# Reactivity of Ketones in Homogeneous Catalytic Hydrogenation with Cationic Rhodium Complexes

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The catalytic hydrogenation of several ketones with cationic rhodium complexes has been investigated at 30 °C with hydrogen at atmospheric pressure. The rate of the reaction depended very much on the structure of both the ketone and phosphine ligand, with triethylphosphine giving the highest activity among the ligands used. An electron-withdrawing substituent in the ketone was found to increase its reactivity among both alkyl and aryl ketones; the rates of reaction of the former ketones were generally faster. Benzyl methyl ketone showed a very high reactivity among aryl ketones, suggesting that the phenyl group may be in a position to interact with the rhodium atom to enhance the reactivity. Unsaturated ketones are hydrogenated catalytically to yield saturated ketones first, which are further hydrogenated to corresponding saturated alcohols. No trace of unsaturated alcohol was observed in this hydrogenation, even when the hydrogenation rate of the olefinic bond in the unsaturated ketone was much smaller than that of the carbonyl group of the corresponding saturated ketone in the consecutive hydrogenation. The reactivities of ketones are discussed in connection with their co-ordination and the hydrogenation mechanisms.

HOMOGENEOUS hydrogenation of the carbonyl group using transition-metal catalysts has been extensively studied under rather severe conditions, although a few complexes are known to be quite reactive under atmospheric pressure at ambient temperature.[1,2] Cationic rhodium complexes, such as $[Rh(diene)(PR_3)_n]^{+}$[3] and $[Rh(bipy)_2]^{+}$,[4] and dimethylglyoximatocobalt [5] are such catalysts. By use of the latter catalyst, asymmetric hydrogenation of some carbonyl compounds was reported using chiral amines. The cationic rhodium complexes are interesting because of their high catalytic activity for the hydrogenation of carbon–oxygen as well as carbon–carbon unsaturated bonds, and the possibility of catalyst design by varying the ligands. Marko *et al.*[6] have reported the effects of phosphorus ligands on the catalytic activity for the hydrogenation of acetone when the cationic complexes were prepared *in situ* from $[Rh(norbornadiene)Cl]_2$ and phosphorus ligands without characterising the co-ordination compound involved in the catalysis.

In the present study, the catalytic activity of cationic rhodium complexes, prepared *in situ* from [Rh(norbornadiene) $(PR_3)_{2 \text{ or } 3}][ClO_4]$, was compared in the hydrogenation of various ketones, including unsaturated ones. The structure of the the active species is expected to influence the catalysis. To elucidate the catalytic mechanism, the following factors required investigation: (1) the influences of the structure of the carbonyl substrates on their reactivities in catalytic hydrogenation (2) the comparative reactivity of carbon–carbon and carbon–oxygen unsaturated bonds; (3) the influences of the phosphorus ligands on the catalytic activity for the hydrogenation of various ketones.

## RESULTS AND DISCUSSION

*Reactivity of Methyl Ketones towards Hydrogenation.*— The conversions of eight methyl ketones after 1-h and 5-h reaction periods are listed in Table 1; four cationic rhodium complexes carrying different phosphorus ligands were used. The conversion levels depended significantly both on the ligands and ketones. For all ketones, the $PEt_3$ complex showed the greatest catalytic activity. In contrast, $PPh_3$ and diphos ones showed essentially no catalytic activity for any of the ketones studied. The catalytic activity decreased in the order $(PEt_3)_2 > (PMe_3)_3 \gg (PPh_3)_2 \approx$ diphos $= 0$. This order of reactivity is the same as that of Marko *et al.*,[6] although the complexes in that work were prepared *in situ*.

TABLE 1

Catalytic activities of cationic rhodium complexes for the hydrogenation of methyl ketones

| R–C(=O)–Me | Conversion (%) | | | |
|---|---|---|---|---|
| | $PEt_3$ | $PMe_3$ | $PPh_3$ | diphos |
| Me | 8.2 [a]/39.7 [b] | 7.7 | 0 | 0 |
| Et | 4.7 [a]/22.1 [b] | | 0 | 0 |
| $Pr^n$ | 3.0 [a]/16.2 [b] | | | |
| $MeOCH_2$ | 80.1 [a]/100 [b] | | 0 | 0 |
| Ph | 5.5 [a]/23.6 [b] | 1.3 [a]/5.0 [b] | 0 | 0 |
| $PhCH_2$ | 6.3 [a]/52.7 [b] | 0.5 [a]/11.7 [b] | 0 | 0 |
| $Ph[CH_2]_2$ | 1.6 [a]/11.5 [b] | | | |
| $(Ph)_2CH$ | 5.9 [a]/19.5 [b] | | | |

Catalyst; 0.1 mmol in 1% aqueous diglyme (50 ml); ketone: $1 \times 10^{-2}$ mol; 1 atm pressure of hydrogen at 30 °C.

[a] Reaction time 1 h. [b] Reaction time 5 h.

The reactivity of the ketones used in the present study varied widely. The highest reactivity, *i.e.* that of the methoxymethyl methyl ketone with the $PEt_3$ complex, indicates the influences of an electron-withdrawing group.

The hydrogenation of all methyl ketones (except benzyl methyl ketone) by the $PEt_3$ complex proceeded smoothly and was completed on prolonged reaction. Benzyl methyl ketone behaved rather unusually; the hydrogenation was very slow at the latter stage of the reaction and completion was not achieved even after 20 h, when conversion was 82% (Figure 1).

In Table 2 and Figures 2—6, the conversions and reaction profiles observed in the hydrogenation of five unsaturated ketones with the $PEt_3$ complex are shown. The hydrogenation of methyl vinyl ketone showed a completely consecutive reaction profile, in which methyl

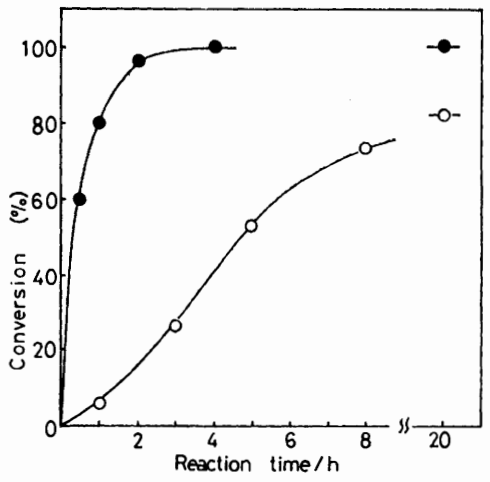



FIGURE 1 Hydrogenation of methoxymethyl methyl ketone and benzyl methyl ketone with $[Rh(NBD)(PEt_3)_2]^+$; catalyst, 0.1 mmol in 1% aqueous diglyme (50 ml); ketone, 10 mmol; reaction temperature, 30 °C; 1 atm $H_2$; ●, $MeOCH_2COMe$; ○, $PhCH_2COMe$

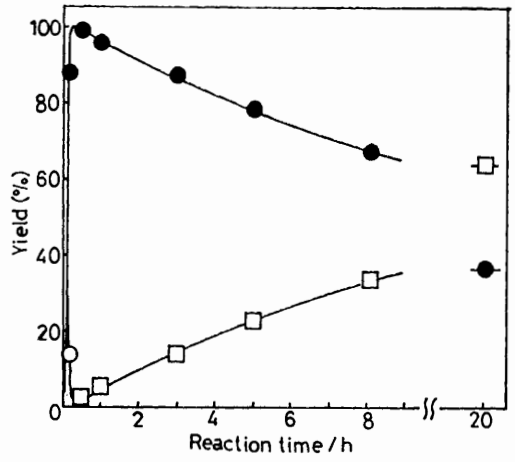



FIGURE 2 Hydrogenation of methyl vinyl ketone with $[Rh(NBD)(PEt_3)_2]^+$; ○, methyl vinyl ketone; ●, methyl ethyl ketone; □, butan-2-ol

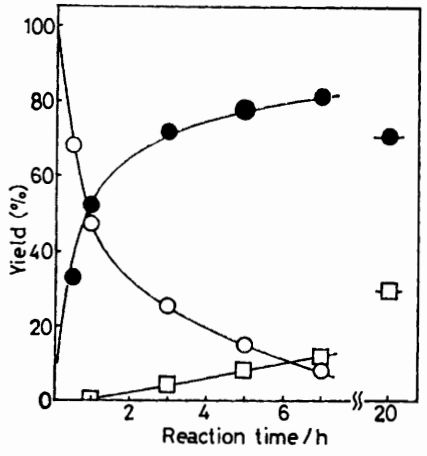



FIGURE 3 Hydrogenation of pent-3-en-2-one with $[Rh(NBD)(PEt_3)_2]^+$; ○, pent-3-en-2-one; ●, pentan-2-one; □, pentan-2-ol

TABLE 2

Catalytic hydrogenation of unsaturated ketones with $[Rh(NBD)(PEt_3)_2][ClO_4]$

| Ketone | Reaction time/h | Yield (%) *a* | *b* | *c* |
|---|---|---|---|---|
| Methyl vinyl ketone [d] | 1 | 95.3 | 4.7 | 0 |
| Pent-3-en-2-one [d] | 5 | 77.3 | 7.8 | 0 |
| Cyclohex-2-enone [e] | 5 | 0.8 | 98.2 | 0 |
| 3-Methylcyclohex-2-enone [e] | 5 | 6.7 | 21.2 | 0 |
| 6-Methylhept-5-en-2-one [d] | 4.5 | 19.6 | 7.4 | 0 |

Catalyst; 0.1 mmol; ketone: 10 mmol; 30 °C; 1 atm $H_2$. [a] Saturated ketone. [b] Saturated alcohol. [c] Unsaturated alcohol. [d] Solvent 1% aqueous diglyme. [e] Solvent methanol.

ethyl ketone was not hydrogenated until all the methyl vinyl ketone had been consumed; no but-1-en-3-ol could be detected during the reaction (Figure 2). Pentan-2-ol was consecutively produced from pent-3-en-2-

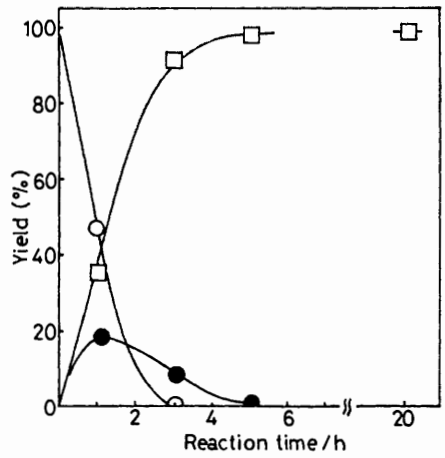



FIGURE 4 Hydrogenation of cyclohex-2-enone with $[Rh(NBD)(PEt_3)_2]^+$; ○, cyclohex-2-enone; ●, cyclohexanone; □, cyclohexanol

one *via* pentan-2-one, which was hydrogenated while some of the unsaturated ketone was still remaining (Figure 3). In the cases of cyclohex-2-enone and 3-methylcyclohex-2-enone, the saturated alcohols

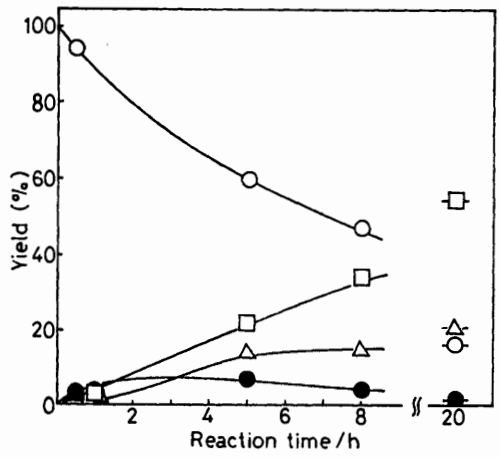



FIGURE 5 Hydrogenation of 3-methylcyclohex-2-one with $[Rh(NBD)(PEt_3)_2]^+$; ○, 3-methylcyclohex-2-enone; ●, 3-methylcyclohexanone; □, 3-methylcyclohexanol; △, unidentified product

were produced at an earlier stage of the reaction while most of the starting substrate was still present in the system. Nevertheless, no unsaturated alcohol could be detected (Figures 4 and 5). It was not possible to hydrogenate 6-methylhept-5-en-2-one, a non-conjugated unsaturated ketone, to 6-methylhept-5-en-2-ol. The olefinic bond of the substrate was hydrogenated much faster than the carbonyl groups of the intermediate 6-methylheptan-2-one or the substrate itself. Two reaction paths should be possible for the hydrogenation of unsaturated ketones, since the rhodium complex is

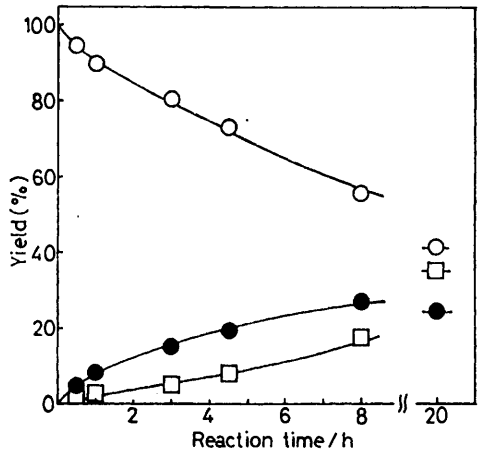
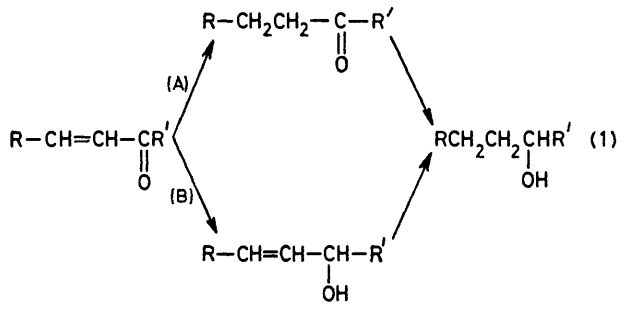



FIGURE 6 Hydrogenation of 6-methylhept-5-en-2-one with $[Rh(NBD)(PEt_3)_2]^+$; ○, 6-methylhept-5-en-2-one; ●, 6-methylheptan-2-one; □, 6-methylheptan-2-ol

expected to catalyse the hydrogenation of both ketone and olefin [equation (1)]. All the unsaturated ketones used here were hydrogenated *via* path (A), no unsaturated alcohol being produced.




The hydrogenation of the olefinic bonds in methyl vinyl ketone and styrene with four rhodium complexes is given in Table 3. Conversions depended very much on the phosphorus ligands. For methyl vinyl ketone, the activity decreased in the order $(PEt_3)_2 \gg (PPh_3)_2 \approx$ diphos $\gg (PMe_3)_3$ and the reactions were almost zero-order in the substrate; the hydrogenation rates of styrene were much slower than those of methyl vinyl ketone with all complexes, the reactivity decreasing in the order $(PPh_3)_2 \approx (PMe_3)_3 \gg (PEt_3)_2 >$ diphos.

*Effects of Additives on the Catalytic Activity.*—The catalyst precursor, $[Rh(norbornadiene)(PR_3)_{2\text{ or }3}]^+$ [except for $(PR_3)_2$ = diphos] is reported to react with 3 mol of hydrogen, producing the dihydrido-species (I)

TABLE 3

Hydrogenation of the olefinic bond in methyl vinyl ketone and styrene with cationic rhodium complexes

| Phosphine | Conversion (%) $H_2C=CH-CO-Me$ [a] | Conversion (%) $PhCH=CH_2$ [b] |
|---|---|---|
| $(PEt_3)_2$ | 87.0 (7.0) [c] | 25.0 |
| $(PMe_3)_3$ | 11.7 | 74.5 |
| $(PPh_3)_2$ | 48.8 | 81.7 |
| diphos | 37.7 | 16.6 |

For reaction conditions, see Table 1.

[a] Reaction time 10 min. [b] Reaction time 1 h. [c] Triethylamine (2 mol) was added.

and norbornane [equation (2)].[7] The cationic dihydrido-species may be in equilibrium with the neutral monohydrido-species (II) [equation (2)].

$$[Rh(norbornadiene)(PR_3)_{2\text{ or }3}]^+ \xrightarrow[-\text{norbornane}]{3H_2} \underset{(I)}{\{[RhH_2(PR_3)_{2\text{ or }3}S_x]^+} \rightleftharpoons \underset{(II)}{[RhH(PR_3)_{2\text{ or }3}S_y]\}} \quad (2)$$

S = solvent molecule

For the hydrogenation of acetone with the $PEt_3$ complex, the addition of 2 mol of $NEt_3$ suppressed the reaction rate to by a factor of ten (Figure 7), indicating

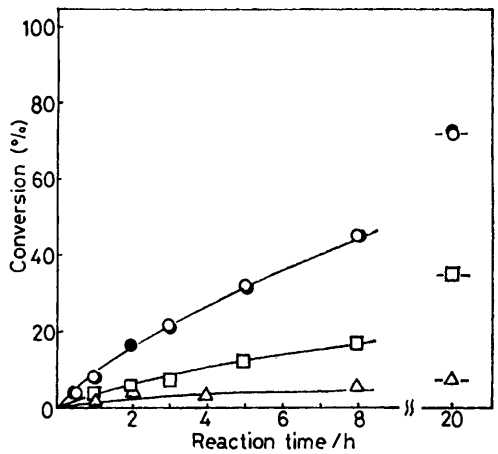
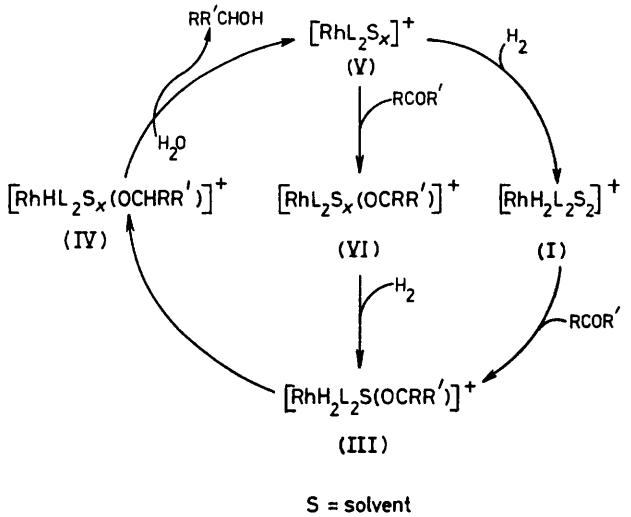



FIGURE 7 Hydrogenation of acetone with $[Rh(NBD)(PEt_3)_2]^+$; catalyst, 0.1 mmol in 1% aqueous diglyme (50 ml); acetone, 10 mmol; reaction temperature, 30 °C; ○, $H_2$ pressure 76 cmHg; ●, $H_2$ pressure 30 cmHg; □, $H_2$ pressure 76 cmHg, with 0.2 mmol $HClO_4$; △, $H_2$ pressure 76 cmHg, with 0.2 mmol $NEt_3$

that the dihydrido-complex (I) is the active species; the monohydrido-species (II) is known to be much more active than the dihydrido-species for the hydrogenation of hex-1-ene.[7] In spite of this explanation, 2 mol of perchloric acid did not cause any increase of the catalytic activity (Figure 7). Protonation of the ketone may cause suppression of the reactivity. Addition of $NEt_3$ also suppressed the hydrogenation of the olefinic bond of methyl vinyl ketone (Table 3). Thus, the dihydrido-species can also be assumed to be the active catalyst for the hydrogenation of the olefinic bond in the conjugated

unsaturated ketones. Some modification can be suggested to the scheme proposed by Osborn *et al.* (Scheme).[3]




SCHEME

*Mechanism of the Catalysis.—Methyl ketones.* As shown in Figure 7, the rate of hydrogenation of acetone with the $PEt_3$ complex at 760 mmHg hydrogen was almost same as that at 300 mmHg, indicating zero-order kinetics in hydrogen. Dependence of reaction rate on the initial concentration of acetone shown in Figure 8

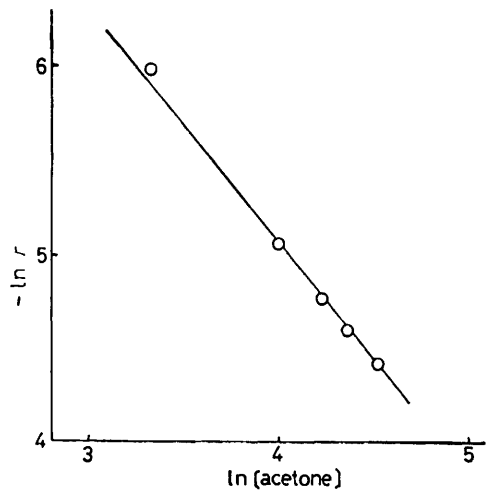



FIGURE 8 Hydrogenation of acetone with $[Rh(NBD)(PEt_3)_2]^+$

indicates an order of 1.1. Reactions of other ketones were also of first-order in the substrate in the conversion range of 50—80%, suggesting that the co-ordination of the carbonyl group of the ketone to the rhodium atom participates in the rate-determining step [(I) ⟶ (III) in the Scheme). Electronic and steric factors of the substituent adjacent to the carbonyl group may influence the co-ordination of the double bond to the rhodium atom. Hydrogenation rates of methyl ketones are *vs.* Taft σ*-values of the substituents are plotted in Figure 9. A linear correlation was observed among saturated methyl ketones. Increasing the electron-withdrawing ability of the substituent enhances the reactivity of the ketone. Another correlation was observed for the derivatives carrying a phenyl group (except for benzyl methyl ketone). Electron-withdrawal by the substituent increases the polarization of the carbonyl group,

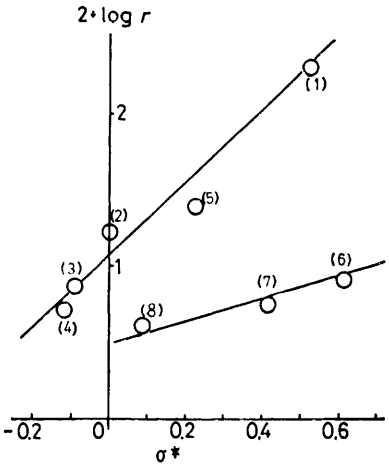
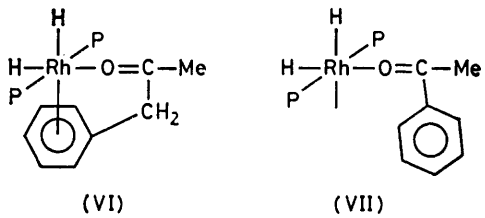



FIGURE 9 Reactivities of methyl ketones; (1) $MeOCH_2COMe$; (2) $Me_2CO$; (3) EtCOMe; (4) $Pr^nCOMe$; (5) $PhCH_2COMe$; (6) PhCOMe; (7) $Ph_2CHCOMe$; (8) $PhCH_2CH_2COMe$

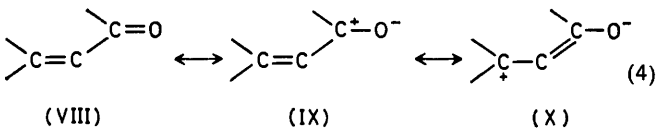
resulting in an increase in the co-ordinating ability and in susceptibility to hydride attack on the carbon atom of the carbonyl. The very high reactivity of benzyl methyl ketone may be related to the co-ordination of its phenyl group;[8] it may be able to chelate to the rhodium atom through both the carbonyl and phenyl groups [(VI), equation (3)], whereas the phenyl group of *e.g.* acetophenone cannot co-ordinate to Rh for steric reasons [(VII), equation (3)]. The two phenyl groups of benzhydryl methyl ketone cannot both co-ordinate to the rhodium atom because of steric hindrance.




*Unsaturated Ketones.*—Unsaturated ketones in the presence of the $PEt_3$ complex are hydrogenated in a consecutive manner *via* path (A) [equation (1)]; no unsaturated alcohol was obtained. The reactivities of the functional groups in unsaturated ketones are in the order olefinic bond > carbonyl groups in saturated ketone ≫ carbonyl group in unsaturated ketone.

The $^{13}C$ n.m.r. chemical shifts of carbonyl carbon in unsaturated ketones are generally to higher field because of conjugation with the olefinic double bond.[9] Electron donation from the π-electron system of the olefinic bond may increase the electron density of the carbonyl group *via* the resonance forms (IX) and (X).[9]

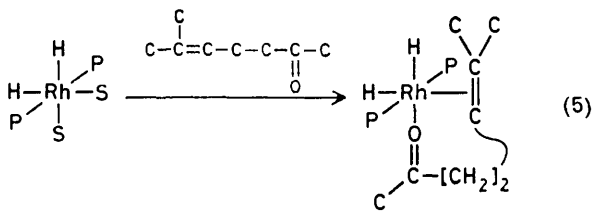
The lower wave-numbers of carbonyl stretch in unsaturated ketones may also support the canonical forms in equation (4). This resonance may decrease both the co-ordinating ability and the susceptibility to hydride attack of the carbon atom of the carbonyl group in unsaturated conjugated carbonyls compared to saturated



(VIII) (IX) (X) (4)

carbonyl compounds, explaining the reactivity order mentioned above.

Strong co-ordination of the olefinic bond results in its preferential hydrogenation. Chelation of non-conjugated unsaturated ketones, such as 6-methylhept-3-en-2-one, *via* the double bond and the carbonyl group may be possible [equation (5)]. *N*-Acetylphenylalanine methyl ester has been reported to co-ordinate to the rhodium–diphos complex in a similar manner.[10] Selective hydrogenation of the olefinic bond may occur in such a chelate since the hydride *cis* to the olefin may become more reactive than the *trans* one due to the superior *trans*-effect of the olefinic double bond to decrease its anionic character.



(5)

*Olefinic Bonds.*—The reactivity of the olefinic bond in unsaturated ketones was decreased by methyl substitution at the α-position (Table 2, Figures 2—6), suggesting that steric hindrance is an important factor. A first-order reaction of the inner olefinic bond in contrast to a zero-order reaction for methyl vinyl ketone may be ascribed to this fact. Methyl vinyl ketone, which co-ordinates strongly to rhodium, is hydrogenated more rapidly by more basic catalysts, as shown by the activity order $PEt_3 \gg PPh_3 \sim$ diphos. The large steric hindrance due to tris-co-ordination of the $PMe_3$ complex may cause its low activity.

For styrene the catalytic activity order, $PPh_3 > PMe_3 \gg PEt_3 >$ diphos, was different from that for methyl vinyl ketone. Reaction rates were also much slower than those of methyl vinyl ketone for all phosphorus ligands. Halpern *et al.*[10] reported that styrene formed an adduct with $[Rh(diphos)]^+$ more easily than hex-1-ene by a factor of 10. This fact suggests that the co-ordination of styrene to species (V) may hinder strongly the formation of a cationic dihydrido-species. In contrast, the dihydrido-species (I) can be formed easily in the hydrogenation of methyl vinyl ketone, becoming the active species.

*Catalytic Activity of Cationic Rhodium Complexes.*—The catalytic activity of cationic rhodium complexes towards ketones was very dependent on the phosphorus ligands. For all ketones used here the catalytic activity order was $(PEt_3)_2 > (PMe_3)_3 \gg (PPh_3)_2$, $\approx$ diphos = 0. This order is in accordance with that of the anionic character of co-ordinated hydrogen in (I), which is linked to the chemical shift of the hydride ligand ($PEt_3$ complex, (δ −17.80; $PPh_3$ complex, δ −16.37). The basicity of the phosphorus ligands ($PEt_3 > PMe_3 > PPh_3$[6]) may tend to hinder the co-ordination of the ketone. Thus, the co-ordination to the $PEt_3$ complex may be most difficult, whereas the co-ordinated ketone may be rapidly hydrogenated by the most reactive hydride, defining the co-ordination as the rate-determining step. In contrast, the rhodium complex of the less basic $PPh_3$ is known to form a stable adduct with acetone, $\{[RhH_2(PPh_3)_2(acetone)(EtOH)][ClO_4]\}$.[7] The rate-determining step may be the hydride shift in this case. The diphos complex $[Rh(NBD)(diphos)]^+$ was reported to form $[Rh(diphos)]^+$ instead of a dihydrido-species under hydrogen pressure,[10] suggesting that the rate-determining step may be the hydride shift and/or hydrogen co-ordination.

## EXPERIMENTAL

The catalyst precursors, $[Rh(NBD)(PR_3)_{2 \text{ or } 3}][ClO_4]$ (NBD = norbornadiene, $PR_3$ = tertiary phosphine), were prepared under a nitrogen atmosphere according to the methods described in the literature.[11] Because the catalyst precursors, especially the $PEt_3$ one, were very unstable in the presence of oxygen and moisture, they were dried under vacuum, and stored in sealed tubes under pure, dry nitrogen. Ketones and olefins were commercially available reagents of the highest grade. They were used without further purification. Diglyme (Wako Junyaku Co.) as a reaction solvent was dried by refluxing with sodium, distilled, and stored in a sealed glass tube.

The reactions were carried out in a glass reactor equipped with greaseless valves described elsewhere.[12] The catalyst precursor( 0.1 mmol) was dissolved in 1% aqueous diglyme (50 ml) under nitrogen; nitrogen was then replaced with hydrogen, the solution being left for 5 min under 1 atm of hydrogen to yield the active hydrido-complex. The ketone (10 mmol) was injected with a syringe through a silicone rubber stopper to start the reaction. The reaction was followed by gas chromatographic analysis (Yanako G180: column, polyethylene glycol 20M, 2 m, polyethylene glycol 4000, 2 m) of a small portion of the reaction mixture (0.2 ml) which was sampled by the equipment [12] at appropriate intervals without any contact of the reaction system with air.

Nuclear magnetic resonance spectra of the hydrido-complexes in $CDCl_3$ were recorded in a sealed tube filled with hydrogen on a JEOL FX-100 spectrometer.

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