Breaking of the C−C Bond of Cyclobutanones by Rhodium(I) and Its Extension to Catalytic Synthetic Reactions

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Abstract: A study of rhodium(I)-catalyzed synthetic transformations involving selective breaking of the C−C bond α to the carbonyl group of cyclobutanones is described. Decarbonylation took place on treatment of a cyclobutanone with an equimolar amount of $(Ph_3P)_3RhCl$ at reflux in toluene to afford the corresponding cyclopropane. The formation of the cyclopropane suggests that Rh(I) undergoes an insertion into the bond between the carbonyl carbon and the α-carbon in the initial step. Catalytic decarbonylation of cyclobutanone was also achieved. The mode and rate of the reaction depended greatly on the ligands of the rhodium(I) complex. When a cyclobutanone bearing a hydrogen atom at the 3-position was used, appropriate choice of the catalyst system led to the selective formation of either a cyclopropane or an alkene. Breaking of the carbon−carbon bond was next combined with hydrogenolysis. When cyclobutanone was treated under hydrogen pressure with a catalytic amount of a rhodium(I) complex having a bidentate diphosphine ligand like 1,2-bis(diphenylphosphino)ethane, a ring-opened alcohol was produced in good yield. Selective breaking of C−C bonds by a soluble transition metal complex is achieved in these practical synthetic processes.

Introduction

The use of transition metals has provided a wide repertoire of transformations in organic synthesis and has recently been extended into the area of manipulation of considerably inert organic functionalities.[1] For example, aromatic and olefinic C−H bonds are catalytically cleaved by late transition metal complexes in synthetic processes.[2] Carbon−carbon bonds are generally even more inert toward transition metals, and hence activation of C−C bonds has gained intensified interest in the field of organometallic chemistry. In the petroleum industry, breaking of C−C bonds has been carried out in the presence of a heterogeneous catalyst at high temperature. Cleavage, however, is totally non-selective; long-chain hydrocarbons are cut into smaller pieces. Under homogeneous conditions, C−C bond cleavage by a process of insertion of transition metals has been mostly observed in stoichiometric reactions,[3] with substrates which are designed for this purpose,[4] with highly strained substrates like cyclopropane and cubane,[5] or with unsaturated ketones.[6,7] Direct observation of thermodynamically stable C−C cleaved complexes also has been reported.[3f,g,4b,h,5e] However, only a few are catalytic rections.[3f,4c,5d,f,7c,e] As a consequence, the problem of C−C bond breaking has been rarely addressed from the viewpoint of synthetic chemistry[5d] and remains a challenging topic of considerable scientific and technological interest. We present here new synthetic processes which involve selective breaking of the C−C single bond α to the carbonyl group of cyclobutanones by soluble rhodium(I) catalysts.[8]

Results and Discussion

Rhodium-Mediated Decarbonylation of Cyclobutanones. Cyclobutanone **1** was treated with an equimolar amount of $(Ph_3P)_3RhCl$ at reflux in toluene for 41 h. Decarbonylation took place to afford quantitatively the corresponding cyclopropane **4** along with *trans*-$[Rh(CO)Cl(PPh_3)_2]$ (**5**).[9] The formation of **4** and **5** suggests that Rh(I) undergoes an insertion into the bond between the carbonyl carbon and the α-carbon, giving the

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(1) For review, see: Crabtree, R. H. *Chem. Rev.* **1985**, *85*, 245.

(2) (a) Murai, S.; Kakiuchi, F.; Sekine, S.; Tanaka, Y.; Kamatani, A.; Sonoda, M.; Chatani, N. *Nature* **1993**, *366*, 529. (b) Kakiuchi, F.; Sekine, S.; Tanaka, Y.; Kamatani, A.; Sonoda, M.; Chatani, N.; Murai, S. *Bull. Chem. Soc. Jpn.* **1995**, *68*, 62. (c) Kakiuchi, F.; Tanaka, Y.; Sato, T.; Chatani, N.; Murai, S. *Chem. Lett.* **1995**, 679. (d) Kakiuchi, F.; Yamamoto, Y.; Chatani, N.; Murai, S. *Chem. Lett.* **1995**, 681. (e) Lim, Y.-G.; Kim, Y. H.; Kang, J.-B. *J. Chem. Soc., Chem. Commun.* **1994**, 2267. (f) Williams, N. A.; Uchimaru, Y.; Tanaka, M. *J. Chem. Soc., Chem. Commun.* **1995**, 1129. (g) Trost, M.; Imi, K.; Davies, I. W. *J. Am. Chem. Soc.* **1995**, *117*, 5371 and references therein.

(3) (a) Schott, A.; Schott, H.; Wilke, G.; Brandt, J.; Hoberg, H.; Hoffmann, E. G. *Liebigs Ann. Chem.* **1973**, 508. (b) Crabtree, R. H.; Dion, R. P. *J. Chem. Soc., Chem. Commun.* **1984**, 1260. (c) Crabtree, R. H.; Dion, R. P.; Gibboni, D. J.; McGrath, D. V.; Holt, E. M. *J. Am. Chem. Soc.* **1986**, *108*, 7222. (d) Hartwig, J. F.; Anderson, R. A.; Bergman, R. G. *J. Am. Chem. Soc.* **1989**, *111*, 2717. (e) Bennett, M. A.; Nicholls, J. C.; Rahman, A. K. F.; Redhouse, A. D.; Spencer, J. L.; Willis, A. C. *J. Chem. Soc., Chem. Commun.* **1989**, 1328. (f) Perthuisot, C.; Jones, W. D. *J. Am. Chem. Soc.* **1994**, *116*, 3647. (g) Suzuki, H.; Takaya, Y.; Takemori, T. *J. Am. Chem. Soc.* **1994**, *116*, 10779. (h) Jun, C.-H.; Kang, J.-B.; Lim, Y.-G. *Tetrahedron Lett.* **1995**, *36*, 277.

(4) (a) Suggs, J. W.; Cox, S. D. *J. Organomet. Chem.* **1981**, *221*, 199. (b) Suggs, J. W.; Jun, C.-H. *J. Am. Chem. Soc.* **1984**, *106*, 3054. (c) Suggs, J. W.; Jun, C.-H. *J. Chem. Soc., Chem. Commun.* **1985**, 92. (d) Suggs, J. W.; Jun, C.-H. *J. Am. Chem. Soc.* **1986**, *108*, 4679. (e) Gozin, M.; Weisman, A.; Ben-David, Y.; Milstein, D. *Nature* **1993**, *364*, 699. (f) Gozin, M.; Aizenberg, M.; Liou, S.-Y.; Weisman, A.; Ben-David, Y.; Milstein, D. *Nature* **1994**, *370*, 42. (g) Liou, S.-Y.; Gozin, M.; Milstein, D. *J. Chem. Soc., Chem. Commun.* **1995**, 1965. (h) Liou, S.-Y.; Gozin, M.; Milstein, D. *J. Am. Chem. Soc.* **1995**, *117*, 9774.

(5) (a) Bishop, K. C. *Chem. Rev.* **1976**, *76*, 461. (b) Tipper, C. F. H. *J. Chem. Soc.* **1955**, 2045. (c) Cassar, L.; Eaton, P. E.; Halpern, J. *J. Am. Chem. Soc.* **1970**, *92*, 6366. (d) Noyori, R.; Kumagai, Y.; Umeda, I.; Takaya, H. *J. Am. Chem. Soc.* **1972**, *94*, 4018. (e) Periana, R. A.; Bergman, R. G. *J. Am. Chem. Soc.* **1986**, *108*, 7346. (f) Fujimura, T.; Aoki, S.; Nakamura, E. *J. Org. Chem.* **1991**, *56*, 2809 and references therein.

(6) Alkynyl ketones: Müller, E.; Segnitz, A. *Liebigs Ann. Chem.* **1973**, 1583.

(7) Diketones: (a) Kolomnikov, I. S.; Svoboda, P.; Vol'pin, M. E. *Izv. Akad. Nauk. Ser. SSSR* **1972**, 2818; *Chem. Abstr.* **1973**, *78*, 97789k. (b) Evans, J. A.; Everitt, G. F.; Kemmitt, R. D. W.; Russell, D. R. *J. Chem. Soc., Chem. Commun.* **1973**, 158. (c) Kaneda, K.; Azuma, H.; Wayaku, M.; Teranishi, S. *Chem. Lett.* **1974**, 215. (d) Liebeskind, L. S.; Baysdon, S. L.; South, M. S.; Iyer, S.; Leeds, J. P. *Tetrahedron* **1985**, *41*, 5839. Cyclobutenones: (e) Huffman, M. A.; Liebeskind, L. S. *J. Am. Chem. Soc.* **1991**, *113*, 2771. (f) Huffman, M. A.; Liebeskind, L. S. *Organometallics* **1992**, *11*, 255.

(8) A preliminary communication: Murakami, M.; Amii, H.; Ito, Y. *Nature* **1994**, *370*, 540.

(9) (a) Evans, D.; Osborn, J. A.; Wilkinson, G. *Inorg. Synth.* **1968**, *11*, 99. (b) Tsuji, J.; Ohno, K. *Tetrahedron Lett.* **1965**, 3969.

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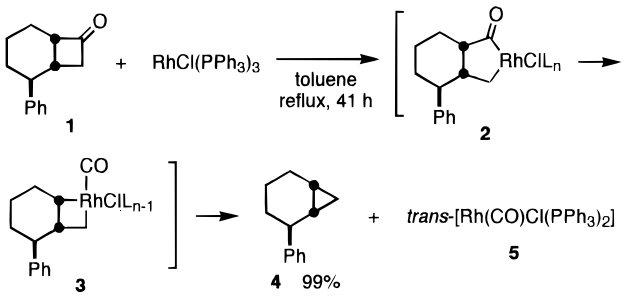
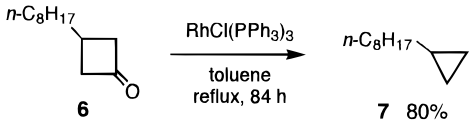
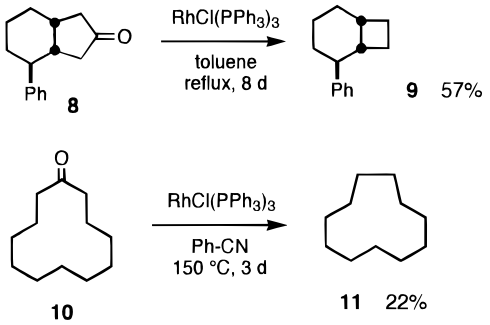


5-membered cyclic acylrhodium **2** in the initial step. Then, the carbonyl group is extruded from the 5-membered ring, with the carbon atom next to the carbonyl carbon migrating onto rhodium to furnish the contracted 4-membered rhodacycle **3**. Subsequent reductive elimination gives rise to cyclopropane **4** together with the rhodium carbonyl complex **5**. When 10 mol % of $(Ph_3P)_3$-RhCl was used, only 10% of cyclopropane **4** was obtained. The decarbonylation reaction failed to occur on treatment with *trans*-$[Rh(CO)Cl(PPh_3)_2]$ at reflux in toluene. It is likely that the binding of carbon monoxide to rhodium in *trans*-[Rh(CO)Cl-$(PPh_3)_2]$ is so strong that regeneration of an active rhodium species possessing a vacant coordination site by CO expulsion fails to occur at the refluxing temperature of toluene (*vide infra*).

Cyclobutanone (**6**) underwent an analogous decarbonylation on treatment with an equimolar amount of $(Ph_3P)_3RhCl$ to afford cyclopropane **7** in 80% yield.



Cyclopentanone (**8**) which is much less strained than cyclobutanone (**1**) also underwent the rhodium-mediated decarbonylation to give cyclobutane (**9**), although less efficiently. Decarbonylation of cyclododecanone (**10**) required higher temperature by the use of benzonitrile as the solvent. These results disclose the potential reactivity of rhodium(I) to insert into the C−C single bond α to the carbonyl group of cyclic ketones.



Thus, cyclic ketones were decarbonylated by the action of a stoichiometric amount of $RhCl(PPh_3)_3$. In organic reactions, a carbonyl functionality acts as an activating and/or directing group. Elaboration of an organic molecule is often carried out on the basis of a carbonyl group, which may ultimately be removed from the carbon skeleton. In this context, decarbonylation reactions are of synthetic value. Decarbonylation of acyl halides and aldehydes has been known to occur under homogeneous conditions, affording the corresponding alkyl halides and alkanes, respectively.[9b,10] The first step is considered to involve insertion of a transition metal into the carbon−halogen or carbon−hydrogen bond. Wilkinson's complex is by far the most frequently used as a stoichiometric decarbonylation *reagent*. Due to the high cost of rhodium, however, a catalytic reaction would be genuinely more useful.[7c,11]

In contrast to the reactions of acyl halides and aldehydes, examples of transition metal-mediated decarbonylation of ketones have been limited to alkynyl ketones,[6] diketones,[7c] or ketones used as solvent.[12] This is probably due to the increased difficulty of insertion of a transition metal into the α C−C bond. We next examined the rhodium catalyst in detail in order to make the present decarbonylation reaction catalytic in rhodium.

Catalytic Decarbonylation of Cyclobutanones. A model cyclobutanone (**12**), carrying a hydrogen atom at the 3-position, was heated in xylene in the presence of 5 mol % of a variety of rhodium(I) complexes listed in Table 1. Although very slowly, decarbonylation occurred on treatment of **12** with *trans*-[Rh-$(CO)Cl(PPh_3)_2]$ in refluxing xylene (137−144 °C), yielding a decarbonylated cyclopropane (**13**) together with a ring-opened alkene (**14**) (runs 1 and 2). It is likely that expulsion of carbon monoxide from rhodium occurred at the refluxing temperature of xylene to regenerate an active rhodium species with a vacant coordination site. When neutral Rh(I) complexes prepared *in situ* by mixing a dinuclear complex $[Rh_2(cod)_2Cl_2]$ (cod = 1,5-cyclooctadiene) with bidentate diphosphines like $Ph_2P(CH_2)_3$-PPh_2 (dppp) and $Ph_2P(CH_2)_4PPh_2$ (dppb) in a molar ratio of 1:2 were used, a significant increase in the rate of decarbonylation was observed, and moreover, alkene formation was exclusively favored (runs 3 and 4). It may be assumed that *cis* chelation gives the rhodium better chance to undergo insertion into the α-bond of **12**. The cationic complex $[Rh(dppe)_2]Cl$ (dppe = $Ph_2P(CH_2)_2PPh_2$), an especially active catalyst for decarbonylation of aldehydes,[11b] was not as effective for cyclobutanone (**12**), probably due to steric reasons (run 5). Another cationic complex having one dppb ligand per rhodium, $[Rh(cod)(dppb)]BF_4$, caused not only decarbonylation, but further double bond migration of the terminal alkene (**14**) to an inner one (**15**) (run 6). On the contrary, the formation of the alkene (**14**) was suppressed by replacing phosphine ligands of a neutral rhodium complex with arsine ligands. Decarbonylation of **12** proceeded gradually with a high cyclopropane/alkene ratio (run 7). Thus, appropriate choice of the catalyst system led to the selective formation of either a cyclopropane or an alkene.

The two catalytic systems for decarbonylation were applied to other cyclobutanones which also bore a hydrogen atom at the 3-position. Whereas a neutral complex prepared *in situ* from $[Rh_2(cod)_2Cl_2]$ and dppp effected selective conversion of the cyclobutanone (**16**) to the alkene (**18**), the $Rh-AsPh_3$ system favored the formation of the cyclopropane (**17**). Cyclopropane **4** was analogously produced from the bicyclic substrate **1** by the use of a catalytic amount of rhodium. However, no alkene formation was observed even with use of the Rh−dppb system. It seems that β elimination with the hydrogen at a bridgehead carbon is unfavorable.

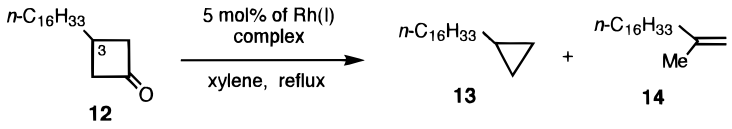
Next, decarbonylation of a cyclobutanone (**19**), lacking the possibility of β-hydride elimination due to the absence of a

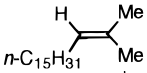
(10) (a) Colquhoun, H. M.; Thompson, D. J.; Twiggs, M. V. *Carbonylation: Direct Synthesis of Carbonyl Compounds*; Plenum: New York, 1991; pp 205−225. (b) Tkatchenko, T. In *Comprehensive Organometallic Chemistry*; Wilkinson, S. G. R., Stone, F. G. A., Abel, E. W., Eds.; Pergamon: Oxford, 1981; Vol. 8, pp 214−219. (c) Bates, R. W. In *Comprehensive Organometallic Chemistry II*; Abel, E. W., Stone, F. G. A., Wilkinson, G., Eds.; Pergamon: Oxford, 1995; Vol. 12 (Hegedus, L. S., Vol. Ed.); pp 373−378.

(11) For catalytic decarbonylation, see: (a) Ohno, K.; Tsuji, J. *J. Am. Chem. Soc.* **1968**, *90*, 99. (b) Doughty, D. H.; Pignolet, L. H. *J. Am. Chem. Soc.* **1978**, *100*, 7083. (c) Grunewald, G. L.; Davis, D. P. *J. Org. Chem.* **1978**, *43*, 3074. (d) O'Connor, J. M.; Ma, J. *J. Org. Chem.* **1992**, *57*, 5075. (e) Obora, Y.; Tsuji, Y.; Kawamura, T. *J. Am. Chem. Soc.* **1995**, *117*, 9814.

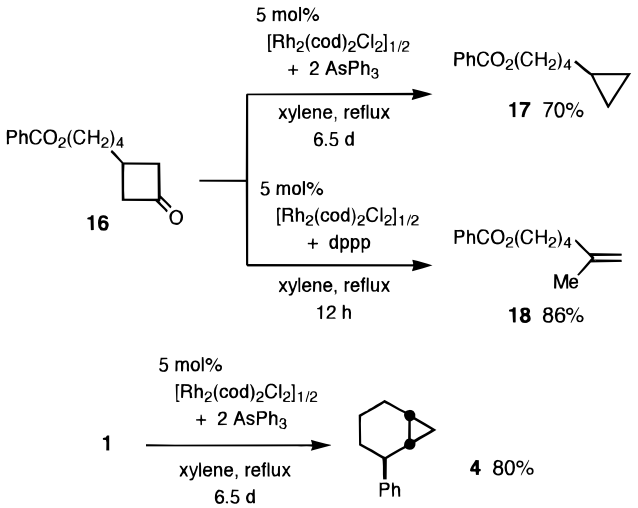
(12) Rusina, A.; Vlček, A. *Nature* **1965**, *208*, 295.

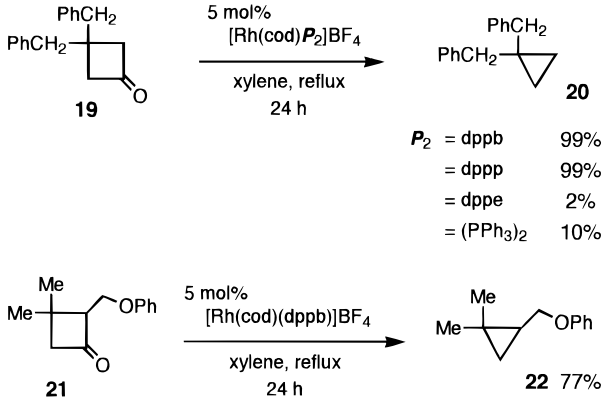
Table 1. Rh(I)-Catalyzed Decarbonylation of Cyclobutanone **12**



run	catalyst	time	products, yield [a]		
1	*trans*-[Rh(CO)Cl(PPh$_3$)$_2$]	23 h	**13** 17%[b]	**14** 6%[b]	
2	*trans*-[Rh(CO)Cl(PPh$_3$)$_2$]	5 d	**13** 40%[b]	**14** 22%[b]	
3	[Rh$_2$(cod)$_2$Cl$_2$]$_{1/2}$ + dppp	10 h	**13** Not detected.	**14** 99%	
4	[Rh$_2$(cod)$_2$Cl$_2$]$_{1/2}$ + dppb	21 h	**13** Not detected.	**14** 98%	
5	[Rh(dppe)$_2$]Cl	24 h	**13** 8%[b]	**14** 16%[b]	
6	[Rh(cod)(dppb)]BF$_4$	24 h	**13** 36%[b]	**14** 32%[b]	 **15** 32%[b]
7	[Rh$_2$(cod)$_2$Cl$_2$]$_{1/2}$ + 2 AsPh$_3$	7 d	**13** 68%	**14** 2%	

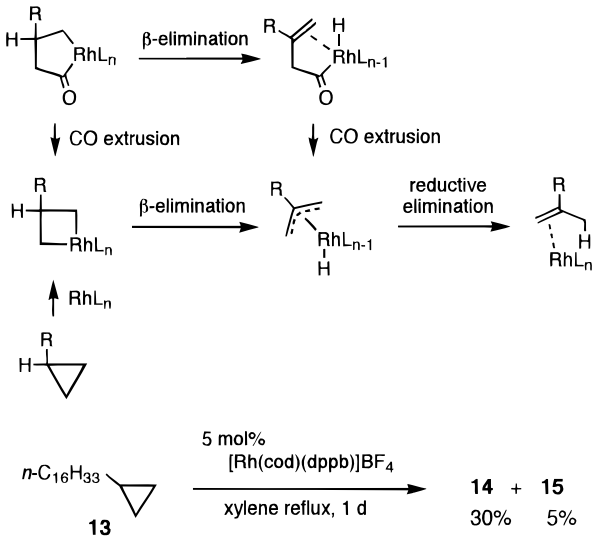
[a] Isolated yield unless specified. [b] Approximate yield based on reactant−products distribution determined by GC analysis.





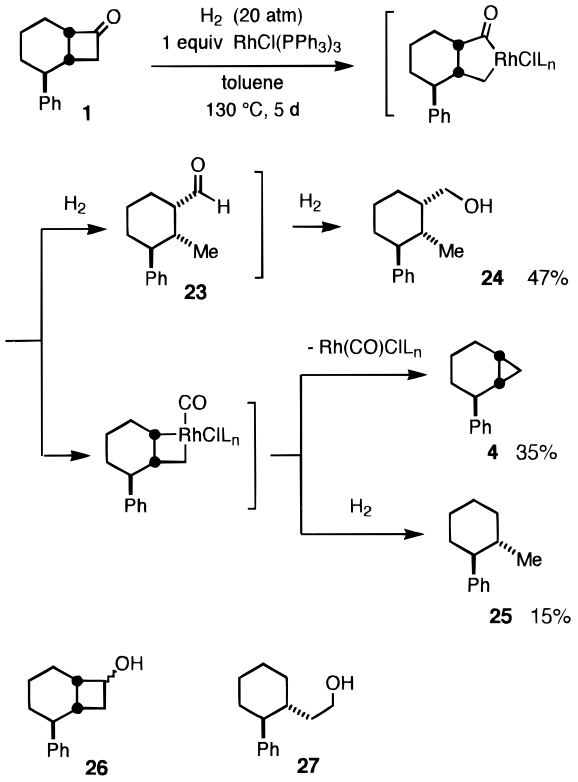
hydrogen atom at the 3-position, was examined using cationic complexes, which were expected to loosen a coordinating CO ligand more easily than neutral complexes owing to decreased Rh−CO back-bonding. Interestingly, the activity depended greatly on the type of phosphine ligand; bidentate ligands dppb and dppp were far superior to dppe and PPh_3. The wider bite angles (∠P−Rh−P) of dppb and dppp than that of dppe might favor the expulsion of carbon monoxide from rhodium.[13] Treatment of **19** with [Rh(cod)(dppb)]BF_4 or [Rh(cod)(dppp)]-BF_4 in refluxing xylene for 24 h produced cyclopropane **20** quantitatively. Cyclobutanone (**21**) was also catalytically decarbonylated, giving cyclopropane **22** in 77% yield. Catalytic decarbonylation of other strain-free cycloalkanones like cyclopentanone has been unsuccessful so far.

There are two possible routes from a 5-membered cyclic acylrhodium to an alkene. β-Hydride elimination can take place with a 5-membered cyclic acylrhodium or a rhodacyclobutane intermediate. The rhodacyclobutane may be directly formed from the 5-membered cyclic acylrhodium or regenerated via insertion of rhodium into the produced cyclopropane. The latter possibility was confirmed by the reaction of the isolated cyclopropane (**13**) with a catalytic amount of [Rh(cod)(dppb)]-BF_4.



(13) The ligand flexibility has been proposed to be responsible for the rate acceleration with dppp as compared with dppe.[11b]

Hydrogenolysis of Cyclobutanones. Selective carbon−carbon bond breaking at the α-position of a carbonyl group by a soluble rhodium complex is a key feature of the decarbonylation reaction mentioned above. We next explored a synthetic reaction wherein the carbonyl carbon is retained in the final product, and thus, breaking of a carbon−carbon bond was combined with a process of hydrogenolysis.[14] When cyclobutanone **1** was treated under a hydrogen atmosphere (20 atm) with 1 equiv of $(Ph_3P)_3RhCl$ at 130 °C for 5 days in toluene in an autoclave, alcohol **24** was produced in 47% yield together with cyclopropane **4** (35%) and a ring-opened hydrocarbon **25** (15%). It is likely that the aldehyde **23** is primarily formed



through the addition of dihydrogen to a 5-membered cyclic acylrhodium and the subsequent reductive elimination. The following second addition of dihydrogen to **23** gives the alcohol **24**. The ring-opened hydrocarbon **25** is formed presumably by hydrogenation of the rhodacyclobutane. The formation of cyclobutanol **26** was not observed, indicating that breaking of the C−C bond proceeds faster than direct hydrogenation of the carbonyl group under the present conditions. Moreover, there was no formation of alcohol **27**. These results show that the insertion of rhodium(I) took place selectively into the less-substituted C−C bond α to the carbonyl group of **1**. During this hydrogenolysis, the original carbonyl group **1** is retained as a hydroxymethyl group in the product **24**.

The effect of phosphine ligands was examined in order to make the reaction catalytic. The use of trialkylphosphine instead of triphenylphosphine gave inferior results in terms of reaction rate as well as product distribution. The rhodium(I) complexes prepared in situ from $[Rh_2(cod)_2Cl_2]$ and bidentate diphosphine ligands were found to be more effective catalysts. As listed in Table 2, the chain length between the two diphenylphosphino groups was important. When dppe or dppp was used as the ligand, the ring-opened alcohol (**24**) was obtained in good yield

(14) Hydrogenolysis of the C−C bond of a ring-strained bicyclic *β*-lactam occurs in the presence of heterogeneous Pd: Konosu, T.; Oida, S. *Chem. Pharm. Bull.* **1992**, *40*, 609.

Table 2. Rhodium-Catalyzed Hydrogenolysis of **1**[a]

run	bidentate diphosphine	**24**, %	**4** + **25**, %
1	dppm	23	5
2	dppe	87	10
3	dppp	82	10
4	dppb	20	40
5	dppf	31	18

[a] A mixture of cyclobutanone **1** $[Rh_2(cod)_2Cl_2]$ (5 mol %) and a bidentate diphosphine (12 mol %) in toluene under H_2 (50 atom) was heated at 140 °C for 2 days. Then, the reaction mixture was reduced with $NaBH_4$.

after reducing the reaction mixture with $NaBH_4$ (runs 2 and 3). Other bidentate ligands like bis(diphenylphosphino)methane (dppm), dppb, and 1,1′-bis(diphenylphosphino)ferrocene (dppf) afforded less active catalysts and produced a significant amount of decarbonylated compounds (**4** and **25**). It was also found that the hydrogenolysis proceeded slightly faster in THF than in toluene.

By the use of a catalytic amount of a Rh(I) complex prepared in situ from $[Rh_2(cod)_2Cl_2]$ and dppe, various cyclobutanones underwent hydrogenolysis of the C−C single bond α to the carbonyl group (Table 3). In runs 2−4, a mixture of an alcohol and an aldehyde was obtained and subsequently treated with $NaBH_4$ to obtain the product as the alcohol. Alcohols including synthetically useful compounds like 3-methylundecanol **30** (a synthetic building block of an insect pheromone)[15] and 2-methyl-1,4-butanediol derivative **31** (a bifunctional isoprenoid building block)[16] were isolated in good yields. Cyclobutanones possessing a substituent at the 2- and 3-positions underwent facile hydrogenolysis. Although the reaction proceeded also with 3,3-disubstituted cyclobutanone (runs 8 and 9), hydrogenolysis of 2,2-disubstituted cyclobutanone was sluggish, probably due to steric reasons (run 10). The bond to the less-substituted α carbon atom was selectively cleaved in the reactions of unsymmetric cyclobutanones (runs 7, 8, and 10). Ether, ester, and Cl−arene functionalities were compatible with the present reaction conditions. Thus, catalytic hydrogenolysis of C−C single bonds is accomplished via Rh(I)-mediated breaking of the C−C bond under a hydrogen atmosphere. The addition of dihydrogen together with relief of the structural strain of the cyclobutanone skeleton may make a large contribution to the driving force of this catalytic reaction.

Conclusion

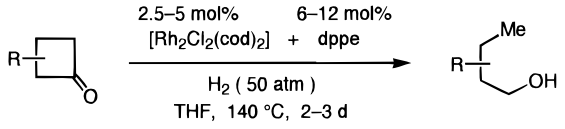
A number of excellent methods are currently available for the synthesis of cyclobutanones.[17] In particular, [2 + 2] cycloaddition reaction of alkenes with ketene derivatives provides a simple and general approach to those compounds, often with control of the regio- and stereochemistry of ring substituents. Therefore, if coupled with the preparation of cyclobutanones from alkenes, the synthetic processes described herein achieve selective manipulations of C−C double bonds as formulated below; the internal sp^2 carbon of a terminal olefin is regioselectively methylated by preparation of a cyclobutanone

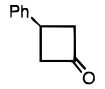
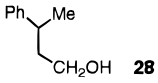
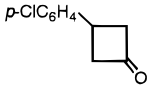
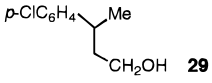
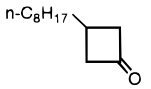
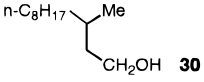
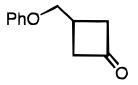
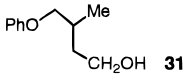
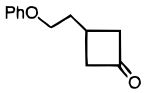
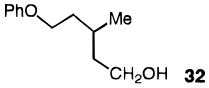
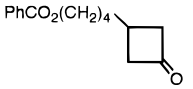
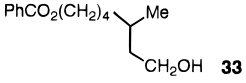
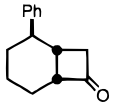
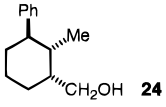
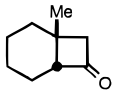
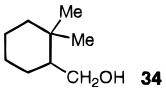
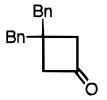
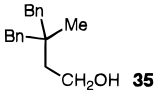
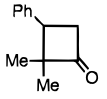
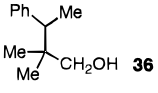
(15) Larcheveque, M.; Sanner, C.; Azerad, R.; Buisson, D. *Tetrahedron* **1988**, *44*, 6407.

(16) Schmid, R.; Hansen, H.-J. *Helv. Chim. Acta* **1990**, *73*, 1258.

(17) (a) Hyatt, J. A.; Raynolds, P. W. In *Organic Reactions*; Joyce, R. M., Ed.; Wiley: New York, 1994; Vol. 45, Chapter 2. (b) Krepski, L. R.; Hassner, A. *J. Org. Chem.* **1978**, *43*, 2879. (c) Bak, D. A.; Brady, W. T. *J. Org. Chem.* **1979**, *44*, 107. (d) Gadwood, R. C.; Mallick, I. M.; DeWinter, A. J. *J. Org. Chem.* **1987**, *52*, 774. (e) Trost, B. M. In *Topics in Current Chemistry, Vol. 133: Small Ring Compounds in Organic Synthesis I*; de Meijere, A., Ed.; Springer-Verlag: Berlin, 1986; pp 3−82. (f) Salaün, J. R. Y. In *Topics in Current Chemistry, Vol. 144: Small Ring Compounds in Organic Synthesis III*; de Meijere, A., Ed.; Springer-Verlag: Berlin, 1988; pp 1−71 and references therein.

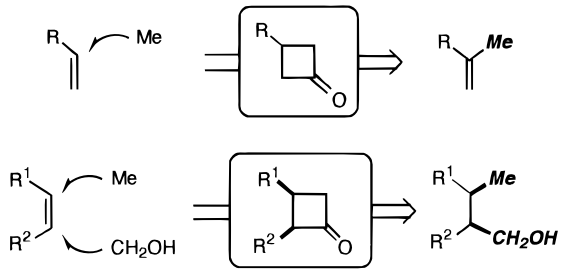
Table 3. Rhodium(I)-Catalyzed Hydrogenolysis of Cyclobutanones



run	cyclobutanone	product	yield, % [a]
1		 **28**	84
2		 **29**	81 [b]
3		 **30**	80 [b]
4		 **31**	71 [b,c]
5		 **32**	83
6		 **33**	71
7		 **24**	87 [c]
8		 **34**	74 [c]
9		 **35**	84 [c]
10		 **36**	9

[a] Isolated yield. [b] After hydrogenolysis, the reaction mixture was treated with $NaBH_4$. [c] Toluene was used as the solvent.

and the following decarbonylation. Analogously, the rhodium-catalyzed hydrogenolysis accomplished regio- and stereoselective *syn* 1,2-addition of methyl and hydroxymethyl groups to C−C double bonds.



Although we have no experimental or theoretical result to provide a basis for an argument for the mechanism of the insertion of rhodium(I) into the α C−C bond, the reactions described here present examples of practical synthetic transformations involving selective breaking of C−C bonds by transition metal complexes under homogeneous conditions. The present study suggests that the insertion of a transition metal into the C−C bond α to a carbonyl group may be a kinetically feasible, fundamental process. Fine-tuning of the ligand set, the most favorable feature of homogeneous catalysts, and designing a reaction to gain a thermodynamic driving force would lead to the development of various kinds of transformations, hopefully including those which can be applied to natural product syntheses.

Experimental Section

General. Column chromatography was performed with silica gel (Wakogel C-200). Preparative thin-layer chromatography (TLC) was performed with silica gel 60 PF_{254} (E. Merck, Darmstadt). ^1H and ^{13}C NMR spectra were acquired in chloroform-*d* at 200 and 50 MHz, respectively. Na_2SO_4 was used to dry organic layers after extraction.

Materials were obtained from commercial sources unless otherwise noted. THF was distilled from sodium diphenylketyl, toluene from $LiAlH_4$, and xylene (an isomers mixture) from CaH_2. Cyclobutanones were prepared by [2 + 2] cycloaddition of alkenes with dichloroketene and the following dechlorination with zinc.[17a]

2-Phenylbicyclo[4.1.0]heptane (4). A toluene solution (2 mL) of $(Ph_3P)_3RhCl$ (23.2 mg, 25 μmol) and **1** (5.0 mg, 25 μmol) was heated at reflux for 41 h under an argon atmosphere. The cooled reaction mixture was filtered through a pad of florisil and the filtrate was purified by preparative thin layer chromatography of silica gel (hexane) to afford **4** (4.3 m, 99%) as a colorless oil: ^1H NMR δ 0.14−0.30 (m, 1 H), 0.60−0.80 (m, 1 H), 0.80−1.40 (m, 4 H), 1.40−1.80 (m, 2 H), 1.80−2.00 (m, 2 H), 2.75−2.90 (m, 1 H), 7.10−7.40 (m, 5 H); ^{13}C NMR δ 10.4, 10.6, 16.1, 18.7, 23.2, 31.9, 42.2, 125.6, 127.6, 128.2, 149.1; HRMS calcd for $C_{13}H_{16}$ (*m*/*z*) 172.1248, found 172.1242.

Octylcyclopropane (7). By a procedure similar to that for **4** (column chromatography, hexane), the title compound (6.1 mg, 80%) was obtained from **6** (9.0 mg, 50 μmol) and $(Ph_3P)_3RhCl$ (46.3 mg, 50 μmol).

2-Phenylbicyclo[4.2.0]octane (9). By a procedure similar to that for **4** (thin layer chromatography, hexane:AcOEt = 5:1), the title compound (10.6 mg, 57%) was obtained as a colorless oil from **8** (21.4 mg, 100 μmol) and $(Ph_3P)_3RhCl$ (92.4 mg, 100 μmol). ^1H NMR δ 1.2−2.0 (m, 10 H), 2.1−2.4 (m, 2 H), 2.6−2.8 (m, 1 H), 7.1−7.4 (m, 5 H); ^{13}C NMR δ 20.7, 21.3, 24.2, 25.0, 32.0, 33.0, 39.0, 47.1, 125.8, 127.8, 128.3, 148.5; HRMS calcd for $C_{14}H_{18}$ (*m*/*z*) 184.1404, found 184.1404.

Cycloundecane (11). A benzonitrile solution (1 mL) of $(Ph_3P)_3RhCl$ (27.7 mg, 30 μmol) and **7** (5.5 mg, 30 μmol) was heated at 150 °C for 3 days under an argon atmosphere. A workup procedure similar to that for **4** (column chromatography, hexane) afforded **11** (1.0 mg, 22%). ^1H NMR δ 1.42 (s, 22 H); ^{13}C NMR δ 26.3; HRMS calcd for $C_{11}H_{22}$ (*m*/*z*) 154.1716, found 154.1722.

Hexadecylcyclopropane (13). A xylene solution (2 mL) of $[Rh_2(cod)_2Cl_2]$ (1.2 mg, 2.5 μmol), $AsPh_3$ (3.1 mg, 10 μmol), and **12** (29.4 mg, 0.10 mmol) was heated at reflux for 7 days under an argon atmosphere. A workup procedure similar to that for **4** (column chromatography, hexane) afforded a mixture of **13** and **14** (18.6 mg, **13:14** = 97:3) as a colorless oil. The following NMR data are those for **13**: ^1H NMR δ −0.06−0.04 (m, 2 H), 0.32−0.45 (m, 2 H), 0.55−0.74 (m, 1 H), 0.89 (t, *J* = 6.5 Hz, 3 H), 1.10−1.50 (m, 30 H); ^{13}C NMR δ 4.3, 10.9, 14.1, 22.7, 29.3, 29.5, 29.7, 31.9, 34.8. Anal. Calcd for $C_{19}H_{38}$: C 85.63; H, 14.37. Found: C, 85.36; H, 14.21.

2-Methyl-1-octadecene (14). A xylene solution (1 mL) of $[Rh_2(cod)_2Cl_2]$ (1.2 mg, 2.5 μmol), dppp (2.5 mg, 6 μmol), and **12** (29.4 mg, 0.10 mmol) was heated at reflux for 10 h under an argon atmosphere. A workup procedure similar to that for **4** (column chromatography, hexane) afforded **14** (27.0 mg, 99%) as a colorless oil: ^1H NMR δ 0.88 (t, *J* = 6.5 Hz, 3 H), 1.10−1.40 (m, 28 H), 1.71 (s, 3 H), 2.00 (t, *J* = 7.4 Hz, 2 H), 4.60−4.70 (m, 2 H); ^{13}C NMR δ 14.1, 22.4, 22.7,

27.7, 29.4, 29.6, 31.9, 37.9, 109.5, 146.4; IR (neat) 1654 cm^{-1}. Anal. Calcd for $C_{19}H_{38}$: C, 85.63; H, 14.37. Found: C, 85.64; H, 14.65.

4-Cyclopropylbutyl Benzoate (17). By a procedure similar to that for **13**, the title compound (30.6 mg, 70%) was obtained from **16** (49.2 mg, 0.20 mmol), $[Rh_2(cod)_2Cl_2]$ (2.5 mg, 5 μmol), and $AsPh_3$ (7.3 mg, 24 μmol): ^{1}H NMR δ −0.01−0.10 (m, 2 H), 0.26−0.50 (m, 2 H), 0.58−0.80 (m, 1 H), 1.20−1.40 (m, 2 H), 1.50−1.70 (m, 2 H), 1.70−1.90 (m, 2 H), 4.32 (t, J = 6.6 Hz, 2 H), 7.40−7.60 (m, 3 H), 8.00−8.10 (m, 2 H); ^{13}C NMR δ 4.4, 10.7, 26.1, 28.6, 34.3, 65.1, 128.3, 129.5, 130.5, 132.8, 166.7; IR (neat) 1724 cm^{-1}. Anal. Calcd for $C_{14}H_{18}O_2$: C, 77.03; H, 8.31. Found: C, 76.86; H, 8.38.

5-Methyl-5-hexenyl Benzoate (18). By a procedure similar to that for **14**, the title compound (18.8 mg, 86%) was obtained from **16** (24.6 mg, 0.10 mmol), $[Rh_2Cl_2(cod)_2]$ (1.2 mg, 2.5 μmol), and dppp (2.5 mg, 6 μmol): ^{1}H NMR δ 1.50−1.90 (m, 4 H), 1.73 (s, 3 H), 2.10 (t, J = 7.3 Hz, 2 H), 4.34 (t, J = 6.4 Hz, 2 H), 4.71 (s, 1 H), 4.73 (s, 1 H), 7.35−7.60 (m, 3 H), 7.95−8.10 (m, 2 H); ^{13}C NMR δ 22.3, 23.9, 28.3, 37.3, 64.9, 110.2, 128.3, 129.5, 130.4, 137.8, 145.4, 166.7; IR (neat) 1724 cm^{-1}. Anal. Calcd for $C_{14}H_{18}O_2$: C, 77.03, H, 8.31. Found: C, 77.13; H, 8.28.

1,1-Dibenzylcyclopropane (20). A xylene solution (1 mL) of [Rh(cod)(dppb)]BF_4 (3.6 mg, 5 μmol) and **19** (25.0 mg, 0.10 mmol) was heated at reflux for 24 h under an argon atmosphere. A workup procedure similar to that for **4** (column chromatography, hexane) afforded **20** (22.2 mg, 99%) as a colorless oil: ^{1}H NMR δ 0.53 (s, 4 H), 2.57 (s, 4 H), 7.10−7.40 (m, 10 H); ^{13}C NMR δ 10.7, 20.8, 41.6, 126.0, 128.0, 129.5, 140.1. Anal. Calcd for $C_{17}H_{18}$: C, 91.84; H, 8.16. Found: C, 91.96; H, 8.34.

2,2-Dimethyl-1-(phenoxymethyl)cyclopropane (22). By a procedure similar to that for **20** (thin layer chromatography, hexane:Et_2O = 10:1), the title compound (17.5 mg, 77%) was obtained from **21** (25.6 mg, 0.10 mmol) and [Rh(cod)(dppb)]BF_4 (3.6 mg, 5 μmol): ^{1}H NMR δ 0.20−0.30 (m, 1 H), 0.60 (dd, J = 8.6, 4.6 Hz, 1 H), 1.00−1.10 (m, 1 H), 1.12 (s, 6 H), 3.84 (dd, J = 10.2, 8.3 Hz, 1 H), 4.07 (dd, J = 10.2, 6.5 Hz, 1 H), 6.86−7.00 (m, 3 H), 7.20−7.34 (m, 2 H); ^{13}C NMR δ 16.2, 18.5, 19.9, 23.2, 27.1, 69.3, 114.7, 120.5, 129.4, 159.2. Anal. Calcd for $C_{12}H_{16}O$: C, 81.77; H, 9.15. Found: C, 81.37; H, 9.12.

***(1R*,2S*,3R*)*-1-(Hydroxymethyl)-2-methyl-3-phenylcyclohexane (24).** A toluene solution (4 mL) of $[Rh_2(cod)_2Cl_2]$ (3.7 mg, 7.5 μmol), dppe (6.0 mg, 15 μmol), and **1** (30 mg, 150 μmol) under a hydrogen atomsphere (50 atm) in an autoclave was heated at 140 °C for 42 h. The cooled reaction mixture was filtered through a pad of florisil and the filtrate was purified by preparative thin layer chromatography of silica gel (hexane:AcOEt = 2:1) to afford **24** (26.5 mg, 87%) as a colorless oil: ^{1}H NMR δ 0.72 (d, J = 6.3 Hz, 3 H), 1.2−2.0 (m, 9 H), 2.1−2.3 (m, 1 H), 3.64 (dd, J = 11.3, 5.2 Hz, 1 H), 3.78 (dd, J = 11.3, 2.1 Hz, 1 H), 7.1−7.4 (m, 5 H); ^{13}C NMR δ 17.1, 26.2, 29.8, 35.8, 38.2, 46.5, 52.2, 65.9, 125.8, 127.6, 128.3, 146.7. Anal. Calcd for $C_{14}H_{20}O$: C, 82.30; H, 9.87. Found: C, 82.24; H, 10.16.

3-Phenyl-1-butanol (28). A THF solution (4 mL) of $[Rh_2(cod)_2Cl_2]$ (4.9 mg, 10 μmol), dppe (9.6 mg, 24 μmol), and 3-phenylcyclobutanone (29 mg, 0.20 mmol) under a hydrogen atmosphere (50 atm) in an autoclave was heated at 140 °C for 48 h. A workup procedure similar to that for **24** (thin layer chromatography, hexane:AcOEt = 2:1) afforded **28** (25.1 mg, 84%) as a colorless oil.

3-(4-Chlorophenyl)-1-butanol (29). A THF solution (5 mL) of $[Rh_2(cod)_2Cl_2]$ (6.2 mg, 12.5 μmol), dppe (12.0 mg, 30 μmol), and 3-(4-chlorophenyl)cyclobutanone (90 mg, 0.50 mmol) under a hydrogen atmosphere (50 atm) in an autoclave was heated at 140 °C for 44 h. The cooled reaction mixture was filtered through a pad of florisil and the filtrate was condensed under reduced pressure. The residue was dissolved in MeOH (1 mL) and treated with $NaBH_4$ (19 mg, 0.50 mmol). The mixture was diluted with aqueous HCl (1 N), extracted with ether, dried, and purified by preparative thin layer chromatography of silica gel (hexane:AcOEt = 2:1) to afford **29** (75 mg, 81%) as a colorless oil: ^{1}H NMR δ 1.25 (d, J = 7.0 Hz, 3 H), 1.4 (br s, 1 H), 1.7−1.9 (m, 2 H), 2.88 (sextet, J = 7.0 Hz, 1 H), 3.40−3.65 (m, 2 H), 7.05−7.20 (m, 2 H), 7.20−7.35 (m, 2 H); ^{13}C NMR δ 22.3, 35.8, 40.8, 60.9, 128.3, 128.5, 131.6, 145.3; HRMS calcd for $C_{10}H_{13}OCl$ (m/z) 184.0652, found 186.0662.

3-Methyl-1-undecanol (30). A THF solution (3 mL) of $[Rh_2(cod)_2Cl_2]$ (4.9 mg, 10 μmol), dppe (9.6 mg, 24 μmol), and 3-octylcyclobutanone (36 mg, 0.2 mmol) under a hydrogen atmosphere (50 atm) in an autoclave was heated at 140 °C for 3 days. A workup procedure similar to that for **29** (column chromatography, hexane:Et_2O = 2:1) afforded **30** (29.5 mg, 80%) as a colorless oil.

3-Methyl-4-phenoxy-1-butanol (31). A toluene solution (5 mL) of $[Rh_2(cod)_2Cl_2]$ (14.8 mg, 30 μmol), dppe (28.6 mg, 72 μmol), and 3-(phenoxymethyl)cyclobutanone (106 mg, 0.60 mmol) under a hydrogen atmosphere (50 atm) in an autoclave was heated at 140 °C for 42 h. A workup procedure similar to that for **29** (thin layer chromatography, hexane:AcOEt = 2:1) afforded **31** (76.9 mg, 71%) as a pale yellow oil: ^{1}H NMR δ 1.07 (d, J = 6.8 Hz, 3 H), 1.5 (br s, 1 H), 1.5−1.7 (m, 1 H), 1.7−1.9 (m, 1 H), 2.1−2.3 (m, 1 H), 3.7−3.9 (m, 2 H), 3.83 (d, J = 6.4 Hz, 2 H), 6.8−7.0 (m, 3 H), 7.2−7.4 (m, 2 H); ^{13}C NMR δ 17.2, 30.3, 36.9, 60.8, 73.0, 114.5, 120.6, 129.4, 158.9. Anal. Calcd for $C_{11}H_{16}O_2$: C, 73.30; H, 8.95. Found: C, 73.02; H, 9.07.

3-Methyl-5-phenoxypentanol (32). A THF solution (3 mL) of $[Rh_2(cod)_2Cl_2]$ (2.5 mg, 5.0 μmol), dppe (12.0 mg, 10 μmol), and 3-(2-phenoxyethyl)cyclobutanone (19.0 mg, 0.10 mmol) under a hydrogen atmosphere (50 atm) in an autoclave was heated at 140 °C for 60 h. A workup procedure similar to that for **24** (thin layer chromatography, hexane:AcOEt = 2:1) afforded **32** (16.1 mg, 83%) as a colorless oil: ^{1}H NMR δ 0.99 (d, J = 6.5 Hz, 3 H), 1.4−2.0 (m, 6 H), 3.6−3.8 (m, 2 H), 3.9−4.1 (m, 2 H), 6.8−7.0 (m, 3 H), 7.2−7.4 (m, 2 H); ^{13}C NMR δ 19.7, 26.8, 36.2, 39.8, 61.0, 65.9, 114.5, 120.6, 129.4, 160.0. Anal. Calcd for $C_{12}H_{18}O_2$: C, 79.14; H, 9.34. Found: C, 74.04; H, 9.50.

7-Hydroxy-5-methylheptyl Benzoate (33). A THF solution (1 mL) of $[Rh_2(cod)_2Cl_2]$ (1.3 mg, 2.6 μmol), dppe (2.4 mg, 6.0 μmol), and 3-[4-(benzoyloxy)butyl]cyclobutanone (24.6 mg, 0.10 mmol) under a hydrogen atmosphere (50 atm) in an autoclave was heated at 140 °C for 48 h. A workup procedure similar to that for **24** (thin layer chromatography, hexane:AcOEt = 2:1) afforded **33** (17.8 mg, 71%) as a colorless oil: ^{1}H NMR δ 0.91 (d, J = 6.5 Hz, 3 H), 1.1−2.0 (m, 10 H), 3.55−3.80 (m, 2 H), 4.32 (t, J = 6.6 Hz, 2 H), 7.3−7.6 (m, 3 H), 7.9−8.0 (m, 2 H); ^{13}C NMR δ 19.5, 23.4, 28.9, 29.4, 36.7, 39.8, 61.1, 65.0, 128.3, 129.5, 130.5, 132.8, 166.7. Anal. Calcd for $C_{15}H_{22}O_3$: C, 71.97; H, 8.86. Found: C, 72.08; H, 8.96.

2,2-Dimethyl-1-(hydroxymethyl)cyclohexane (34). A toluene solution (5 mL) of $[Rh_2(cod)_2Cl_2]$ (12.3 mg, 25 μmol), dppe (23.9 mg, 60 μmol), and 1-methyl-*cis*-bicyclo[4,2,0]octan-7-one (138 mg, 1.0 mmol) under a hydrogen atmosphere (50 atm) in an autoclave was heated at 140 °C for 3 days. A workup procedure similar to that for **24** (column chromatography, hexane:Et_2O = 1:1) afforded **34** (104 mg, 74%) as a colorless oil.

3-Benzyl-3-methyl-4-phenyl-1-butanol (35). A toluene solution (5 mL) of $[Rh_2(cod)_2Cl_2]$ (4.9 mg, 19 μmol), dppe (9.6 mg, 24 μmol), and 3,3-dibenzylcyclobutanone (100 mg, 0.4 mmol) under a hydrogen atmosphere (50 atm) in an autoclave was heated at 140 °C for 42 h. A workup procedure similar to that for **24** (thin layer chromatography, hexane:AcOEt = 2:1) afforded **35** (85 mg, 84%) as a colorless oil: ^{1}H NMR δ 0.90 (s, 3 H), 1.56 (t, J = 7.7 Hz, 2 H), 1.6 (br s, 1 H), 2.65 (s, 4 H), 3.83 (t, J = 7.7 Hz, 2 H), 7.1−7.4 (m, 10 H); ^{13}C NMR δ 24.0, 37.2, 40.7, 46.8, 59.5, 126.0, 127.8, 130.7, 138.5. Anal. Calcd for $C_{18}H_{22}O$: C, 84.99; H, 8.72. Found: C, 84.83; H, 8.75.

2,2-Dimethyl-3-phenyl-1-butanol (36). A THF solution (4 mL) of $[Rh_2(cod)_2Cl_2]$ (6.2 mg, 13 μmol), dppe (12.0 mg, 30 μmol), and 2,2-dimethyl-3-phenylcyclobutanone (87.0 mg, 0.50 mmol) under a hydrogen atmosphere (50 atm) in an autoclave was heated at 140 °C for 60 h. A workup procedure similar to that for **24** (thin layer chromatography, hexane:AcOEt = 2:1) afforded **36** (8.2 mg, 9%) as a colorless oil.

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