

(Pentamethylcyclopentadienyl)rhodium and -iridium Complexes: Approaches to New Types of Homogeneous Catalysts

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Considerable research over the last 15 years has centered on complexes of the platinum metals which, in homogeneous solution or heterogeneously when supported on a suitable carrier, have good catalytic properties.¹

Most of these new catalysts have involved complexes of the platinum metals with tertiary phosphines and similar ligands. The need for such ligands, especially in reactions which occur under reducing conditions, arises from the ease with which irreversible decomposition to the metals otherwise occurs. Phosphines are *soft* ligands that bind well to the platinum metals in both low and intermediate oxidation state complexes, and their presence inhibits decomposition on reduction. One example is the classical "Wilkinson complex" hydrogenation catalyst, $[\text{Rh}(\text{Ph}_3\text{P})_3\text{Cl}]$.²

However, a catalytic system which had good activity, under useful conditions, combined with high specificity and long life, and which in addition did not contain such labile phosphine ligands would have some distinct additional advantages. For example, since phosphines and similar ligands have themselves high reactivity toward electrophiles, oxygen, and oxidizing agents, their absence from any catalytic system wherein free ligand is generated should result in an increase in versatility.

The design of such a catalyst poses some difficulties since, in order for it to be active homogeneously, the metal-ligand bonds must be able to survive the necessary changes in oxidation state and coordination number that occur during the catalytic cycle. In principle, this can be achieved through the use of sufficiently bulky and strongly bound ligands, but unfortunately such ligands can also seriously inhibit the desired reactions at the metal to the degree that the complexes become catalytically useless. It is therefore essential to make a careful choice of ligand in order to arrive at the best overall compromise between stability and reactivity.

The chemistry of some new types of rhodium and iridium compounds is reviewed here; apart from their unusual chemical properties, they also act as very efficient catalysts, and although their potential has not yet been fully explored, it is clear that we have succeeded in arriving at a catalytic system that meets the requirements outlined above.

Peter Maitlis is Head of Inorganic Chemistry at the University of Sheffield. He received his B.Sc. degree from Birmingham University and his Ph.D. (in 1956) at Queen Mary College, University of London. After some time as Assistant Lecturer at Queen Mary College, he went to Cornell and Harvard where he worked with A. T. Blomquist and F. G. A. Stone. Professor Maitlis was on the staff of McMaster University from 1962 until 1972, when he took up the Chair of Inorganic Chemistry at Sheffield. His research interests are concerned with the interactions of organic molecules with transition metals and the mechanisms of their reactions.

η^5 -Pentamethylcyclopentadienylrhodium and -iridium Complexes

The pentamethylcyclopentadienyl ($\eta^5\text{-C}_5\text{Me}_5$) half-sandwich complexes of Rh and Ir [e.g., $[\text{Rh}(\text{C}_5\text{Me}_5)\text{Cl}_2]_2$, **1**] offer a quite exceptional blend of stability and reactivity seldom found even among phosphine complexes. This arises from the strong C_5Me_5 -metal bond (which survives acidic and basic as well as reducing and oxidizing conditions) on one side and from the lability of the ligands on the other which allows useful reactions to occur. The C_5Me_5 ligand also acts as a useful NMR probe (singlet in the ^1H spectrum) and confers good solubility character to its complexes as well as making them generally easy to crystallize. The complexes, particularly in the III oxidation state, are normally air-stable.

But why *pentamethylcyclopentadienyl*? Won't the unsubstituted and simpler cyclopentadienyl do? In fact it will not. $[\text{Rh}(\text{C}_5\text{H}_5)\text{Cl}_2]_n$ is known but, in contrast to $[\text{Rh}(\text{C}_5\text{Me}_5)\text{Cl}_2]_2$, it is amorphous and insoluble in all but powerfully coordinating solvents and is probably polymeric. Reliable and reproducible synthesis of $[\text{Rh}(\text{C}_5\text{H}_5)\text{Cl}_2]_n$ is difficult; however, worst of all once the $\text{Rh}-\text{C}_5\text{H}_5$ bond has been formed, it turns out to be quite reactive and easily cleaved by a variety of reagents (including hydrogen) which do not affect the $\text{Rh}-\text{C}_5\text{Me}_5$ bond. For all its esoteric appearance, the synthesis of $[\text{Rh}(\text{C}_5\text{Me}_5)\text{Cl}_2]_2$ is very simple: it merely involves refluxing in methanol the commercially available $\text{RhCl}_3 \cdot x\text{H}_2\text{O}$ with hexamethylbicyclo[2.2.0]hexadiene [hexamethyl(Dewar benzene), **2**], which may be bought or made directly from 2-butyne.³

Kang's discovery of the complex **1a** was in part serendipitous. We were interested in the reactivity of Dewar benzenes toward transition metals and the disclosure of a simple route to the Dewar benzene **2**⁴ prompted us to explore its reactivity toward rhodium chloride. We obtained, in high yield, a red crystalline solid which was diamagnetic and showed only a singlet

(1) See, for example, B. R. James, "Homogeneous Hydrogenation", Wiley, New York, N.Y., 1973; P. N. Rylander, "Organic Syntheses with Noble Metal Catalysts", Academic Press, 1973; "Catalysis, Heterogeneous and Homogeneous", Elsevier, Amsterdam, 1975; "Aspects of Homogeneous Catalysis", R. Ugo, Ed., Carlo Manfredi, Milan, and D. Reidel, Boston, Mass.: Vol. 1 (1970), 2 (1974).

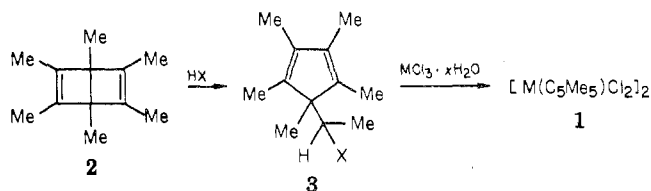
(2) J. A. Osborne, F. H. Jardine, J. F. Young, and G. Wilkinson, *J. Chem. Soc. A*, 1711 (1966); J. Halpern and C. S. Wong, *J. Chem. Soc., Chem. Commun.*, 629 (1973); J. Halpern, T. Okamoto, and A. Zakhariiev, *J. Mol. Catal.*, 2, 65 (1977).

(3) J. W. Kang, K. Moseley, and P. M. Maitlis, *J. Am. Chem. Soc.*, 91, 5970 (1969); see also B. L. Booth, R. N. Haszeldine, and M. Hill, *J. Chem. Soc. A*, 1299 (1969), and *J. Organometallic Chem.*, 16, 491 (1969).

(4) W. Schäfer and H. Hellman, *Angew. Chem., Int. Ed. Engl.*, 5, 518 (1967).

in the ^1H NMR spectrum (at δ 1.6) and which we therefore supposed to be a rhodium complex of *hexamethylbenzene*, formed by a metal-assisted valence isomerization of the Dewar benzene **3**. However, the analytical data did not fit any reasonable combination of C_6Me_6 , Rh, and Cl and we were finally forced to abandon this line of thought and to accept the surprising conclusion that a ring contraction to give a π -pentamethylcyclopentadienyl complex had taken place.⁵

The reason for this strange occurrence came somewhat later when Paquette and others found that the Dewar benzene **2** underwent a reaction with acid (e.g.,



HCl) to give the 1-substituted ethylpentamethylcyclopentadiene (**3**).⁶ In the reaction of **2** and $\text{RhCl}_3 \cdot x\text{H}_2\text{O}$ to give **1a**, the compound (**3**, X = Cl or OMe) is generated in situ; the acid comes from partial hydrolysis of the $\text{RhCl}_3 \cdot x\text{H}_2\text{O}$ and which was shown to give an acid solution in water.³

Attempts to prepare the C_5Me_5 -iridium analogue (**1b**) directly from the Dewar benzene **2** were not successful, but we obtained it again in high yield when **3** (X = Cl) was first prepared from **2** and then reacted with $\text{IrCl}_3 \cdot x\text{H}_2\text{O}$ in methanol.³

The chief role of the metal ion in these reactions appears to be to complex the cyclopentadiene **3** and to assist the cleavage of the CH_3CHX - side chain; the driving force for the overall process must be the very high stability of the C_5Me_5 -metal bond in **1**. Moseley found that a byproduct of these reactions was dimethyl acetal, $[\text{MeCH}(\text{OMe})_2]$, which arose through methanolysis of the CH_3CHX - side chain.³

It is also possible to synthesize **1** from pentamethylcyclopentadiene, but unhappily a simple, convenient, and inexpensive route to this precursor is still lacking. However, a satisfactory synthesis of ethyltetramethylcyclopentadiene⁷ has recently been reported, and the $\text{C}_5\text{Me}_4\text{Et}$ analogues of **1** have now become available;⁸ their properties are very similar to those of **1a** or **1b** but they are more soluble, especially in less polar solvents.

If the C_5Me_5 ring is assumed to occupy three coordination sites about the metal in **1** then, together with the three chlorine ligands (two bridging, one terminal), each metal atom has pseudooctahedral coordination (sometimes termed "three-legged piano stool") as shown by the X-ray crystal structures of the isostructural complexes **1a** and **1b** (Figure 1).⁹ Six-coordination is almost invariably found for low-spin (d^6) Rh(III) and Ir(III) complexes.

Replacement of the chloride ligands occurs very easily; amines and tertiary phosphines cleave the

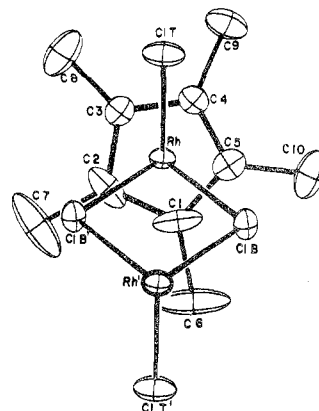
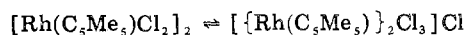


Figure 1. A portion of the $[\text{Rh}(\eta^5\text{-C}_5\text{Me}_5)\text{Cl}_2]_2$ molecule projected onto one C_5Me_5 ring, showing the "three-legged piano-stool" arrangement of ligands about Rh; the other C_5Me_5 ring is omitted for clarity. (Reproduced from ref 9.)

chlorine bridges to give the monomeric $[\text{M}(\text{C}_5\text{Me}_5)\text{Cl}_2\text{L}]$ (**4**, Scheme I). Another reaction of some interest is the formation of salts; it seems likely that in solution there is an equilibrium,



and the tris- μ -chloro binuclear cation (**5**) is easily obtained on adding $\text{Na}[\text{BPh}_4]$ to a solution of **1a**.¹⁰

A nice illustration of the surprising stability of these organometallics is that the rhodium complex **1a** dissolves in hot aqueous sodium hydroxide; from this solution the tris- μ -hydroxo compound (**6**, X = Cl) may be obtained as large orange crystals.¹⁰ The formation of binuclear cationic complexes with three bridging ligands is a recurrent feature of these C_5Me_5 -metal compounds; similar complexes are also now being found elsewhere,¹¹ and it appears that such systems are easily formed and have a high stability.

A wide variety of other metathesis reactions have also been carried out by Kang, Rigby, and others: chloride can be replaced by carboxylate,¹⁰ other halides,³ NO_2 , N_3 ,¹² etc., and some of these are shown in Scheme I.

Dicationic Complexes $[\text{M}(\text{C}_5\text{Me}_5)\text{L}_3]^{2+}$: Soft Centers and Hard Shells

Very useful dicationic mononuclear complexes are also easily made. For example, we found that treatment of **1** with AgPF_6 in the presence of a solvent ($s =$ acetonitrile, pyridine, acetone, THF, methanol, etc.) gives complexes of type **7**; when the ligands bind reasonably strongly ($s =$ MeCN, Me_2SO , pyridine,¹³ $(\text{MeO})_3\text{P}$ ¹⁴) these tris complexes can be isolated and characterized.¹³

The solvent molecules are easily displaced (e.g., reaction with arenes gives **8**), and therefore the more labile solvent complexes (especially **7**, $s =$ acetone) are valuable intermediates for the synthesis of dicationic sandwich compounds and related complexes. Many

(10) J. W. Kang and P. M. Maitlis, *J. Organometal. Chem.*, **30**, 127 (1971).

(11) E. A. Kelley, P. M. Bailey, and P. M. Maitlis, *J. Chem. Soc., Chem. Commun.*, 289 (1977). See also R. O. Gould, C. L. Jones, D. R. Robertson and T. A. Stephenson, *ibid.*, 232 (1977).

(12) W. Rigby, J. A. McCleverty, and P. M. Maitlis, unpublished results.

(13) C. White, S. J. Thompson, and P. M. Maitlis, *J. Chem. Soc., Dalton Trans.*, 1654 (1977).

(14) C. White, S. J. Thompson, and P. M. Maitlis, *J. Organometal. Chem.*, **136**, 87 (1977).

(5) J. W. Kang and P. M. Maitlis, *J. Am. Chem. Soc.*, **90**, 3259 (1968).

(6) L. A. Paquette and G. R. Krow, *Tetrahedron Lett.*, 2139 (1968);

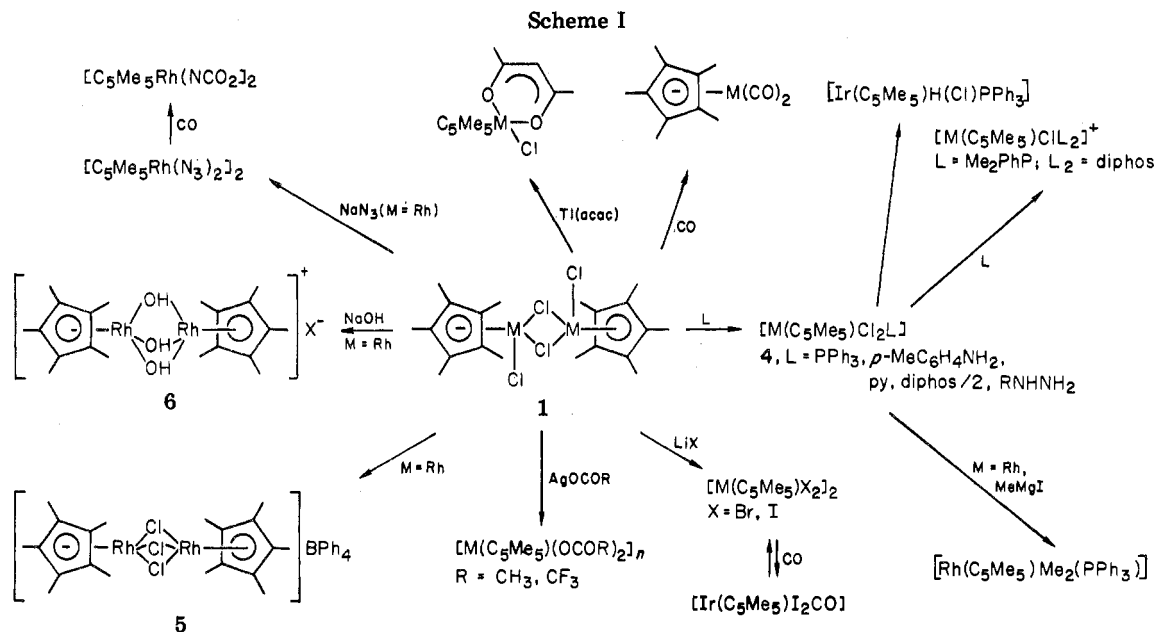
R. Criegee and H. Gruner, *Angew. Chem., Int. Ed. Engl.*, **6**, 467 (1968);

(7) D. Feitler and G. Whitesides, *Inorg. Chem.*, **15**, 466 (1976).

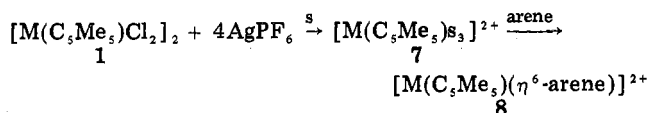
(8) J. Burrows, G. Fairhurst, C. White, and P. M. Maitlis, unpublished results.

(9) M. R. Churchill and S. A. Julis, *Inorg. Chem.*, **16**, 1488 (1977); M.

R. Churchill, S. A. Julis, and F. A. Rotella, *Inorg. Chem.*, **16**, 1137 (1977).



quite stable compounds of type 8 are known, and we may regard them as having soft centers and hard shells



in that they π -bond easily to unsaturated hydrocarbons and yet have a high positive charge overall. This rather unusual combination of properties has allowed White and Thompson to investigate the chemistry of a variety of organic ligands in highly positively charged environments.

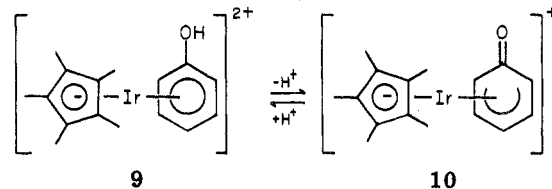
A more quantitative insight into the state of the metal here is given by the dimethyl sulfoxide complexes $[M(C_5Me_5)(Me_2SO)_3](PF_6)_2$; IR studies indicate the rhodium complex to be only O-bonded both in solution [$\nu(SO)$ 935 cm^{-1}] and in the solid [$\nu(SO)$ 926 cm^{-1}], but the iridium complex is both O- and S-bonded in the solid [$\nu(SO)$ 901, 1135 cm^{-1}] and only S-bonded in solution [$\nu(SO)$ 1128 cm^{-1}].¹³ Clearly therefore the iridium is a *softer* center than the rhodium, a point which is well borne out by the greater stability of the dicationic iridium sandwich complexes by comparison with their rhodium analogues.

The reaction 7 \rightarrow 8 can also be reversed in suitable cases, and an order of stability for these η^6 -arene complexes can be obtained. The η^6 -arene rhodium complexes are more labile than the iridium ones, and for each series stability is enhanced in proportion to the number of alkyl substituents on the benzene. For example, *p*-xylene in $[Rh(C_5Me_5)(p\text{-xylene})]^{2+}$ is displaced by dimethyl sulfoxide at 20 $^\circ C$ to give 7 ($M = Rh$, $s = Me_2SO$), and the analogous η^6 -benzene complex is rapidly solvolyzed by acetone at 20 $^\circ C$; by contrast, $[Ir(C_5Me_5)(benzene)]^{2+}$ is stable in Me_2SO solution.¹³

This observation is not unexpected since, even on very qualitative arguments, it may be anticipated that electron-releasing substituents (methyl groups) on the organic ligands would stabilize highly positively charged complexes.

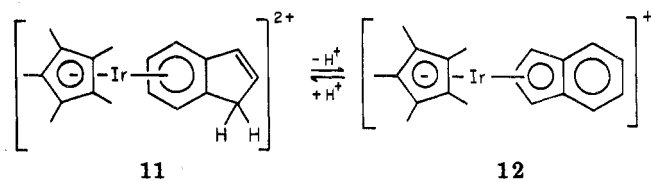
Apart from nucleophilic attack at the metal leading to total displacement of the η^6 ligand, both proton loss and nucleophilic attack at the ligand have been ob-

served. An interesting example of the former is the deprotonation of the η^6 -phenol complex 9 to [Ir-



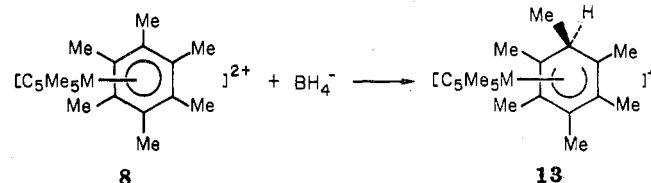
(C_5Me_5)(C_6H_5O)]²⁺, which is most satisfactorily described as an η^5 -oxocyclohexadienyl complex, 10.¹⁵

Another example is with indene; here deprotonation of the indene complex is accompanied by a change from η^6 coordination of the metal to the benzene ring, as in 11, to an η^5 coordination of the five-membered ring, 12.



Indole undergoes analogous transformations.¹³

Nucleophilic attack occurs when the ligand is not easily deprotonated; for example, the η^6 -hexamethylbenzene complexes give the η^5 -hexamethylcyclohexadienyl complexes 13 with sodium borohydride.¹⁶



Attack by hydride and other nucleophiles at the ring always occurs *exo* to the metal.

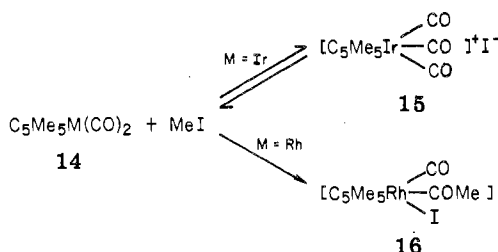
The 18-Electron Rhodium(I) and Iridium(I) Complexes

In addition to the very wide chemistry that the (pentamethylcyclopentadienyl)rhodium and -iridium

(15) C. White, S. J. Thompson, and P. M. Maitlis, *J. Organometal. Chem.*, 127, 415 (1977).

(16) C. White and P. M. Maitlis, *J. Chem. Soc. A*, 3322 (1971).

complexes display in the +III oxidation state, there is also an extensive chemistry in the +I (18-electron) oxidation state. Among the simplest complexes of this type are the carbonyls 14 which Kang obtained by

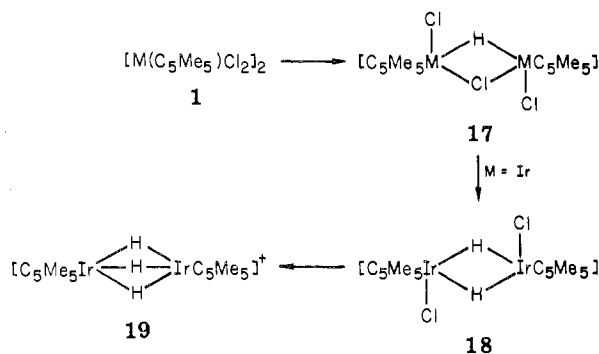


atmospheric pressure carbonylation of the chlorides in the presence of zinc metal (for 1a)¹⁷ or sodium carbonate (for 1b).³ These dicarbonyls undergo the oxidative addition reactions so characteristic of d⁸ complexes; for example, methyl iodide gives the adduct 15 reversibly with the iridium carbonyl 14b and the acetyl complex 16 with the rhodium carbonyl 14a.

The other important class of formally five-coordinate compounds of the metal in the I oxidation state are the [M(C₅Me₅)diene] complexes discussed below.

Bridged Hydride Complexes and the Heterolytic Activation of H₂

Since metal hydrides are the active species in metal-catalyzed hydrogen-transfer reactions, the hydrides derived from 1 are of particular interest. Moseley

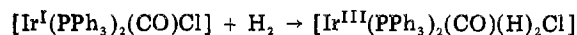


showed that the mononuclear iridium complex [Ir(C₅Me₅)Cl₂(PPh₃)] (4, L = PPh₃, M = Ir) reacts in ethanol/base to give the expected mononuclear complex containing a terminal hydride [Ir(C₅Me₅)(H)(Cl)(PPh₃)] [$\nu(\text{Ir-H}) = 2090 \text{ cm}^{-1}$].¹⁸ The dichlorides 1a and 1b are also readily reduced (by H₂/base or BH₄⁻ or KOH/2-propanol), but in this case White obtained the *binuclear mono-μ-hydrido* complexes 17.¹⁹

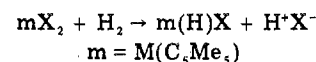
The iridium complex 17b, under more vigorous conditions, can be further converted into the di-μ-hydride 18²⁰ and, finally, into the tri-μ-hydride cation 19. Similar series are generated on reaction of the acetates or the trifluoroacetates, and the complexes [M(C₅Me₅)₂HX₂]⁺ and [M(C₅Me₅)₂H₂X]⁺ (X = CF₃CO₂, CH₃CO₂) have been made. However, no rhodium analogues of 18 or 19 could be obtained, and

even the rhodium-di-μ-hydrido-μ-acetato and -μ-trifluoroacetato complexes were rather unstable.¹⁹ These μ-hydrido complexes are, however, quite remarkably air-stable, particularly in the solid.

The reaction of each of these complexes with molecular hydrogen formally involves a *heterolytic* activation (H⁺...H⁻) of H₂ by the metal in which the hydridic hydrogen then replaces another anionic ligand in the complex. In this case there is no net change in formal oxidation state of the metal, and it may be contrasted with the more usual *homolytic* activation where an oxidative addition of H₂ occurs and where the metal changes from, for example, square-planar d⁸ to pseudooctahedral d⁶, as in Vaska's complex.²¹

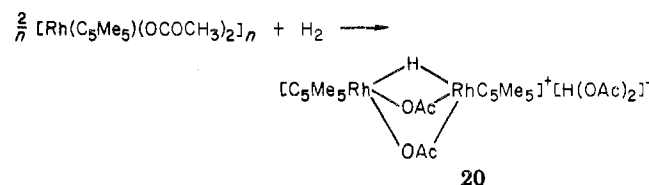


Clearly then, as acid is formed in the heterolytic activation, such reactions are expected to be base-



promoted. Thus the activation of molecular H₂ by the chlorides 1 or by [M(C₅Me₅)(OCOCH₃)₂]_n occurs at 20 °C and 1 atm only in the presence of base.

However, since acetic acid is a very weak acid the acetato complexes [M(C₅Me₅)(OCOCH₃)₂]_n react even in the absence of base, and a very simple demonstration experiment can be performed to show this heterolytic activation. When [Rh(C₅Me₅)(OCOCH₃)₂]_n is dissolved in a mixture of diethyl ether and hexane a yellow-brown solution is obtained; if this solution is now exposed briefly to H₂ under ambient conditions the solution immediately turns dark red and the ionic and insoluble dark-brown μ-hydrido complex 20 is precipitated out.



Air does not inhibit this reaction, and it is a remarkable indication of the readiness with which Rh-H bonds are formed in this activation of hydrogen that H₂ can be selectively sucked out of an air-hydrogen mixture above the surface of the solution.

The structures of these hydrido complexes were elucidated by normal spectroscopic means as well as by X-ray structure determinations of 17a,²² 17b,⁹ and [Ir(C₅Me₅)₂H(OCOCH₃)₂]_nPF₆²³ and by X-ray and neutron-diffraction determination of the tri-μ-hydride 19.²⁴ The M...M distances in the four molecules are 2.906 (1), 17a; 2.903 (1), 17b; 3.02, [(IrC₅Me₅)₂H(OAc)₂]⁺; and 2.455 (1) Å, 19, respectively. Particularly when these distances are compared with those in the dichloride dimers [3.719 (1), 1a, and 3.769 (1) Å, 1b⁹], it is clear that the bridging hydrides tie the metals together very effectively and that the greater the number of bridging hydrides the stronger is this interaction. Indeed it has been suggested that the complex 19 could be considered to possess a "triply protonated Ir≡Ir triple bond".²⁴ While there is no

(17) J. W. Kang and P. M. Maitlis, *J. Organometal. Chem.*, **26**, 393 (1971).

(18) K. Moseley, J. W. Kang, and P. M. Maitlis, *J. Chem. Soc. A*, 2875 (1970).

(19) C. White, A. J. Oliver, and P. M. Maitlis, *J. Chem. Soc., Dalton Trans.*, 1901 (1973).

(20) D. S. Gill and P. M. Maitlis, *J. Organometal. Chem.*, **87**, 559 (1975).

(21) L. Vaska and M. F. Wernecke, *Trans. N.Y. Acad. Sci.*, **31**, 70 (1971).

(22) M. R. Churchill and S. W. Ni, *J. Am. Chem. Soc.*, **95**, 2150 (1973).

(23) P. M. Bailey and P. M. Maitlis, unpublished results.

(24) R. Bau, W. E. Carroll, R. G. Teller, and T. F. Koetzle, *J. Am. Chem. Soc.*, **99**, 3872 (1977).

Table I
 Activity of Hydrogenation Catalysts in 2-Propanol

Catalyst	Conditions		Relative rates	Substrate	Product
	H ₂ , atm	Temp, °C			
[Rh(C ₅ Me ₅)Cl ₂] ₂ ^a	1	20	9.8 ^d	Cyclohexene	Cyclohexane
[Rh(C ₅ Me ₅)Br ₂] ₂ ^a	1	20	6.5 ^d	Cyclohexene	Cyclohexane
[Rh(C ₅ Me ₅)I ₂] ₂ ^a	1	20	0.6 ^d	Cyclohexene	Cyclohexane
[{Rh(C ₅ Me ₅) ₂ HCl ₃ }] ₂ ^a	1	20	5.1 ^d	Cyclohexene	Cyclohexane
[Ir(C ₅ Me ₅)Cl ₂] ₂ ^b	1	20	27.3 ^d	Cyclohexene	Cyclohexane
[{Ir(C ₅ Me ₅) ₂ HCl ₃ }] ₂ ^b	1	20	15.3 ^d	Cyclohexene	Cyclohexane
[{Ir(C ₅ Me ₅) ₂ H ₂ Cl ₂ }] ₂ ^b	1	20	13.2 ^d	Cyclohexene	Cyclohexane
[{Ir(C ₅ Me ₅) ₂ H ₃ }] ₂ ⁺	1	20	0 ^d	Cyclohexene	Cyclohexane
[Rh(PPh ₃) ₃ Cl] ₂ ^c	1	20	4.3 ^d	Cyclohexene	Cyclohexane
[{Rh(C ₅ Me ₅) ₂ HCl ₃ }] ₂ ^a	1	20	9.1 ^d	4-Methyl-1-pentene	4-Methylpentane
[{Rh(C ₅ Me ₅) ₂ HCl ₃ }] ₂ ^a	1	20	7.1 ^d	1-Hexene	Hexane
[{Rh(C ₅ Me ₅) ₂ HCl ₃ }] ₂ ^a	1	20	5.1 ^d	Cyclopentene	Cyclopentane
[{Rh(C ₅ Me ₅) ₂ HCl ₃ }] ₂ ^a	1	20	3.5 ^d	4-Methylcyclohexene	Methylcyclohexane
[{Rh(C ₅ Me ₅) ₂ HCl ₃ }] ₂ ^a	1	20	2.8 ^d	2-Methyl-1-pentene	2-Methylpentane
[{Rh(C ₅ Me ₅) ₂ HCl ₃ }] ₂ ^a	1	20	2.6 ^d	<i>cis</i> -4-Methyl-2-pentene	4-Methylpentane
[{Rh(C ₅ Me ₅) ₂ HCl ₃ }] ₂ ^a	1	20	1.4 ^d	<i>trans</i> -4-Methyl-2-pentene	4-Methylpentane
[{Rh(C ₅ Me ₅) ₂ HCl ₃ }] ₂ ^e	100	20	0.75 ^f	Vinylcyclohexene	Ethylcyclohexane
[{Rh(C ₅ Me ₅) ₂ HCl ₃ }] ₂ ^e	100	20	4.0 ^f	1,5-Hexadiene	Hexane
[{Rh(C ₅ Me ₅) ₂ HCl ₃ }] ₂ ^e	100	20	4.0 ^f	Mesityl oxide	Methyl isobutyl ketone
[{Rh(C ₅ Me ₅) ₂ HCl ₃ }] ₂ ^e	100	20	10.0 ^f	Vinyl acetate	Ethyl acetate (33%)
[{Rh(C ₅ Me ₅) ₂ HCl ₃ }] ₂ ^e	100	20	10.0 ^f	Diphenylacetylene	Stilbene (70%) Dibenzyl (30%)
[Rh(C ₅ Me ₅)Cl ₂] ₂ ^g	50	50	100 ^h	Benzene	Cyclohexane
[Rh(C ₅ Me ₅)Cl ₂] ₂ ^g	50	50	100 ^h	Toluene	Methylcyclohexane
[Rh(C ₅ Me ₅)Cl ₂] ₂ ^g	50	50	100 ^h	<i>o</i> -Xylene	<i>cis</i> - and <i>trans</i> -1,2-dimethyl- cyclohexane (6.2:1)
[Rh(C ₅ Me ₅)Cl ₂] ₂ ^g	50	50	60 ^h	Ethylbenzene	Ethylcyclohexane
[Rh(C ₅ Me ₅)Cl ₂] ₂ ^g	50	50	45 ^h	<i>tert</i> -Butylbenzene	<i>tert</i> -Butylcyclohexane
[Rh(C ₅ Me ₅)Cl ₂] ₂ ^g	50	50	100 ^h	Acetophenone	Methyl cyclohexyl ketone
[Rh(C ₅ Me ₅)Cl ₂] ₂ ^g	50	50	73 ^h	<i>N,N</i> -Dimethylaniline	<i>N,N</i> -Dimethylcyclohexylamine

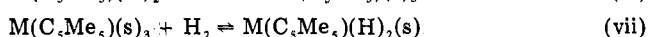
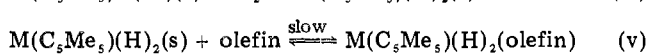
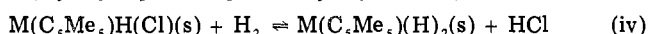
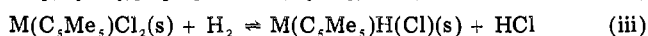
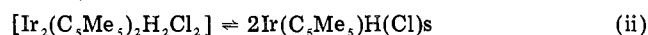
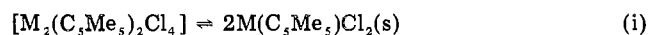
^a Catalyst (0.04 mmol), olefin (11.8 mmol), triethylamine (7.2 mmol) in 2-propanol. ^b As for (a) except with 0.36 mmol of triethylamine. ^c As for (a) except without triethylamine. ^d Measured as H₂ uptake in mL min⁻¹. ^e Catalyst (0.01 mmol), olefin (7.6 mmol) in 2-propanol (5 ml). ^f Relative rates expressed in hours required for complete reaction. ^g Catalyst (0.05 mmol), arene (2 mL), triethylamine (1.5 mmol) in 2-propanol (18 mL) for 36 h. ^h Rates expressed as percentages of product relative to benzene → cyclohexane which is 100% complete under these conditions.

iridium complexes in 2-propanol under conditions of high basicity, is totally inactive as a catalyst and that no rhodium analogue of this complex appears to exist.

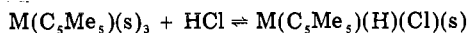
These results testify further to the kinetic inertness of M-H-M bridge bonds in these systems and suggest moreover that such bridges are absent in the most active catalysts. Evidence in favor of this comes from the observation that the most active systems were those based on the dichloride dimers [M₂(C₅Me₅)₂Cl₄] which showed activity proportional to [catalyst]^{1/2}, implying that the actual catalysts involved were monomer complexes of the type [M(C₅Me₅)H(X)s] (s = solvent or vacant site). Measurements during the first 10–20% of reaction indicated further that the rates were also proportional to [p(H₂)]² and that the olefin dependence was first order at low and zero order at high olefin concentration. The same dependence on [catalyst]^{1/2} and on olefin concentration was observed for the iridium di-μ-hydride 18, but here the dependence on hydrogen concentration was of the form [p(H₂)]¹.

These data suggest that for the dichloride dimers (and for [Ir(C₅Me₅)HCl]₂) the reaction paths in eq i–vii are probably most significant.

In the first steps (i, ii) solvent-assisted cleavage into monomers occurs. In steps iii and iv these heterolytically activate H₂ to give the probable “true” catalyst, [M(C₅Me₅)(H)₂(s)], which then reacts with olefin and more hydrogen in a cycle (steps v–vii). Steps vi and vii involve a formal reductive elimination (M^{III} → M^I + alkane) and an oxidative addition of H₂ to M^I, respectively, and this part of the process is broadly similar



or



to the mechanism which has been deduced for olefin hydrogenation catalyzed by [Rh(PPh₃)₃Cl]².

On the other hand, the mono-μ-hydride complexes 17, which showed a first-order dependence on [catalyst]¹, largely appear to react by a path where intermediates analogous to 23 (olefin in place of diene) play a key role and where dissociation to monomer does not occur to a significant extent in the initial stages. Strong support for the idea that an initial olefin activation is important here comes from the observation that (in dichloromethane in the absence of hydrogen and base) [Ir(C₅Me₅)₂HCl₃] is a very much better olefin isomerization catalyst than [Ir(C₅Me₅)HCl]₂ while [Ir(C₅Me₅)Cl₂]₂ is inactive.

Dienes and functional groups on the olefin tended to repress hydrogenation at 1 atm, but on increasing the hydrogen pressure satisfactory reduction could be achieved; the functional groups were, in general, not reduced under these conditions.

Under similar conditions, the rhodium dichloride complex **1a** is about twice as active (per rhodium atom) toward cyclohexene as the Wilkinson complex, and the iridium dichloride complex **1b** is about a factor of three more active still. However, whereas $[\text{RhCl}(\text{PPh}_3)_3]$ catalyzes the reduction of cyclohexene fifty times faster than 1-methylcyclohexene, the corresponding factor is only about 3 for **1a** and 7 for **1b**. This probably reflects a greater steric constraint in $[\text{RhCl}(\text{PPh}_3)_3]$ than in $[\text{Rh}(\text{C}_5\text{Me}_5)\text{Cl}_2]_2$.

A measure of the steric factors involved may be obtained from the cone angle, θ .³¹ For $\text{C}_5\text{Me}_5\text{-Rh}$ it is calculated to be 185° while for Ph_3P $\theta = 145^\circ$ and for the grouping *fac*- $\{(\text{Ph}_3\text{P})_2\text{Cl}\}$ /Rh θ is estimated as 230° . Clearly we may therefore anticipate the $\text{C}_5\text{Me}_5\text{-M}$ catalysts to be sterically rather less demanding than $[\text{Rh}(\text{Ph}_3\text{P})_3\text{Cl}]$.

Arene Hydrogenation Catalysts

While the homogeneous catalysis of olefin hydrogenation has now become almost a commonplace reaction, the hydrogenation of benzene and substituted benzenes is difficult even with heterogeneous catalysts.³² A few homogeneous catalysts have been reported to reduce benzenes to cyclohexanes³³ but they mostly appear to be rapidly deactivated or to have a limited range.

It is therefore of especial interest that Russell recently demonstrated that (pentamethylcyclopentadienyl)-rhodium complexes such as **1a** show reasonable activity for the reduction of benzene and substituted benzenes to cyclohexanes (Table I) at 50°C and 50 atm of hydrogen.³⁴ Again, base was a necessary cocatalyst and

2-propanol was the solvent of choice; this indicates, as is to be expected, the importance of a heterolytic hydrogen activation step in the reaction mechanism. No detectable amounts of metal were formed under these conditions, and turnover numbers of over 400 equiv of benzene to cyclohexane per rhodium have been obtained; in general, cyclohexenes and cyclohexadienes were not detected in the products. By contrast, the iridium complex **1b** showed only 28% of the activity of **1a**; this may correlate with the greater stability of the Ir^{III} -arene by comparison with the Rh^{III} -arene complexes previously noted, and it is interesting that **1a** reduces most easily those alkylated benzenes that form the least stable complexes in **8**. $[\text{Rh}(\text{Ph}_3\text{P})_3\text{Cl}]$ only showed 3% of the activity of **1a**, and $[\text{Co}(\text{C}_5\text{Me}_5)\text{I}_2]_2$ decomposed to metal under the same conditions.

Analysis of the products formed by **1a**-catalyzed reduction of the *o*-, *m*-, and *p*-xylenes showed a high stereoselectivity for the formation of the *cis*-dimethylcyclohexanes [*cis:trans* = 6.2:1 (*o*-xylene), 3.8:1 (*m*-xylene), and 2:1 (*p*-xylene)]. Our preliminary results also show that the catalyst can tolerate at least some functional groups on the arene, for example, $-\text{CO}_2\text{R}$, $-\text{COR}$, $-\text{NMe}_2$, OMe .

Activity as hydrogenation catalysts certainly only represents one aspect of the chemistry of these very versatile complexes, and more applications will undoubtedly be found. The recent syntheses of alkyl-substituted tetramethylcyclopentadienes makes the formation of $[\text{M}(\text{C}_5\text{Me}_4\text{R})\text{X}_2]_2$ complexes possible, and it should also be possible to attach $(\text{C}_5\text{Me}_4\text{R})\text{-RhX}_2$ onto polymers to give supported catalysts.

The studies described here are due primarily to the dedicated efforts of my co-workers both in Sheffield and at McMaster University in Canada. I should in particular like to thank and to pay tribute to the excellent work of Dr. Colin White, Dr. J. W. Kang, Dr. K. Moseley, Dr. A. J. Oliver, Dr. H. B. Lee, Dr. D. S. Gill, Dr. S. J. Thompson, and Dr. M. J. H. Russell.

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The Prenyl Transfer Reaction. Enzymatic and Mechanistic Studies of the 1'-4 Coupling Reaction in the Terpene Biosynthetic Pathway

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The terpene biosynthetic pathway is used to synthesize a wide variety of small molecules which are often

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lipophilic and fulfill a multiplicity of functions. Important examples are sterols (structural components of eukaryotic membranes), carotenes (photoreceptors in visual and photosynthetic systems), and phosphorylated polyprenols (membrane-soluble carriers of sugars in the biosynthesis of bacterial cell wall polysaccharides and eukaryotic glycoproteins). In other systems the hydrophobic polyisoprenoid chain is used to anchor respiratory coenzymes (ubiquinone, porphyrin a) or chlorophyll to membranes. Terpenes are also involved in communication between organs (hormones) and organisms (pheromones). In addition to these few