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Homogeneous hydrogenation of ketones in the presence of $H_2Ru(CO)_2(PPh_3)_2$ †

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The hydrogenation of ketones to alcohols in the presence of a hydrido ruthenium triphenylphosphine complex, $H_2Ru(CO)_2(PPh_3)_2$, has been investigated. Acetophenone was hydrogenated at 120 °C with a conversion of 69% after 24 h. The yield is 85% working at 140 °C. A kinetic investigation of the reaction was also performed: the reaction is first order with respect to the hydrogen pressure, substrate and catalyst concentration. The rate of hydrogenation depends on the nature of the substrate: steric and electronic effects have a strong influence on the hydrogenation of ketones. 2,2,2-Trifluoroacetophenone is almost completely hydrogenated at 120 °C after 3 h. A mechanism has been tentatively suggested for the hydrogenation of ketones in which the coordination of the substrate to the metal is followed by its insertion into the ruthenium–hydrido bond with formation of the corresponding alkoxide. This complex reacts with hydrogen, restoring the catalyst and forming the alcohol. We have also tested the activity of this catalyst in the hydrogenation of an *α,β*-unsaturated ketone (*trans*-4-phenylbut-3-en-2-one). The C=C double bond is preferentially hydrogenated with a high chemoselectivity (92.4% at 100 °C). The data collected on the hydrogenation of *trans*-4-phenylbut-3-en-2-one suggest a different mechanism in which the rate-determining step is the interaction between the C=C double bond of the ketone with the metal–hydrido bond. Experimental evidence is reported to support this different hypothesis.

Keywords: hydrogenation; ketones; ruthenium; homogeneous catalysis; hydride

INTRODUCTION

In recent years the need for sterically defined compounds, i.e. alcohols, is increasing, especially in the field of pharmaceutical and agrochemical products. In this context a considerable effort has been devoted to this problem and the hydrogenation of aldehydes and ketones has been performed in the presence of transition-metal complexes. The homogeneous catalytic hydrogenation of these substrates leads to better results in terms of both stereo- and regio-selectivity for the industrial synthesis. Several organometallic complexes have been proposed as possible catalysts in homogeneous phase; the best compounds are Group VIII metal complexes, in particular rhodium or ruthenium compounds.[1,2]

Ruthenium complexes have already been employed in the hydrogenation of alkynes,[3] alkenes,[3] aldehydes,[4,5] ketones[5,6] and α,β-unsaturated ketones.[7] The most convenient catalytic precursors are phosphine-substituted hydrido ruthenium compounds because these complexes do not promote the decarbonylation of the starting substrate.

Several reaction mechanisms have been reported for the hydrogenation of aldehydes and ketones using these precursors.[4,8,9] The catalytically active species involved in this reaction are usually supposed to be hydrido complexes, even if the starting catalyst does not contain hydridic hydrogens.

The rate-determining step is usually attributed to the initial coordination of the carbonyl group to the metal through the oxygen atom to give, in the subsequent step, a metal alkoxide as the key intermediate. The following steps are the reaction with molecular hydrogen or hydrogen donors, followed by the elimination of the hydrogenated

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product while the initial catalyst is restored. Nevertheless very few examples are reported of isolated and characterized transition-metal alkoxides[8,10,11,12] that are suggested in the catalytic cycle. These compounds are stable when electron-withdrawing groups are present:[8] for example, by reaction of 2,2,2-trifluoroacetophenone with $HCo(N_2)(PPh_3)$ or $H_2Ru(PPh_3)_4$ metal alkoxides have been isolated and characterized through ^1H NMR, ^{31}P NMR, and IR spectroscopy.

Recently, we have found a simple and quantitative method for the synthesis of the pure hydrido ruthenium complex $H_2Ru(CO)_2(PPh_3)_2$.[13] It has therefore been possible to evaluate its catalytic activity because it has been proposed as an intermediate in the homogeneous hydrogenation of carbonyl groups in the presence of the Ru(0) $[Ru(CO)_3(PPh_3)_2]$ or the Ru(II) $[Ru(CO)_2(CH_3COO)_2(PPh_3)_2]$ complexes.[4,14]

RESULTS AND DISCUSSION

The catalytic activity of the ruthenium complex $H_2Ru(CO)_2(PPh_3)_2$ in the hydrogenation of simple ketones has been studied with the aim of detecting the best hydrogenation conditions and of obtaining information on the reaction mechanism.

Hydrogenation tests were carried out using acetophenone as the reference substrate: the influence of reaction parameters such as temperature, hydrogen pressure, and substrate and catalyst concentration was evaluated. Under appropriate reaction conditions a kinetic investigation of the reaction was also performed. The rate of hydrogenation of substituted ketones having substituents with different steric and electronic effects on the C=O group was also investigated.

The hydrogenation of an α, β-unsaturated ketone (*trans*-4-phenylbut-3-en-2-one) has also been investigated. The chemoselectivity of the reaction, i.e. the preferential activity of this catalyst in the hydrogenation of the carbonylic group and/or the C=C double bond, has been evaluated.

2.1 Hydrogenation of acetophenone

Several tests have been carried out in toluene as solvent with a substrate/catalyst ratio of 87:1. The conversion of the substrate has been evaluated by gas chromatographic analysis (GC) and the identity of the products confirmed with pure samples or by GC–MS analysis. A total chemoselectivity of the reaction has always been achieved, i.e. the only hydrogenated product was 1-phenylethanol.

Table 1 Influence of temperature on the hydrogenation of acetophenone in the presence of $H_2Ru(CO)_2(PPh_3)_2$[a]

T (°C)	Yield (%)
80	3.0
100	7.3
110	13.3
120	16.5
140	39.0

[a] Catalyst, 1.73×10^{-5} mol; substrate, 1.50×10^{-3} mol; solvent, 4.0 ml toluene; $p(H_2)$, 50 atm at 20 °C; reaction time, 3 h.

2.1.1 Influence of reaction temperature

In order to determine the most appropriate conditions, several experiments were carried out in the temperature range between 80 and 140 °C, under a hydrogen pressure of 50 atm with a reaction time of 3 h. At 80 °C the hydrogenation rate is very low: a conversion of only 3.0% has been obtained after 3 h; at 140 °C the conversion to 1-phenylethanol reaches 39.0% (Table 1).

The reaction rate at 120 °C appeared appropriate for a kinetic investigation.

2.1.2 Influence of hydrogen pressure

Reactions were performed under a constant hydrogen pressure in the range between 5 and 100 atm, at 120 °C with a reaction time of 3 h and a catalyst concentration of 4.31 mmol l^{-1}.

A positive effect of hydrogen pressure has been shown, and the conversion to 1-phenylethanol increases from 8.5% at 5 atm to 16.5% at 50 atm (Table 2). Using the data reported in Table 2 a linear relation was found between $\ln(C_0/C)$ and

Table 2 Influence of hydrogen pressure on the hydrogenation of acetophenone in the presence of $H_2Ru(CO)_2(PPh_3)_2$[a]

$p(H_2)$ (atm)	Yield (%)
5	8.5
20	11.5
30	14.0
50	16.5
80	20.1
100	21.6

[a] Catalyst, 1.73×10^{-5} mol; substrate, 1.50×10^{-3} mol; solvent, 4.0 ml toluene; T, 120 °C; reaction time, 3 h.

Table 3 Influence of reaction time on the hydrogenation of acetophenone in the presence of $H_2Ru(CO)_2(PPh_3)_2$[a]

Reaction time (h)	Yield (%)
3	16.5
6	27.4
14	48.7
24	69.0

[a] Catalyst, 1.73×10^{-5} mol; substrate, 1.50×10^{-3} mol; solvent, 4.0 ml toluene; *T*, 120 °C; p(H_2), 50 atm.

$p(H_2)$, as expected for a first-order reaction rate with respect to hydrogen pressure. Integration of the kinetic equation [1]:

$$-dC/dt = k_pC \cdot p(H_2) \quad [1]$$

where *C* is the substrate concentration, p(H_2) is the hydrogen pressure and *t* is the reaction time, gives Eqn [2]:

$$k_p = \{1/[t \cdot p(H_2)]\} \cdot \ln[C_0/C] \quad [2]$$

The specific rate is $k_p = 2.5 \times 10^{-5}$ atm^{-1} min^{-1}.

2.1.3 Influence of substrate concentration

The reaction was carried out at 120 °C under a pressure of hydrogen of 50 atm and a catalyst concentration of 4.31 mmol l^{-1}. The conversion to 1-phenylethanol is enhanced by increasing the reaction time from 16.5% after 3 h to 69.0% after 24 h (Table 3).

In agreement with the kinetic equation [3],

$$k_c = (1/t) \cdot \ln[C_0/C] \quad [3]$$

a linear relation between $\ln(C_0/C)$ and *t* has been obtained according to a first-order reaction rate with respect to the concentration of the substrate. The specific rate is $k_c = 1.8 \times 10^{-3}$ min^{-1}.

A reaction was carried out at 140 °C under a hydrogen pressure of 50 atm for a reaction time of 15 h in order to test the catalytic activity in more drastic conditions. A 85.3% conversion of acetophenone was reached, in agreement with the maintenance of the catalytic activity even at a higher temperature after a prolonged reaction time.

Table 4 Influence of catalyst concentration on the hydrogenation of acetophenone in the presence of $H_2Ru(CO)_2(PPh_3)_2$[a]

[Catalyst] (mmol l^{-1})	Yield (%)
1.08	11.9
2.16	13.9
4.31	16.5

[a] Substrate, 1.50×10^{-3} mol; solvent, 4.0 ml toluene; T, 120 °C; $p(H_2)$, 50 atm; reaction time, 3 h.

Table 5 Free activation energy (ΔG^{**}) as a function of temperature for the hydrogenation of acetophenone in the presence of $H_2Ru(CO)_2(PPh_3)_2$[a]

T (°C)	ΔG^{**} (kcal mol^{-1})
80	29.756
100	30.806
110	31.170
120	31.820
140	32.652

[a] $\Delta G^{**} = -RT\ln(kh/K_bT)$ values have been calculated from the data in Table 1 (*h* and K_b are the Planck and Boltzmann constants, respectively).

2.1.4 Influence of catalyst concentration

The influence of the catalyst concentration has been evaluated by carrying out a series of tests in which the other parameters were all kept constant. The data obtained are reported in Table 4.

In agreement with the kinetic equation [4],

$$k_{cat} = \{1/(t[cat])\} \ln[C_0/C] \quad [4]$$

a linear relation has been obtained between $\ln[C_0/C]$ and *t*, so the reaction has a partial first order with respect to the catalyst concentration. The specific rate is $k_{cat} = 9.04 \times 10^{-2}$ l mol^{-1} min^{-1}.

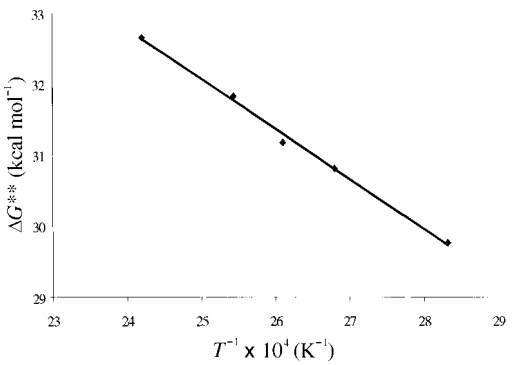
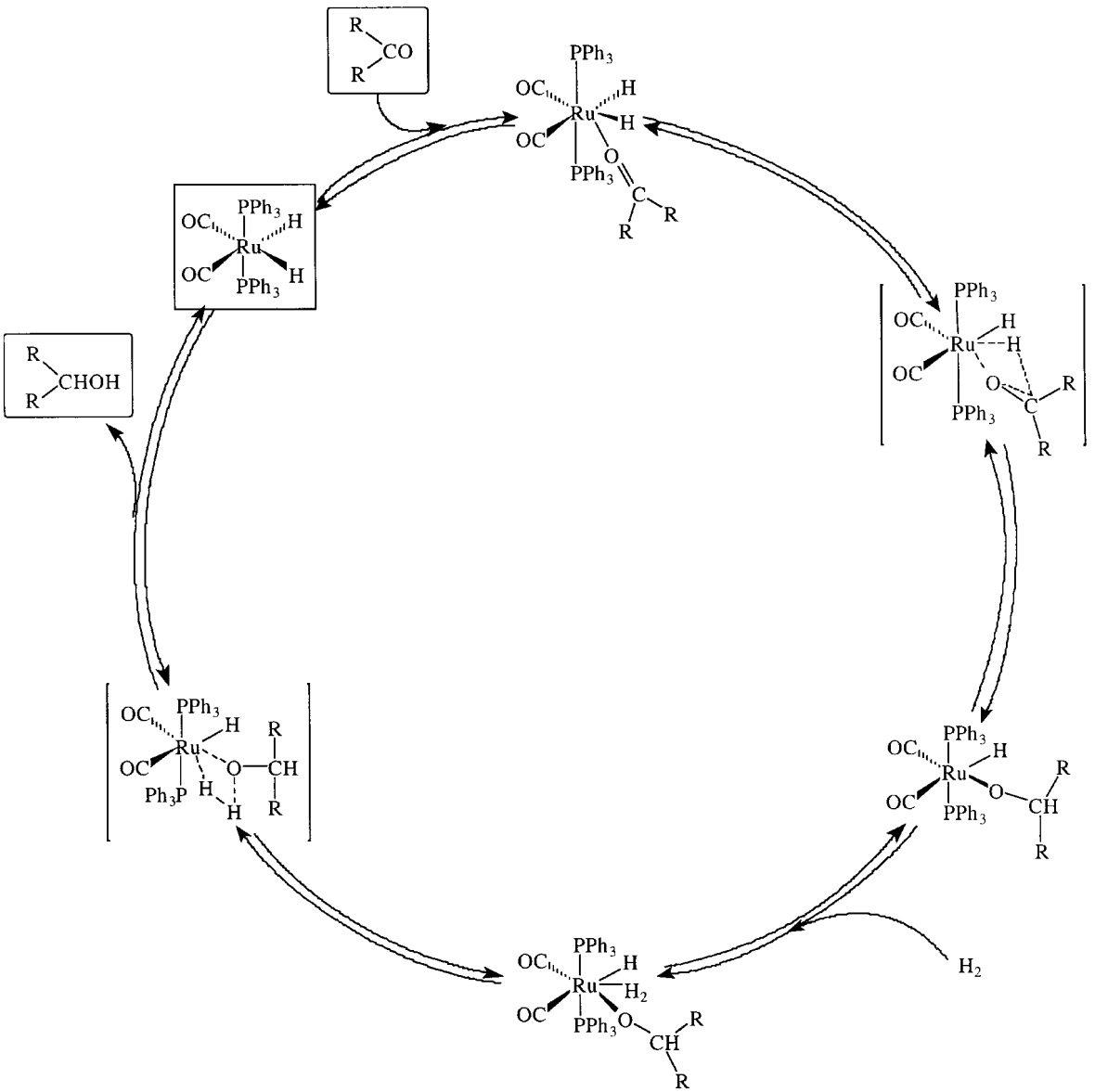


Figure 1 Free activation energy values (ΔG^{**}) as a function of 1/*T* for the hydrogenation of acetophenone in the presence of $H_2Ru(CO)_2(PPh_3)_2$.



Scheme 1

2.1.5 Activation parameters

The activation parameters ΔG^{**} was also evaluated using the data reported in Table 1 and Eqn [5]:

$$\Delta G^{**} = -RT \ln(kh/K_b T) \qquad [5]$$

where h and K_b are the Planck and Boltzmann constants, respectively (Table 5). Through a curve-fitting of the linear regression ΔG^{**} as a function of T ($\Delta G^{**} = \Delta H^{**} - T\Delta S^{**}$), it was calculated that $\Delta H^{**} = 12.65$ kcal mol^{-1} and $\Delta S^{**} = -48.52$ cal mol^{-1} (Fig. 1). These values are related to the rate-determining step and a negative value of ΔS^{**} is an indication that the step involved in the formation of the active complex is an associative process. In fact the negative change of entropy suggests, in the rate-determining step, the formation of a species having a larger steric hindrance than the initial dihydrido ruthenium complex.

These data (Table 5) support the hypotheses of a catalytic process in which the rate-determining step

Table 6 Hydrogenation of ketones to the corresponding alcohols in the presence of $H_2Ru(CO)_2(PPh_3)_2$[a]

Substrate	Product	Yield (%)
CH_3COCH_3 (**1**)	$CH_3CH(OH)CH_3$	23.2
$CH_3CH_2COCH_3$ (**2**)	$CH_3CH_2CH(OH)CH_3$	24.7
$CH_3CH_2CH_2COCH_3$ (**3**)	$CH_3CH_2CH_2CH(OH)CH_3$	25.5
$(CH_3)_2CHCOCH_3$ (**4**)	$(CH_3)_2CHCH(OH)CH_3$	14.0
$(CH_3)_3CCOCH_3$ (**5**)	$(CH_3)_3CCH(OH)CH_3$	2.8
$CH_3COCH_2COCH_3$ (**6**)	$CH_3CH(OH)CH_2COCH_3$	4.0
$CH_3COCH_2COOCH_2CH_3$ (**7**)	$CH_3CH(OH)CH_2COOCH_2CH_3$	15.4
$C_6H_5COC_6H_5$ (**8**)	$C_6H_5CH(OH)C_6H_5$	5.7
$C_6H_5COCH_3$ (**9**)	$C_6H_5CH(OH)CH_3$	16.5
$C_6H_5COCF_3$ (**10**)	$C_6H_5CH(OH)CF_3$	99.8

[a] Catalyst, 1.73×10^{-5} mol; substrate, 1.50×10^{-3} mol; solvent, 4.0 ml toluene; *T*, 120 °C; $p(H_2)$, 50 atm at 20 °C; reaction time, 3 h.

of the reaction is the ketone coordination to the metal hydride (Scheme 1). It is presumably followed by the formation of a metal alkoxide. In a subsequent step, hydrogen reacts with this complex and through elimination of the alcohol restores the catalytically active hydrido species. Unfortunately the metal alkoxide intermediate is not observed; however, this fact is in agreement with the low stability of these complexes.[15]

2.2 Influence of the substrate

The ability of ruthenium dihydride to hydrogenate different ketones has been tested in a series of experiments using substrates having a different steric hindrance or containing a substituent having different electronic effects. Analysis of the reaction products shows that the reaction is always chemioselective because the alcohol corresponding to the starting ketone is formed exclusively, as shown in Table 6.

2.2.1 Influence of chain length

The conversions achieved using methyl ketones having a linear alkyl moiety of increasing length, such as acetone (**1**), butan-2-one (**2**) and pentan-2-one (**3**), were compared (Table 6). The data show that the chain length of the alkyl moiety bonded to the carbonyl group does not influence the rate of the hydrogenation appreciably.

2.2.2 Influence of steric hindrance caused by the substituent adjacent to the carbonyl group

The data obtained in the hydrogenation of **1, 2**, 3-methylbutan-2-one (**4**) and 3,3-dimethylbutan-2-one (**5**) are reported in Table 6. The conversion decreases with increasing steric hindrance caused by the alkyl moiety of the ketone, i.e. the lowest conversion was obtained with **5**, a ketone having an alkyl group with a remarkable steric effect. We can conclude that the hydrogenation of ketones in the presence of $H_2Ru(CO)_2(PPh_3)_2$ is hardly influenced by steric effects of the substituent linked to the carbonyl group of the ketones.

These data are in agreement with the hypothesis of a catalytic process in which the rate-determining step is the coordination of the ketone to the metal hydride. In the presence of a bulky substituent on the ketone, e.g. a t-butyl group, the attack of the substrate on the metal hydride complex is very difficult, and consequently the reaction rate is reduced.

A hydrogenation experiment has been performed in more drastic conditions to test whether the conversion of **5** could be increased. The reaction was carried out at 140 °C under a hydrogen pressure of 50 atm, for a reaction time of 15 h: the conversion reached 33.8%. Comparing this result with that achieved with acetophenone (**9**) (Section 2.1.3), we observe that the steric effect of the t-butyl group is such that although for a higher reaction temperature and a longer reaction time the conversion increases, it is still not very high.

Analogous behaviour is shown in the hydrogenation of **1, 9** and diphenyl ketone (**8**). Conversions decrease in this series from 23.2%, to 16.5% to 5.7%, respectively (Table 6).

2.2.3 Influence of electronic effects due to the substituents linked to the carbonyl group

An alkyl moiety having electron-withdrawing groups shows a positive effect on the conversion: with 2,2,2-trifluoroacetophenone (**10**) as substrate, the conversion to the corresponding alcohol

Table 7 Influence of reaction temperature on the hydrogenation of *trans*-4-phenylbut-3-en-2-one in the presence of $H_2Ru(CO)_2(PPh_3)_2$[a]

	Reaction products: yields (%)		
T (° C)	*trans*-4-Phenylbut-3-en-2-ol	4-Phenylbutan-2-one	4-Phenylbutan-2-ol
40	—	1.6	0.2
60	—	3.6	0.2
70	0.4	8.0	0.5
80	0.8	17.4	0.8
100	1.9	54.5	2.6
120	—	72.9	25.1

[a] Catalyst, 1.73×10^{-5} mol; substrate, 1.50×10^{-3} mol; solvent, 4.0 ml toluene; $p(H_2)$, 50 atm at 20 °C; reaction time, 3 h.

increases (conversion 99.8%; Table 6) if correlated with the result obtained with **9** (conversion 16.5%; Table 6).

The results achieved in the hydrogenation of acetylacetone (**6**) and ethyl acetoacetate (**7**) can be rationalized by considering a positive effect due to the presence of an electron-withdrawing substituent and a negative role played by the keto–enol equilibrium. In the presence of these substrates the keto–enol equilibrium is shifted towards the enol form, especially with **6**. Otherwise very little shifting of the ketone to the enol form is present in substrates containing only one carbonyl group.[16]

The enol forms of β-diketones and β-ketoesters are stabilized by intramolecular hydrogen bonds and by conjugation of the carbon–carbon double bond with the carbonyl group. This strong intramolecular hydrogen bond minimizes the molecular dipole of the C=O group, reducing the negative charge on the oxygen of the carbonyl group and therefore the interaction with the catalyst. The low catalytic activity in the hydrogenation of **6** and **7** may be attributed to the stabilization of the enol form by hydrogen bonding.

A 100% conversion was reached in the hydrogenation of acetylacetone working at 140 °C under a hydrogen pressure of 50 atm for a reaction time of 24 h. 4-Hydroxypentan-2-one (yield 2.1%) and 2,4-pentanediol (yield 97.9%) were formed. By increasing the temperature and reaction time the conversion increased but a different chemoselectivity was obtained because the hydrogenation of both carbonyl groups occurs with almost total formation of the corresponding diol.

2.3 Hydrogenation of *trans*-4-phenylbut-3-en-2-one (benzylidenacetone)

Several hydrogenation tests of *trans*-4-phenylbut-3-en-2-one were carried out to study the influence of the reaction parameters on the chemoselectivity, using a substrate/catalyst ratio of 87:1. The hydrogenation products, identified through GC and GC–MS analyses, were 4-phenylbutan-2-one, 4-phenylbutan-2-ol and *trans*-4-phenylbut-3-en-2-ol.

Table 8 Influence of hydrogen pressure on the hydrogenation of *trans*-4-phenylbut-3-en-2-one in the presence of $H_2Ru(CO)_2(PPh_3)_2$[a]

	Reaction products: yields (%)		
$p(H_2)$ (atm)	*trans*-4-Phenylbut-3-en-2-ol	4-Phenylbutan-2-one	4-Phenylbutan-2-ol
5	0.9	22.6	1.0
20	2.6	35.0	1.7
50	1.9	54.5	2.6
100	1.4	79.0	6.2

[a] Catalyst, 1.73×10^{-5} mol; substrate, 1.50×10^{-3} mol; solvent, 4.0 ml toluene; *T*, 100 °C; reaction time, 3 h.

Table 9 Influence of solvent on the hydrogenation of *trans*-4-phenylbut-3-en-2-one in the presence of $H_2Ru(CO)_2(PPh_3)_2$[a]

Solvent	Reaction products: yield (%)		
	trans-4-Phenylbut-3-en-2-ol	4-Phenylbutan-2-one	4-Phenylbutan-2-ol
Toluene	1.9	54.5	2.6
Dioxane	2.8	58.8	3.9
THF	2.5	79.4	5.3
(n-C_4H_9)O	—	78.3	21.7

[a] Catalyst, 1.73×10^{-5} mol; substrate, 1.50×10^{-3} mol; T, 100 °C; $p(H_2)$, 50 atm at 20 °C; reaction time, 3 h.

2.3.1 Influence of temperature

The temperature range between 40 and 120 °C was explored, under a hydrogen pressure of 50 atm and a reaction time of 3 h (Table 7). The dihydridoruthenium complex is catalytically active at a lower temperature (40 °C) than that necessary to hydrogenate acetophenone (80 °C; Table 1).

The substrate conversion was enhanced by increasing the temperature, from 1.8% at 40 °C to 98.0% at 120 °C. The saturated ketone is always the main product, with a chemoselectivity of 92.4% at 100 °C.

There is also a low, but significant, isomerization of the initial ketone from *trans*-to *cis*-4-phenylbut-3-en-2-one, working in the temperature range 40–80 °C, as confirmed by the GC and GC–MS analyses.

2.3.2 Hydrogen pressure

The reactions were performed under a hydrogen pressure in the range between 5 and 100 atm, at 100 °C with a reaction time of 3 h (Table 8).

The substrate conversion was enhanced by increasing the hydrogen pressure, from 23.6% at 5 atm to 86.6% at 100 atm.

Taking into account the pseudo first-order kinetic rate equation (see Section 2.1.2), a linear relation was obtained with respect to the hydrogen pressure with a specific rate of $k_p = 2.1 \times 10^{-4}$ atm^{-1} min^{-1}.

The hydrogen pressure influenced the reaction rate but the influence on the chemoselectivity was not very high: the best value (chemoselectivity 92.2%) was obtained using a hydrogen pressure of 5 atm.

2.3.3 Influence of the solvent

The hydrogenation of *trans*-4-phenylbut-3-en-2-one was investigated using the following solvents: toluene, dioxane, tetrahydrofuran, di-*n*-butyl ether. The reaction has been carried out at 100 °C with a reaction time of 3 h and a hydrogen pressure of 50 atm (Table 9). It is not possible to employ ethanol or methanol as solvents, because in these solvents the catalyst partially decomposes during its preparation.

The substrate conversion in aprotic solvents was enhanced in the order toluene < dioxane < tetrahydrofuran < di-*n*-butyl ether, while the chemoselectivity to 4-phenylbutan-2-one increased from toluene to dioxane to tetrahydrofuran but decreased in di-*n*-butyl ether.

2.3.4 Activation parameters

Using the procedure reported in section 2.1.5 and the data reported in Table 7, the values of the activation parameters are: $\Delta H^{**} = 18.60$ kcal mol^{-1} and $\Delta S^{**} = -27.67$ cal mol^{-1} (Table 10; Figure 2).

The negative value of ΔS^{**} is an indication that in this case also the rate-determining step involves an associative process and the formation of a complex having a larger steric hindrance than the initial dihydrido ruthenium complex.

The absolute value of ΔS^{**} is smaller than that evaluated with acetophenone: it means that with

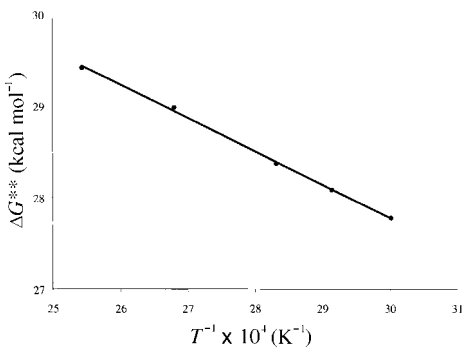


Figure 2 Free activation energy (ΔG^{**}) as a function of $1/T$ for the hydrogenation of *trans*-4-phenylbut-3-en-2-one in the presence of $H_2Ru(CO)_2(PPh_3)_2$.

Table 10 Free activation energy (ΔG^{**}) as a function of temperature for the hydrogenation of *trans*-4-phenylbut-3-en-2-one in the presence of $H_2Ru(CO)_2(PPh_3)_2$[a]

T (°C)	ΔG^{**} (kcal mol^{-1})
60	27.773
70	28.084
80	28.370
100	28.978
120	29.417

[a] $\Delta G^{**} = -RT\ln(kh/K_bT)$ values have been calculated from the data in Table 7 (h and K_b are the Planck and Boltzmann constants, respectively).

both ketones we have a reduction in the degrees of freedom, but with *trans*-4-phenylbut-3-en-2-one the process involves a lower loss of entropy.

3 CONCLUSIONS

On the basis of the data obtained and in analogy to those reported in the literature,[3,9,15] a mechanism has been suggested where the rate-determining step is the ketone coordination to the metal–hydrogen bond with formation of a four-centre transition state (Scheme 1). The following step is the ketone insertion into the ruthenium–hydrido bond, with formation of the corresponding alkoxide. The subsequent step is the addition of a hydrogen molecule, which is followed by the elimination of the hydrogenated product and restoration of the starting catalyst.

The negative value of ΔS^{**} supports the hypothesis that the rate-determining step is the coordination of the ketone to the metal. A further support to this hypothesis is given by the conversions obtained with different ketones (Table 6). The rate is decreased by increasing the steric hindrance of the substrate: the hydrogenation is favoured with substrates having a reduced steric hindrance: butan-2-one > 3-methylbutan-2-one > 3,3-dimethylbutan-2-one. An electron-withdrawing substituent also increases the reaction rate by increasing the polarity of the C=O group.

The hydrogen pressure exerts a positive influence on the third step, because an increase of this parameter favours the alkoxide hydrogenolysis. A phosphine displacement, as supposed in the mechanism reported by Sanchez-Delgado,[4,9] may be excluded. A ^{31}P NMR experiment carried out using a solution of the catalyst in C_6D_6 as solvent and a large excess of acetophenone (substrate/catalyst = 1000:1) at 60 °C does not show any free phosphine in the solution after 3 h.

On the basis of the data reported we can exclude the formation of a coordinatively unsaturated species $[Ru(CO)_2(PPh_3)_2]$ by reductive elimination of hydrogen from $H_2Ru(CO)_2(PPh_3)_2$ which is followed by the addition of ketone to the unsaturated species. This last step is a very fast reaction, according to the data reported by Perutz,[17] so the reaction rate should display a zero order with respect to the substrate concentration; instead, we have shown that the reaction rate is first order with respect to this parameter. The first-order rate with respect to hydrogen pressure contributes further evidence to exclude the formation of $[Ru(CO)_2(PPh_3)_2]$ from $H_2Ru(CO)_2(PPh_3)_2$.

In the same way, the elimination of the alcohol from the hydridoalkoxy intermediate may be excluded because the hydrogen addition to the unsaturated species $[Ru(CO)_2(PPh_3)_2]$, which must be formed, is also very fast,[17] so the reaction rate should display a zero order with respect to the hydrogen pressure instead of the first order observed.

The data achieved in the hydrogenation of *trans*-4-phenylbut-3-en-2-one show that this catalyst hydrogenates the C=C double bond preferentially with respect to the carbonyl group, with a high chemoselectivity both at low temperature (66.7% at 40 °C) and at high temperature (92.2% at 100 °C).

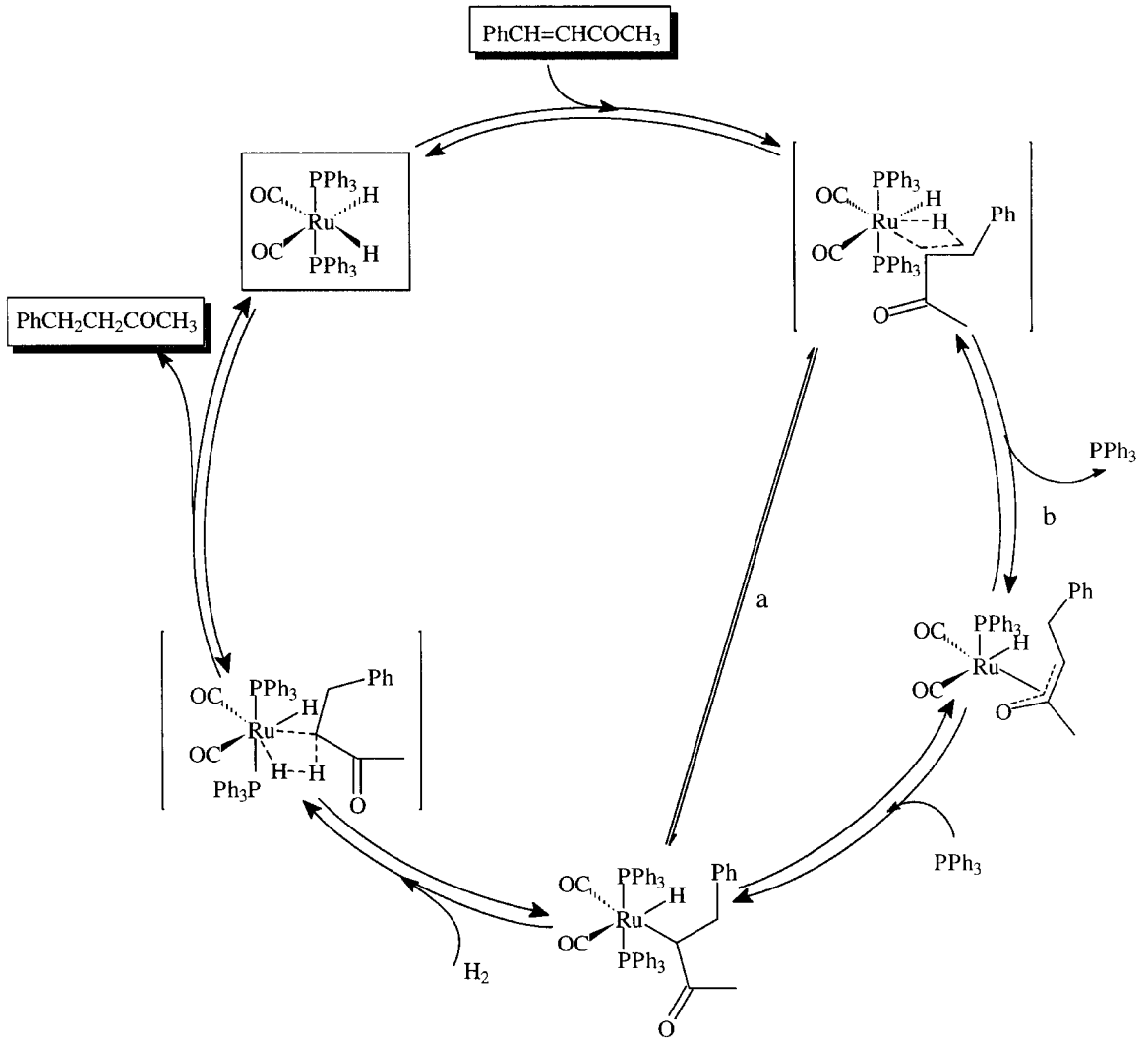
The mechanism suggested is similar to that reported in the literature for $[(PP_3)RuH(H_2)]BPh_4$.[7] The rate-determining step is postulated to be, in our case, the interaction of the C=C double bond of the ketone with the metal–hydrido bond (Scheme 2). In the following step there are two possible paths:

(a) the hydrogen migration on the carbon atom in position 4, giving an alkyl species;
(b) the displacement of a phosphine ligand by the carbonyl group forming a π-oxoallylic species which is followed by the phosphine coordination to obtain an alkyl species.

The data collected are not sufficient to discriminate between these two paths.

In the following step, under hydrogen pressure, the saturated ketone 4-phenylbutan-2-one is formed, and the catalytic species restored.

This mechanism is in agreement with a negative ΔS^{**} value which indicates, in this case also, an associative process with reduction of the degrees of



Scheme 2

freedom. This supports the hypothesis that the rate-determining step is the formation of a species with a high steric hindrance, not very different from that formed by the interaction of a ketone with the metal hydride.

The following considerations are in agreement with a mechanism (Scheme 2) slightly different from that reported for simple ketones (Scheme 1):

(1) the lower temperature necessary to achieve a catalytic activity (40 °C) when using *trans*-4-phenylbut-3-en-2-one than that necessary for acetophenone;
(2) the preferential hydrogenation of the C=C double bond with respect to the C=O,
(3) the isomerization of the C=C double bond;
(4) The different ΔS^{**} values obtained.

EXPERIMENTAL

4.1 Instruments

Gas chromatographic analysis (GC) was performed using a Shimadzu GC-14A system with a C-R4A integrator, or using a Perkin Elmer Autosystem with a NELSON 1022 unit for elaboration of the

data; both instruments had flame ionization detectors. Gas chromatographic–mass spectroscopic (GC–MS) analysis was carried out on a Carlo Erba QMD 1000 GC–MS data system equipped with an MS5 capillary column (Hewlett-Packard, 30 m, internal diameter 0.25 μm).

The packed columns (2 m) were:

(a) PPG: Polypropylenglycol LB-550-X (15%) on Chromosorb W;
(b) FFAP: 'Free Fatty Acids Phase' (5%) on Chromosorb G AW-DMSC;
(c) CW 20M: Carbowax 20M (15%) on Chromosorb:

NMR spectra were registered using a Varian VXR 300 spectrometer operating at 299.944 MHz for ^{1}H, at 75.429 MHz for ^{13}C and at 121.421 MHz for ^{31}P NMR spectra; tetramethylsilane was used as the reference for ^{1}H and ^{13}C NMR spectra. In ^{31}P NMR spectra downfield values from external H_3PO_4 (85%) were taken as positive. ^{13}C and ^{31}P NMR spectra were acquired as proton decoupled spectra.

IR spectra were recorded with an FT-IR Perkin-Elmer model 1760-X spectrometer using IRDM software.

4.2 Materials

All reactions and manipulations were performed with the Schlenk technique under dry nitrogen.

The complexes $Ru_3(CO)_9(PPh_3)_3$,[18] $Ru(CO)_3(PPh_3)_2$,[19] $Ru(CO)_2(CH_3COO)_2(PPh_3)_2$[20] and $H_2Ru(CO)_2(PPh_3)_2$[13] were prepared as described in the literature.

Diphenylmethanol, ethyl 3-hydroxybutyrate and 3-methylbutan-2-ol were synthesized from the corresponding ketones by reduction with $NaBH_4$ by the method described elsewhere.[21]

trans-4-Phenylbut-3-en-2-ol was prepared as described by Kwart and Kirk.[22]

The synthesized products were characterized by ^{1}H and ^{13}C NMR spectroscopy, GC and GC–MS analysis. The data collected are in agreement with those reported in the literature.

4.3 Catalytic activity of $H_2Ru(CO)_2(PPh_3)_2$ in the hydrogenation of ketones

4.3.1 General procedure

The catalyst $H_2Ru(CO)_2(PPh_3)_2$ was prepared as previously described.[13] In a glass vial placed in a stainless-steel autoclave, under dry nitrogen, 1.72×10^{-5} mol of $Ru(CO)_2(CH_3COO)_2(PPh_3)_2$, 6.60×10^{-4} mol of Na_2CO_3 and 4.0 ml of the selected solvent were introduced; the autoclave was then sealed and hydrogen added up to 100 atm at room temperature. The vessel was heated at 100 °C for 24 h; after cooling at room temperature, the gas was vented, and after filtration a pale yellow solution was obtained. The solution of the catalyst was placed in a glass vial contained in a stainless-steel autoclave, then 1.50×10^{-3} mol of substrate was introduced (substrate/catalyst ratio = 87:1). The autoclave was sealed and hydrogen added to the pressure required (see Tables). The vessel was heated at the prefixed temperature for the time reported, then after cooling at room temperature the gas was vented and the solution was checked by GC using pure standard as reference.

4.4 Identification of products

The catalytic activity of $H_2Ru(CO)_2(PPh_3)_2$ was evaluated in the hydrogenation of the following ketones: acetophenone, acetone, butan-2-one, pentan-2-one,3-methylbutan-2-one,3,3-dimethylbutan-2-one, ethyl acetoacetate, acetylacetone, benzophenone, 2,2,2-trifluoroacetophenone and *trans*-4-phenylbut-3-en-2-one. The product of ketone hydrogenation was identified by GC analysis using the following procedures. The data obtained are reported in Tables 1–10.

4.4.1 Acetophenone

A CW 20M column was kept at 60 °C for 10 min, then heated to 160 °C at a rate of 5 °C min^{-1} and kept at this temperature for 30 min.

4.4.2 Acetone

A PPG column was kept at 40 °C for 10 min, then heated to 100 °C at a rate of 3 °C min^{-1} and kept at this temperature for 10 min.

4.4.3 Butan-2-one, pentan-2-one, 3-methylbutan-2-one and 3,3-dimethylbutan-2-one

A PPG column was heated at 50 °C.

4.4.4 Ethyl acetoacetate

A PPG column was kept at 40 °C for 10 min, heated to 100 °C at a rate of 10 °C min^{-1} and kept at this temperature for 10 min, then heated to 130 °C at a rate of 10 °C min^{-1} and kept at this temperature for 30 min.

4.4.5 Acetylacetone

A CW20M column was kept at 50 °C for 25 min,

heated to 100 °C at a rate of 2 °C min^{-1} and kept at this temperature for 4 min, then heated to 200 °C at a rate of 5 °C min^{-1} and kept at this temperature for 35 min.

4.4.6 Benzophenone

A FFAP column was heated at 200 °C.

4.4.7 2,2,2-Trifluoroacetophenone

A CW20M column was kept at 60 °C for 10 min, then heated to 180 °C at a rate of 10 °C min^{-1} and kept at this temperature for 40 min.

4.4.8 *trans*-4-Phenylbut-3-en-2-one

A FFAP column was kept at 50 °C for 2 min, then heated to 180 °C at a rate of 10 °C min^{-1} and kept at this temperature for 20 min.

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