of **13** (eq 14) proceeds by a dissociative mechanism. The rate of this process is retarded by added PMe_3, and partial decomposition in the presence of $P(CD_3)_3$ brings about incorporation of this ligand in the trans-hydride position exclusively. A plausible mechanism for the catalytic process is thus fast oxidative addition of 4-pentenal to

(38) D. Milstein, *J. Chem. Soc., Chem. Commun.*, 1357 (1982).

Scheme V



4 to yield complex **13**, followed by slow PMe_3 dissociation to form the 5-coordinate Rh(III) complex **14**. Intramolecular insertion into the Rh–H bond of **14** followed by reductive elimination leads to cyclopentanone and regenerates the catalyst (Scheme V). An alternative mechanism involving insertion into the Rh–C bond of **14** is unlikely on the basis of studies of the $Rh(PPh_3)_3Cl$-catalyzed cyclization of 4-pentenal-1-*d*.[30c]

Intermolecular metal-catalyzed hydroacylation of olefins[30a,31] is synthetically less developed than the intramolecular version. This process also involves addition of an olefin to a *cis*-hydridoacylrhodium complex as demonstrated by reaction of a chelate-stabilized hydridoacylrhodium complex, analogous to **9**, with 1-octene.[30a]

Concluding Remarks

Oxidative addition reactions of Rh(I) and Ir(I) trimethylphosphine complexes afforded a series of *cis*-alkyl and *cis*-acyl hydrides that proved to be useful in contributing to our understanding of Rh-catalyzed homogeneous processes. Whereas the *cis*-hydridoacylrhodium complexes are relevant to the product-forming step in the hydroformylation reaction, complexes **5–6**, **10**, and **13** are *actual intermediates* in $Rh(PMe_3)_3Cl$-catalyzed epoxide isomerization, aldehyde decarbonylation, and olefin hydroacylation reactions, respectively.

A number of elimination reactions from Rh(III) have been identified. Alkyl–hydride reductive elimination is intramolecular, dissociative, and thermodynamically favored, the stability of the *cis*-hydridoalkyl complexes being kinetic in nature. *cis*-Hydridoacylrhodium(III) compounds undergo three competing reactions: reductive elimination of the aldehyde, decarbonylation to the alkane, and, where possible, intramolecular hydroacylation. All three elimination modes proceed from a common coordinatively unsaturated intermediate formed by rate-determining dissociation of PMe_3 from the trans-hydride position. The acyl–hydride reductive elimination is a facile, reversible intramolecular process, although thermodynamically unfavorable, requiring removal of the product aldehyde or Rh(I) complex from the equilibrium mixture. Further work in our laboratory is capitalizing on these observations in making rational improvements in catalytic processes.

I am indebted to my colleagues at Du Pont for valuable discussions and to the Du Pont Co. for creating the kind of atmosphere which made this research possible. Special thanks are due to Dr. T. H. Tulip for reading the manuscript and making valuable suggestions.