

Ruthenium catalyzed hydrogenation of methyl phenylacetate under low hydrogen pressure

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Abstract

PhCH₂CO₂Me has been efficiently hydrogenated to yield PhCH₂CH₂OH (**1**) and PhCH₂CO₂CH₂CH₂Ph (**2**) even under relatively low hydrogen pressure (<10 atm) by using ruthenium-phosphine catalysis composed of Ru(acac)₃, P(*n*-C₈H₁₇)₃ in the presence of Zn. Effect of both P(*n*-C₈H₁₇)₃ and Zn plays an essential role in order for this hydrogenation to proceed catalytically. Although the activity was not strongly influenced by the hydrogen pressure employed, the observed activity was strongly dependent upon the reaction temperature, substrate concentration, and solvent used. We assume that ruthenium hydride species plays an important role in this catalysis cycle. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Hydrogenation of ester; Ruthenium; Homogeneous catalyst

1. Introduction

The direct hydrogenation of ester to the corresponding alcohol catalytically under mild conditions has been one of the most important challenging subjects from the aspect of “green and sustainable chemistry (GSC)”, because most of the conventional processes have been achieved by a stoichiometric reduction using metal-hydrides like LiAlH₄ [1,2]. On the other hand, it has been used commercially to produce higher (fatty) alcohols from palm oil, etc. by hydrogenation using so-called Adkins-type heterogeneous catalyst [3], although the process requires both high temperature (>200°C) and high hydrogen pressure (>140–200 atm).

The direct hydrogenation of ester to afford alcohol using homogeneous transition metal catalysts have also been reported [4–13], but most of these required both high reaction temperature (150–230°C) and high hydrogen pressure (50, 85–100 atm) [3–12]. For example, Teunissen and Elsevier recently introduced an efficient hydrogenation of dimethyl oxalate to ethylene glycol in the presence of ruthenium catalyst [11,12]. The use of phosphine ligand played an important role to induce the catalytic reaction with high activity, and the activity increased in the order: PCy₃ < Ph₂P(CH₂)₂PPh₂ < PPh₃ < PhP[(CH₂)₂PPh₂]₂, [CH₂P(Ph)CH₂CH₂PPh₂]₂ ≪ MeC(CH₂PPh₂)₃ [11]. Later, they improved the activity by using fluorinated alcohols like 1,1,1,3,3,3-hexafluoro-2-propanol as the solvent [12], because, as presented by Grey et al. [4], the transesterification with substrate affording esters containing electron-withdrawing groups adjacent to the carboxycarbonyl should be activated, which would thus facilitate the hydrogenation. However, the

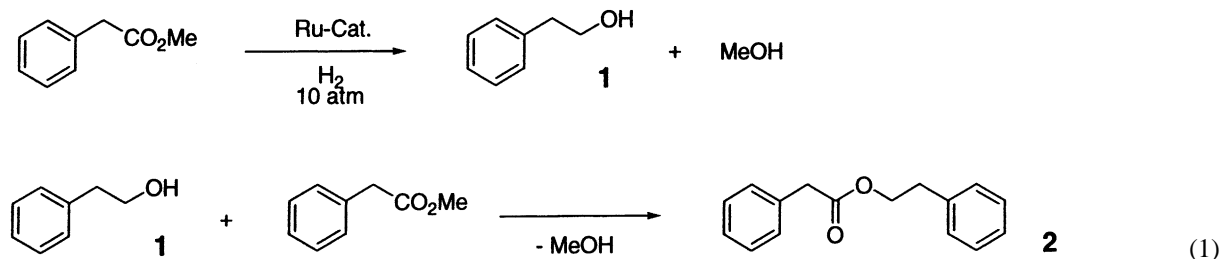
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catalytic activity significantly decreased by lowering the hydrogen pressure.

Although the attempts for hydrogenation of ester under mild conditions seemed difficult, catalytic hydrogenation of acid anhydrides to yield lactones by homogeneous catalysis has been well known [5,14–19]. One of the successful examples in this subject should be the synthesis of γ -butyrolactone by using ruthenium catalyst developed by Mitsubishi Chemical Company [18,19]. In addition, there is one well-known recent example for hydrogenation of carboxylic acids to aldehydes by palladium catalysts in the presence of pivalic anhydride [20].

A lot of useful reactions have been developed recently using stoichiometric and catalytic amount of ruthenium complexes [21], especially we have extensively studied the chemospecific reduction of aromatic nitro group under CO/H₂O conditions [22–26]. We also reported ethylene polymerization and ethylene/1-hexene copolymerization by ruthenium catalyst containing bis(oxazoline)pyridine ligand [27]. Since we wanted to expand our ruthenium chemistry to find a new catalyst for a valuable reaction practically, also since catalytic hydrogenation of ester affording alcohol has been one of the most challenging subjects mentioned above, we thus decided to explore the possibility.

Since we have reported more recently that PhCH₂CO₂Me could be hydrogenated to the alcohol in the presence of ruthenium catalyst even under low hydrogen pressure (H₂ 10 atm) [13], we wish to introduce the more details concerning this catalysis in the present paper (Eq. (1)).



2. Experimental

All manipulations were carried out under nitrogen atmosphere or in vacuum. Solvents such as

tetra(ethylene glycol) dimethyl ether (tetraglyme), 1,1,1,3,3,3-hexafluoro-2-propanol (HFIP), xylene, and methanol were used of reagent grades (Wako Chemical Co.), and stored under nitrogen in the presence of molecular sieves. Other reagents such as methyl phenylacetate, Zn, etc. were used of reagent grades. [RuCl₂(*p*-cymene)]₂, [RuI₂(*p*-cymene)]₂, and [Ru(CF₃SO₃)₂(*p*-cymene)]₂ were prepared according to the previous report [28].

The catalytic reactions were typically carried out as follows: in an autoclave (20 ml) made of stainless steel was charged Ru(acac)₃ (acac: acetylacetonato), P(*n*-C₈H₁₇)₃, solvent, methyl phenylacetate, and additives such as Zn under nitrogen atmosphere. The reaction mixture was stirred under H₂ at 180 or 200°C. Reaction product was then determined by GLC using an internal standard and was identified by using GLC by co-injection with the authentic samples under different conditions. Identification was made by comparison of retention time of the chromatogram (column: DB-1 30 m, 0.25 mmφ × 0.25 μm), and GC-MS (GC-MS QP 5000, Shimadzu Co. Ltd.).

3. Results and discussion

3.1. Hydrogenation of PhCH₂CO₂Me catalyzed by ruthenium phosphine complexes

3.1.1. Various factors affecting the catalytic activity

We focused on the ruthenium-phosphine catalysis for the reaction, not only because most of the

efficient catalyst system reported previously are based on this catalysis, but also because we assumed at the initial stage that the nature of ruthenium-hydride species would play an essential key role for the catalysis cycle, as we previously demonstrated in

Table 1
Hydrogenation of PhCH₂CO₂Me by ruthenium-phosphine catalyst^a

Run No.	Phosphine (P/Ru) ^b	Additives (A/Ru) ^b	Solvent	Time (h)	Yield/TON ^c		Total
					1	2	
1	MeC(CH ₂ PPh ₂) ₃ (2)	NEt ₃ (20)	MeOH ^d	5	0.2	–	0.2
2	MeC(CH ₂ PPh ₂) ₃ (2)	NEt ₃ (20)	HFIP ^d	15	0.3	–	0.3
3	MeC(CH ₂ PPh ₂) ₃ (2)	Zn (10)	Tetraglyme	15	0.9	1.6	2.5
4	Ph ₂ P(CH ₂) ₂ PPh ₂ (4)	Zn (10)	Tetraglyme	15	0.4	1.7	2.1
5	Ph ₂ P(CH ₂) ₂ PPh ₂ (8)	Zn (10)	Tetraglyme	15	0.3	1.7	2.0
6	Ph ₂ P(CH ₂) ₃ PPh ₂ (2)	Zn (10)	Tetraglyme	15	0.6	1.5	2.1
7	Ph ₂ P(CH ₂) ₄ PPh ₂ (1.5)	Zn (10)	Tetraglyme	15	1.0	2.6	3.6
8	Ph ₂ P(CH ₂) ₄ PPh ₂ (2)	Zn (10)	Tetraglyme	15	1.6	3.4	5.0
9	Ph ₂ P(CH ₂) ₆ PPh ₂ (1.7)	Zn (10)	Tetraglyme	15	0.2	0.7	0.9
10	Ph ₂ P(CH ₂) ₆ PPh ₂ (4.2)	Zn (10)	Tetraglyme	15	0.3	1.0	1.3
11	Ph ₂ P(CH ₂) ₆ PPh ₂ (6.7)	Zn (10)	Tetraglyme	15	0.5	1.7	2.2
12	P(<i>tert</i> -Bu) ₃ (10)	Zn (10)	Tetraglyme	15	0.6	1.8	2.4
13	P(<i>n</i> -C ₈ H ₁₇) ₃ (10)	–	Tetraglyme	5	0.5	0.3	0.8
14	P(<i>n</i> -C ₈ H ₁₇) ₃ (10)	Zn (10)	Tetraglyme	5	1.2	2.9	4.1
15	P(<i>n</i> -C ₈ H ₁₇) ₃ (10)	Zn (10)	Tetraglyme	15	4.4	5.3	9.7
16	PPh ₃ (5) ^e	Zn (10)	Tetraglyme	15	–	–	–
17	PPh ₃ (10) ^e	Zn (10)	Tetraglyme	15	–	–	–

^a Reaction conditions: Ru(acac)₃ 0.02 mmol, solvent 3.0 ml, PhCH₂CO₂Me 1.0 mmol, 200°C, H₂ 10 atm.

^b Molar ratio of phosphine ligand/Ru or additive/Ru.

^c TON (turnover number) = (molar amount of product)/(mol-Ru), PhCH₂CH₂OH (**1**) and PhCH₂CO₂CH₂CH₂Ph (**2**).

^d Catalyst previously reported in [12], HFIP: (CF₃)₂CHOH.

^e Reaction temperature, 170°C.

the reduction of aromatic nitro group using rhodium-phosphine catalysts under CO/H₂O conditions [29].

Table 1 summarizes the results for hydrogenation of methyl phenylacetate with various ruthenium-phosphine catalysts (H₂ 10 atm, 200°C, in tetraglyme). The major reaction products in the catalytic hydrogenation were PhCH₂CH₂OH (**1**) and PhCH₂CO₂CH₂CH₂Ph (**2**). As we described in our preliminary communication [13], as we will also describe the more details concerning both the product distribution and product pathway below, **2** was formed by the transesterification of **1** with PhCH₂CO₂Me. Therefore, TON values can be calculated as the molar amount of both **1** and **2** produced based on ruthenium charged.

It turned out that the reaction proceeded catalytically if Zn was added into the reaction mixture (runs 3–8, 10–12, and 14–15). The use of P(*n*-C₈H₁₇)₃ was quite effective in this catalysis (runs 14–15), and the activity increased in the order (under the optimized phosphine/ruthenium molar ratios): Ph₂P(CH₂)₂PPh₂, Ph₂P(CH₂)₃PPh₂, Ph₂P(CH₂)₆PPh₂, MeC(CH₂PPh₂)₃, P(*tert*-Bu)₃ <

Ph₂P(CH₂)₄PPh₂ ≪ P(*n*-C₈H₁₇)₃. In addition, the use of PPh₃ in place of P(*n*-C₈H₁₇)₃ at 170°C (runs 16, 17), due to that PPh₃ is known to be decomposed over 180°C [30], showed no catalytic activity. These results are interesting contrast with those reported by Teunissen and Elsevier [11], and the fact that P(*n*-C₈H₁₇)₃ was quite effective was somewhat similar to that reported in the synthesis of γ -butyrolactone by ruthenium catalyst [19]. On the other hand, it might be interesting to note that the catalyst system composed of Ru(acac)₃, MeC(CH₂PPh₂)₃, and NEt₃ (in methanol or HFIP), which has been known as the efficient catalyst system [12], showed low activity under these conditions (runs 1, 2).

As shown in Table 2, the use of Zn plays an important key role in order for this reaction to proceed catalytically under these conditions, and the absence of P(*n*-C₈H₁₇)₃ and/or Zn showed extremely low activities (runs 13, 19). Since the reaction did not take place without ruthenium (run 18), it is clear that ruthenium catalyze this catalytic reaction. The use of Ti(O^{*i*}Pr)₄ or Cu in place of Zn was also found to be effective,

Table 2

Hydrogenation of PhCH₂CO₂Me by Ru(acac)₃-P(*n*-C₈H₁₇)₃ catalyst: effect of additives^a

Run No.	Phosphine (P/Ru) ^b	Additives (A/Ru) ^b	Time (h)	Yield/TON ^c		Total
				1	2	
18 ^d	P(<i>n</i> -C ₈ H ₁₇) ₃	Zn	5	–	–	–
19	None	–	5	–	–	–
13	P(<i>n</i> -C ₈ H ₁₇) ₃ (10)	–	5	0.5	0.3	0.8
14	P(<i>n</i> -C ₈ H ₁₇) ₃ (10)	Zn (10)	5	1.2	2.9	4.1
20	P(<i>n</i> -C ₈ H ₁₇) ₃ (10)	Ti(O ^{<i>i</i>} Pr) ₄ (5)	14.5	2.9	2.8	5.7
21	P(<i>n</i> -C ₈ H ₁₇) ₃ (10)	<i>p</i> -TsOH ^e (8)	5	1.0	–	1.0
22	P(<i>n</i> -C ₈ H ₁₇) ₃ (10)	CH ₃ SO ₃ H (8)	5	1.2	–	1.2
23	P(<i>n</i> -C ₈ H ₁₇) ₃ (10)	NEt ₃ (2.5)	5	1.1	0.3	1.4
24	P(<i>n</i> -C ₈ H ₁₇) ₃ (10)	Al (10)	15	2.0	1.6	3.6
25	P(<i>n</i> -C ₈ H ₁₇) ₃ (10)	Cu (10)	15	3.5	2.0	5.5
14	P(<i>n</i> -C ₈ H ₁₇) ₃ (10)	Zn (10)	5	1.2	2.9	4.1
15	P(<i>n</i> -C ₈ H ₁₇) ₃ (10)	Zn (10)	15	4.4	5.3	9.7

^a Reaction conditions: Ru(acac)₃ 0.02 mmol, tetraglyme 3.0 ml, PhCH₂CO₂Me 1.0 mmol, 200°C, H₂ 10 atm.^b Molar ratio of phosphine/Ru or additive/Ru.^c TON (turnover number) = (molar amount of product)/(mol-Ru), PhCH₂CH₂OH (1) and PhCH₂CO₂CH₂CH₂Ph (2).^d Comparative experiment without Ru(acac)₃, P(*n*-C₈H₁₇)₃ 0.20 mmol, Zn 0.20 mmol.^e *p*-Toluenesulfonic acid.

and the use of CH₃SO₃H and *p*-toluenesulfonic acid, which have been known as the efficient reaction promoters for the synthesis of γ -butyrolactone by hydrogenation [18,19], slightly increased the activity. The *exact* role of these additives was, however, not so clear at this moment. Rapid decrease in the activity was not observed in this catalysis (runs 14, 15), and the yield increased for longer reaction hours.

Since *p*-cymene complexes of the type, [RuX₂(*p*-cymene)]₂, have been important starting compounds of divalent ruthenium complexes [31,32], we thus examined the hydrogenation with these complexes in place of Ru(acac)₃. As shown in Table 3, no significant differences in the catalytic

activity were observed (runs 15, 27–28) except [Ru(CF₃SO₂)₂(*p*-cymene)]₂, and these results thus suggest that Ru(acac)₃ can be used without the loss of the activity as the starting catalyst precursor. Since the *p*-cymene ligand was replaced with *tert*-phosphine readily to form Ru(II)-phosphine complexes, it is thus highly suggested that the same active species plays a role in this catalytic reaction.

It should be noted that the activity enhanced remarkably, if the amount of PhCH₂CO₂Me into the reaction mixture was increased (Table 4). Based on a brief estimation from the plots between the TON value (after 5 h) and the initial PhCH₂CO₂Me concentration especially at relatively low concentration region

Table 3

Hydrogenation of PhCH₂CO₂Me by ruthenium complex: P(*n*-C₈H₁₇)₃ catalysts^a

Run No.	Complexes	Time (h)	Yield/TON ^b		Total
			1	2	
15	Ru(acac) ₃	15	4.4	5.3	9.7
26	[Ru(CF ₃ SO ₂) ₂ (<i>p</i> -cymene)] ₂	15	0.7	1.5	2.2
27	[RuCl ₂ (<i>p</i> -cymene)] ₂	14.5	3.7	4.1	7.8
28	[RuI ₂ (<i>p</i> -cymene)] ₂	14.5	4.3	4.2	8.5

^a Reaction conditions: Ru complex 0.02 mmol (as Ru metal), P(*n*-C₈H₁₇)₃ 0.20 mmol, Zn 0.20 mmol, tetraglyme 3.0 ml, PhCH₂CO₂Me 1.0 mmol, 200°C, H₂ 10 atm.^b TON (turnover number) = (molar amount of product)/(mol-Ru), PhCH₂CH₂OH (1) and PhCH₂CO₂CH₂CH₂Ph (2).

Table 4
Hydrogenation of PhCH₂CO₂Me by Ru(acac)₃-P(*n*-C₈H₁₇)₃-Zn catalyst^a

Run No.	Additives (A/Ru) ^b	PhCH ₂ CO ₂ Me (mmol)	Solvent (ml)	Time (h)	Yield/TON ^c		Total
					1	2	
15	Zn (10)	1.0	Tetraglyme (3.0)	15	4.4	5.3	9.7
14	Zn (10)	1.0	Tetraglyme (3.0)	5	1.2	2.9	4.1
29	Zn (10)	2.0	Tetraglyme (3.0)	5	1.5	4.0	5.5
30	Zn (10)	3.0	Tetraglyme (3.0)	5	1.6	6.5	8.1
31	Zn (10)	4.0	Tetraglyme (3.0)	5	3.0	11.7	14.7
32	Zn (10)	10.0	Tetraglyme (1.5)	5	1.0	19.5	20.5
33	Zn (10)	20.0	–	5	0.3	13.9	14.2
15	Zn (10)	1.0	Tetraglyme (3.0)	15	4.4	5.3	9.7
34	Zn (10)	1.0	Xylene (3.0)	15	2.7	8.4	11.1
35	Zn (10)	1.0	Toluene (3.0)	15	2.8	8.2	11.0

^a Reaction conditions: Ru(acac)₃/P(*n*-C₈H₁₇)₃ = 0.02/0.20 mmol, 200°C, H₂ 10 atm.

^b Molar ratio of additive/Ru.

^c TON (turnover number) = (molar amount of product)/(mol-Ru), PhCH₂CH₂OH (1) and PhCH₂CO₂CH₂CH₂Ph (2).

(Table 4, runs 14, 29–31), the order of 0.94 was obtained (Fig. 1), which means that the rate depended upon the initial substrate concentration almost linearly with first order under these conditions. On the other hand, the activity without solvent was low (run 33), suggesting that the suitable amount of solvent was required to promote this catalytic reaction. It would also be clear that the rate for transesterification is faster than that for hydrogenation under these conditions, because the ratio of product 2 versus 1 increased at higher substrate concentration region (runs 14, 29–33). The activity did not change if xylene or toluene was used in place of tetraglyme as the solvent under these conditions (runs 15, 34–35), but the product distribution

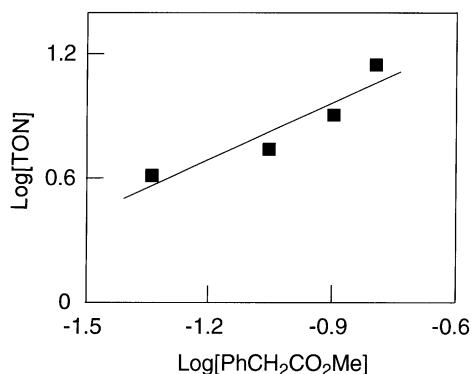


Fig. 1. Plots of TON values (after 5 h) vs. initial PhCH₂CO₂Me concentration (mmol/ml) in the ruthenium catalyzed hydrogenation (Table 4, runs 14, 29–31).

changed slightly probably due to the solvent effect in the transesterification of 1 with the substrate.

It also turned out that the catalytic activity increased by reducing the amount of solvent charged (Table 5, runs 34, 38–40). The same explanation described in Table 4 can be considered that the increase in the initial concentration of substrate enhanced the catalytic activity. It might be interesting to note that the catalytic activity also increased by reducing the amount of Zn into the reaction mixture, although we did not observe the decrease in the activity if Zn was used with the molar ratio of 40 in place of 10 under the conditions of run 14 (5.2 turnovers in tetraglyme). It was postulated that Zn initiate a fast reduction of the acetylacetonate complex [11], but no significant improvement in the activity was observed in the hydrogenation of dimethyl oxalate using Ru(acac)₃-MeC(CH₂PPh₂)₃ catalyst. On the other hand, it is clear that Zn plays an essential key role for the present catalyst system, and the moderate catalytic activity was also observed if Zn(acac)₂ was used in place of Zn (16.9 turnovers after 15 h under the same conditions in run 40, and 24.4 turnovers after 15 h under the same conditions of run 45 except that Zn(acac)₂ was used in place of Zn, respectively). Although the exact role for Zn was still not clear at this moment, it seems likely that the increase in the activity upon the addition of Zn would be due to the activation of substrate by weak coordination to the carbonyl group, which would promote the reaction with ruthenium-hydride species.

Table 5

Hydrogenation of PhCH₂CO₂Me by Ru(acac)₃-P(*n*-C₈H₁₇)₃-Zn catalyst: effect of solvent^a

Run No.	Zn ^b	P(<i>n</i> -C ₈ H ₁₇) ₃ (P/Ru) ^b	PhCH ₂ CO ₂ Me (mmol)	Solvent (ml)	Time (h)	Yield/TON ^c		Total
						1	2	
34	10	10	1.0	Xylene (3.0)	15	2.7	8.4	11.1
36	10	10	1.0	Xylene (1.25)	15	5.4	8.5	13.9
37	5.0	10	1.0	Xylene (1.25)	15	6.8	9.3	16.1
38	2.5	10	1.0	Xylene (1.25)	15	7.5	11.4	18.9
39	2.5	10	1.0	Xylene (0.75)	15	9.8	12.2	22.0
40	2.5	10	1.0	Xylene (0.50)	15	10.4	13.5	23.9
41	2.5	2	1.0	Xylene (1.25)	5	0.7	0.2	0.9
42	2.5	5	1.0	Xylene (1.25)	5	0.8	5.7	6.5
43	2.5	5	1.0	Xylene (1.25)	15	2.6	12.3	14.9
38	2.5	10	1.0	Xylene (1.25)	15	7.5	11.4	18.9

^a Reaction conditions: Ru(acac)₃/P(*n*-C₈H₁₇)₃ = 0.02/0.20 mmol, 200°C, H₂ 10 atm.^b Molar ratio based on ruthenium.^c TON (turnover number) = (molar amount of product)/(mol-Ru), PhCH₂CH₂OH (1) and PhCH₂CO₂CH₂CH₂Ph (2).

Effect of P(*n*-C₈H₁₇)₃/Ru molar ratio toward the catalytic activity was examined, and the ratio of 10 would be suited for the high activity (runs 38, 41–43). The activity with the ratio of 2 was significantly lower than that of 5, suggesting that ruthenium complex containing three or four phosphine ligands would play a role in the catalysis cycle. We assume that the reason why the ratio of 10 was more suited than that of 5 would be due to the stability of the catalytically-active species over the reaction time,

because some part of P(*n*-C₈H₁₇)₃ was converted to P(*n*-C₈H₁₇)(OCH₂CH₂Ph)₂ in the reaction mixture after the long reaction hours, as mentioned below.

Results concerning the solvent effect for the catalytic activity are summarized in Table 6. It is important to note that the product distribution depended upon solvent used under these conditions (runs 40, 45). This would be due to the different rates in transesterification of 1 with substrate among these solvents [xylene and 1,2-dimethoxyethane (dme)]

Table 6

Hydrogenation of PhCH₂CO₂Me by Ru(acac)₃-P(*n*-C₈H₁₇)₃-Zn catalyst: effect of solvent^a

Run No.	Zn ^b	PhCH ₂ CO ₂ Me (mmol)	Solvent (ml)	Time (h)	Yield/TON ^c		Total
					1	2	
40	2.5	1.0	Xylene (0.50)	15	10.4	13.5	23.9
44	2.5	1.0	2-Methoxy ethanol (0.50)	15	4.7	3.2	7.9
45	2.5	1.0	Dme ^d (0.50)	15	20.4	7.7	28.1
46	2.5	2.0	Dme ^d (0.25)	15	55.9	11.3	67.2
47	2.5	2.0	EtO(CH ₂ O) ₂ Et ^e (0.25)	15	28.3	23.4	51.7
48	2.5	2.0	Tetrahydrofuran (0.25)	15	45.3	15.0	60.3
49	2.5	2.0	1,4-Dioxane (0.25)	15	43.7	21.2	64.9
50	2.5	2.0	Diglyme ^f (0.25)	15	59.9	14.2	74.1
51	2.5	2.0	Diglyme ^f (0.25)	20	67.5	10.2	77.7
52	5	10.0	Dme ^d (1.25)	20	59.8	119.6	179.4

^a Reaction conditions: Ru(acac)₃/P(*n*-C₈H₁₇)₃ = 0.02/0.20 mmol, 200°C, H₂ 10 atm.^b Molar ratio of Zn/Ru.^c TON (turnover number) = (molar amount of product)/(mol-Ru), PhCH₂CH₂OH (1) and PhCH₂CO₂CH₂CH₂Ph (2).^d Dme: 1,2-dimethoxyethane.^e Di(ethylene glycol) diethyl ether.^f Diglyme: di(ethylene glycol) dimethyl ether.

Table 7

Hydrogenation of PhCH₂CO₂Me by Ru(acac)₃-P(*n*-C₈H₁₇)₃-Zn catalyst: effect of temperature and hydrogen pressure^a

Run No.	PhCH ₂ CO ₂ Me (mmol)	Solvent (ml)	Temperature (h)	H ₂ (atm)	Yield/TON ^b		Total
					1	2	
40	1.0	Xylene (0.50)	200	10	10.4	13.5	23.9
53	1.0	Xylene (0.50)	180	10	2.7	11.3	14.0
54	1.0	Xylene (0.50)	160	10	–	2.1	2.1
55	1.0	Dme ^c (0.50)	200	20	16.4	6.8	23.2
45	1.0	Dme ^c (0.50)	200	10	20.4	7.7	28.1
56	1.0	Dme ^c (0.50)	200	8	21.9	8.1	30.0
57	1.0	Dme ^c (0.50)	200	6	19.8	7.7	27.5
58	2.0	Diglyme ^d (0.25)	200	25	35.2	22.3	57.5
59	2.0	Diglyme ^d (0.25)	200	20	67.3	13.0	80.3
50	2.0	Diglyme ^d (0.25)	200	10	59.9	14.2	74.1

^a Reaction conditions: Ru(acac)₃/P(*n*-C₈H₁₇)₃ = 0.02/0.20 mmol, Zn 0.05 mmol, 15 h.^b TON (turnover number) = (molar amount of product)/(mol-Ru), PhCH₂CH₂OH (**1**) and PhCH₂CO₂CH₂CH₂Ph (**2**).^c Dme: 1,2-dimethoxyethane.^d Diglyme: di(ethylene glycol) dimethyl ether.

under these conditions. The observed catalytic activities were relatively high not only if the initial amount of PhCH₂CO₂Me charged was increased, but also if solvent was reduced to a minimum amount, as shown in Table 6 (runs 46–51). Under these conditions, effect of solvent for the activity became remarkable: dme and di(ethylene glycol) dimethyl ether (diglyme) were found to be effective (runs 46, 50). One example can be shown that the turnover number of 179 could be attained if PhCH₂CO₂Me was charged in large amount (10.0 mmol) in dme. The turnover numbers observed here (runs 46–52) should be noteworthy, especially because these are, as far as we know, the highest activities in this kind of hydrogenation under low hydrogen pressure.

Results concerning the temperature dependence for the activity are summarized in Table 7. The catalytic activity decreased significantly at low temperature

(runs 40, 53–54), especially the extremely low activity was observed at 160°C (2.1 turnovers, run 54).

It should also be noteworthy that the activity did not decrease by lowering the hydrogen pressure, if dme was used as the solvent (runs 45, 56, 57). In addition, the activity slightly decreased at higher hydrogen pressures (runs 55, 58). These facts are potentially interesting findings to note, especially because the previous catalysts for the hydrogenation require extremely high hydrogen pressure, and the activity was strongly influenced by the pressure employed.

3.2. Product distribution in the catalytic hydrogenation

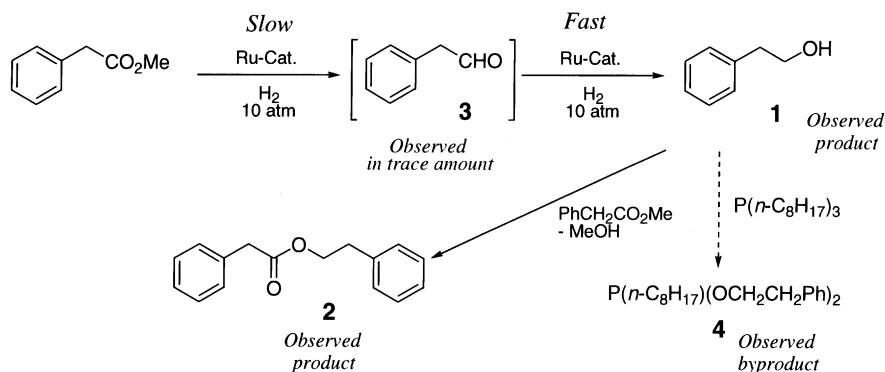
The reaction products in this catalytic reaction were 2-phenylethanol (**1**) and its ester with phenylacetic acid (**2**), as shown in Table 8. In addition, the

Table 8

Product distribution in hydrogenation of PhCH₂CO₂Me by Ru(acac)₃-P(*n*-C₈H₁₇)₃-Zn catalyst^a

Run No.	PhCH ₂ CO ₂ Me (mmol)	H ₂ (atm)	Conversion (%)	Product in mmol (TON) ^b			Selectivity of 1 + 2 ^c (%)
				1	2	1 + 2	
50	2.00	10	83.9	1.198 (59.9)	0.284 (14.2)	1.482 (74.1)	88.3
59	2.00	20	85.0	1.346 (67.3)	0.260 (13.0)	1.606 (80.3)	94.5

^a Reaction conditions: Ru(acac)₃/P(*n*-C₈H₁₇)₃/Zn = 1/10/2.5 (molar ratio), Ru(acac)₃ 0.02 mmol, diglyme 0.25 ml, 200°C, 15 h.^b TON (turnover number) = (molar amount of product)/(mol-Ru), PhCH₂CH₂OH (**1**) and PhCH₂CO₂CH₂CH₂Ph (**2**).^c Selectivity of **1** + **2** (%) = [(molar amount of **1** + **2** produced)/(molar amount of PhCH₂CO₂Me reacted)] × 100.



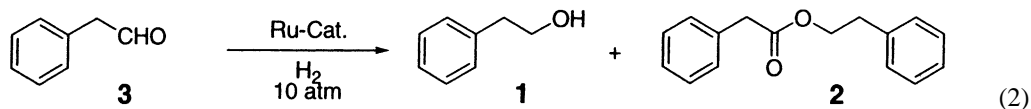
Scheme 1.

corresponding aldehyde, PhCH_2CHO , was also observed on GC chromatogram in a trace amount. Since the selectivity of the desired products based on the amount of substrate reacted was not perfect (88.3–94.5%), we thus analyzed the by-product by GC–MS. It turned out that the product replaced two of the *n*-octyl group in $\text{P}(n\text{-C}_8\text{H}_{17})_3$ with $\text{PhCH}_2\text{CH}_2\text{OH}$, $\text{P}(n\text{-C}_8\text{H}_{17})(\text{OCH}_2\text{CH}_2\text{Ph})_2$ (**4**) which was identified by GC–MS, was observed on GLC chromatogram in the reaction mixture in relatively large amount. Since **4** could be obtained in 16% when $\text{PhCH}_2\text{CH}_2\text{OH}$ was treated with $\text{P}(n\text{-C}_8\text{H}_{17})_3$ in dme at 200°C ,¹ the reason for the lack of selectivity would be due to the formation of **4** (and PhCH_2CHO in trace amount) in the reaction mixture, as shown in Scheme 1. This result

selectivity, and the product was then reacted with substrate by transesterification to give **2**, or the product was then reacted with phosphine to afford **4**.

3.3. Hydrogenation of PhCH_2CHO by $\text{Ru}(\text{acac})_3\text{-P}(n\text{-C}_8\text{H}_{17})_3\text{-Zn}$ catalyst

Since only a trace amount of the corresponding aldehyde, PhCH_2CHO , could be observed on GLC chromatogram, also since the possibility to produce **2** by aldehyde coupling (Tishchenko-type) reaction was not totally deleted only with the above results, we examined the reaction of aldehyde under the same conditions (Eq. (2)). The results are summarized in Table 9.



also indicates that the initial reaction product in the catalytic reaction was $\text{PhCH}_2\text{CH}_2\text{OH}$ with exclusive

¹ When $\text{PhCH}_2\text{CH}_2\text{OH}$ (**1**, 2.0 mmol) was treated with $\text{P}(n\text{-C}_8\text{H}_{17})_3$ (0.2 mmol) in dme (0.25 ml) at 200°C for 15 h (H_2 10 atm), 16% of **1** (by GC) was converted to $\text{P}(n\text{-C}_8\text{H}_{17})(\text{OCH}_2\text{CH}_2\text{Ph})_2$ which could be identified by GC–MS. We believe that this should be the reason for relatively low selectivity. The reaction products in this catalytic reaction were thus $\text{PhCH}_2\text{CH}_2\text{OH}$, $\text{PhCH}_2\text{CO}_2\text{CH}_2\text{CH}_2\text{Ph}$, PhCH_2CHO (trace amount), and $\text{P}(n\text{-C}_8\text{H}_{17})(\text{OCH}_2\text{CH}_2\text{Ph})_2$ and others, and the selectivity of $\text{PhCH}_2\text{CH}_2\text{OH}$ component based on the reacted $\text{PhCH}_2\text{CO}_2\text{Me}$ should be thus almost exclusive.

The hydrogenation of aldehyde proceeded at significant rates and the yield of **1** was almost quantitative (TON \Rightarrow 1140, run 61). The reaction was also completed at 180°C with lower ruthenium concentrations (run 62), and only a trace amount of **2** which would be generated by aldehyde coupling was also detected. These results strongly indicate that the aldehyde formed by the hydrogenation of ester quickly converted to the corresponding alcohol in this catalysis, and these results also strongly suggest that the product **2** in hydrogenation of $\text{PhCH}_2\text{CO}_2\text{Me}$ would be generated by ester replacement reaction (Scheme 1).

Table 9
Hydrogenation of PhCH₂CHO by Ru(acac)₃-P(*n*-C₈H₁₇)₃-Zn catalyst^a

Run No.	Ru (mmol)	Additive (A/Ru) ^b	PhCH ₂ CHO (mmol)	Temperature (°C)	Yield (%) ^c	
					1	2
60	0.02	Zn (2.5)	1.0	200	>94	0.8
61	0.005	Zn (10)	6.0	200	>95	1.8
62	0.005	Zn (10)	6.0	180	>98	1.5

^a Reaction conditions: molar ratio of Ru(acac)₃/P(*n*-C₈H₁₇)₃ = 1/10, xylene 1.25 ml, H₂ 10 atm, 5 h.

^b Molar ratio of Zn/Ru.

^c PhCH₂CH₂OH (1) and PhCH₂CO₂CH₂CH₂Ph (2).

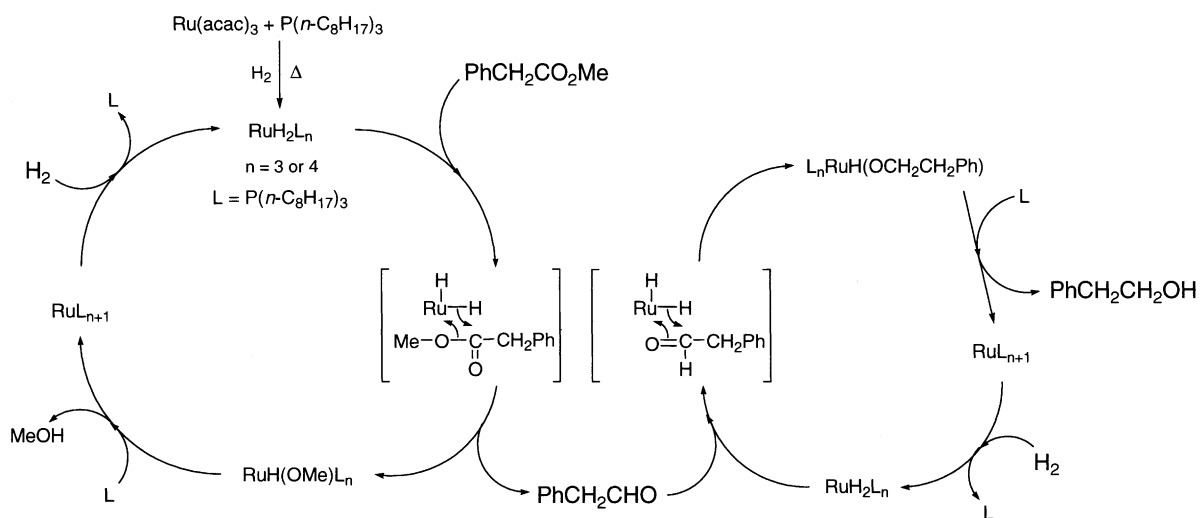
4. Mechanistic considerations

It has been reported that both RuH₂(PR₃)₄ and RuH₂(PR₃)₃ species (R: *n*-octyl) are generated in the reaction mixture consisted of Ru(acac)₃ and PR₃ under H₂ at >170°C, which had been confirmed by ¹H, ³¹P and FD-MS analysis [19]. Since relatively excess amount of P(*n*-C₈H₁₇)₃ are required to exhibit the activity in the present catalytic hydrogenation of PhCH₂CO₂Me, also since ruthenium-hydride would be easily formed under these conditions from the above report [19], it is thus suggested that ruthenium-hydride species like RuH₂[P(*n*-C₈H₁₇)₃]_{*n*} (*n* = 3 and/or 4) plays an essential key role for this catalytic reduction.

Since, the activity was not strongly influenced by the hydrogen pressure but depended upon both the initial

PhCH₂CO₂Me concentration and the solvent used, the rate determining step in the present catalysts should be thus different from that previously reported. Almost first order dependence was obtained between the TON value (after 5 h) and the initial PhCH₂CO₂Me concentration especially at relatively low concentration region as shown in Fig. 1, we assume that the rate determining step in the catalysis cycle would be the reaction of ester with hydride species.

The role of Zn would not be the fast reduction of Ru(acac)₃ to form catalytically-active species, but be the *indirect* activation of substrate by weak coordination that would promote the reaction with ruthenium-hydride species, since both Zn and Zn(acac)₂ enhanced the activity. These assumptions would also be supported by the previous report [19] as described above that ruthenium-hydride species



can be readily generated under these reaction conditions. Taking into account the above discussions, the tentative reaction scheme can be shown in Scheme 2. We were now studying to find a more active catalyst in the hydrogenation based on these results.

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References

- [1] S.N. Ege, Organic Chemistry, DC Heath & Company, Lexington, 1989, p. 596.
- [2] J. March, Advanced Organic Chemistry, Wiley/Interscience, New York, 1992.
- [3] T. Turek, D.L. Trimm, N.W. Cant, Catal. Rev.-Sci. Eng. 36 (1994) 645.
- [4] R.A. Grey, G.P. Pez, A. Wallo, J. Am. Chem. Soc. 103 (1981) 7536.
- [5] M. Bianchi, G. Menchi, F. Francalanci, F. Piacenti, U. Matteoli, P. Frediani, C. Botteghi, J. Organomet. Chem. 188 (1980) 109.
- [6] U. Matteoli, M. Bianchi, G. Menchi, P. Frediani, F. Piacenti, J. Mol. Catal. 44 (1988) 347.
- [7] U. Matteoli, G. Menchi, M. Bianchi, F. Piacenti, J. Organomet. Chem. 299 (1986) 233.
- [8] U. Matteoli, G. Menchi, M. Bianchi, F. Piacenti, S. Ianelli, M. Nardelli, J. Organomet. Chem. 498 (1995) 177.
- [9] Y. Hara, H. Inagaki, S. Nishimura, K. Wada, Chem. Lett. (1992) 1983.
- [10] K. Ishii, F. Mizukami, S. Niwa, M. Toba, H. Ushijima, T. Sato, J. Am. Oil. Soc. 73 (1996) 465.
- [11] H.T. Teunissen, C.J. Elsevier, Chem. Commun. (1997) 667.
- [12] H.T. Teunissen, C.J. Elsevier, Chem. Commun. (1998) 1367.
- [13] K. Nomura, H. Ogura, Y. Imanishi, J. Mol. Catal. A 166 (2001) 345.
- [14] J.E. Lyons, J. Chem. Soc., Chem. Commun. (1975) 412.
- [15] P. Morand, M. Kayser, J. Chem. Soc., Chem. Commun. (1976) 314.
- [16] K. Osakada, T. Ikariya, S. Yashikawa, J. Organomet. Chem. 231 (1982) 79.
- [17] T. Ikariya, K. Osakada, Y. Ishii, S. Osawa, M. Saburi, S. Yoshikawa, Bull. Chem. Soc. Jpn. 57 (1984) 897.
- [18] Y. Hara, K. Wada, Chem. Lett. (1991) 553.
- [19] Y. Hara, C. Miyazawa, K. Takahashi, K. Wada, Nippon Kagaku Kaishi (1999) 567.
- [20] K. Nagayama, I. Shimizu, A. Yamamoto, Chem. Lett. (1998) 1143.
- [21] T. Naota, H. Takaya, S.-I. Murahashi, Chem. Rev. 98 (1998) 2599.
- [22] K. Nomura, Chem. Lett. (1991) 1679.
- [23] K. Nomura, J. Mol. Catal. 73 (1992) L1.
- [24] K. Nomura, J. Mol. Catal. A 95 (1995) 203.
- [25] K. Nomura, J. Mol. Catal. A (Rev.) 130 (1998) 1.
- [26] K. Nomura, Catal. Surveys Jpn. (Rev.) 2 (1998) 59.
- [27] K. Nomura, W. Sidokmai, Y. Imanishi, Macromolecules 32 (1999) 4732.
- [28] M.A. Bennett, A.K. Smith, J. Chem. Soc., Dalton Trans. (1974) 233.
- [29] K. Nomura, M. Ishino, M. Hazama, J. Mol. Catal. 65 (1991) L5.
- [30] P.E. Garrou, Chem. Rev. 85 (1985) 171.
- [31] H. Nishiyama, Y. Itoh, H. Matsumoto, S.-B. Park, K. Itoh, J. Am. Chem. Soc. 116 (1994) 2223.
- [32] S. Komiyama (Ed.), Synthesis of Organometallic Compounds, A Practical Guide, Wiley, New York, 1997.