Asymmetric Hydrogenation of Ketones Catalyzed by Ruthenium Hydride Complexes of a Beta-aminophosphine Ligand Derived from Norephedrine

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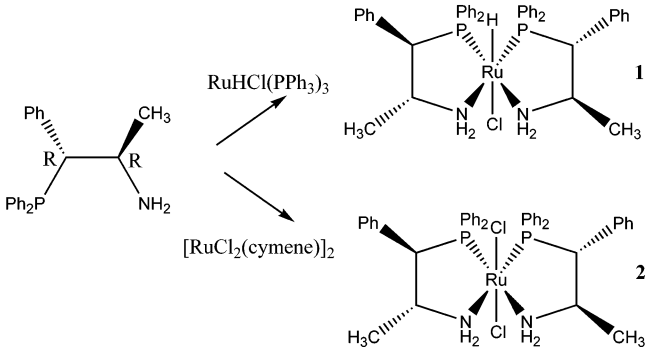
Received July 16, 2004

A series ruthenium complexes with the chiral P−N ligand (1*R,*2*R*)-$PPh_2CHPhCHMeNH_2$ derived from (1*S,*2*R*)-norephedrine are synthesized starting from the complexes $RuHCl(PPh_3)_3$ or $RuHCl(P-P)(PPh_3)$ (P−P= (*R*)-binap or (*S*)-binap). These are precatalysts for the efficient asymmetric hydrogenation of simple ketones. For the hydrogenation of acetophenone to 1-phenylethanol, the enantioselectivity observed can be related to the structure of the precatalysts determined by X-ray diffraction. This relationship breaks down for the hydrogenation of pinacolone.

Introduction

The asymmetric hydrogenation of simple ketones catalyzed by ruthenium complexes with chiral diphosphine and diamine ligands is a useful and convenient method to prepare chiral alcohols, which are widely used in the fine chemicals industry. The chiral alcohols are also useful building blocks for organic synthesis. Precatalysts of the type *trans*-$RuXY(PAr_2\text{-}Q\text{-}PAr_2)(NH_2\text{-}Q\text{-}NH_2)$ (X = Y = Cl;[1−11] X = H, Y = BH_4;[12] X = H, Y = Cl;[13] X = H, Y = H[14]) containing chiral diphosphine (PAr_2-Q-PAr_2) and diamine (NH_2-Q-NH_2) ligands (where Q is a linking group), have been used successfully in the asymmetric hydrogenation of ketones. Complexes containing aminophosphine ligands of the type PR_2-Q-NH_2 have not been extensively studied.[15,16] Our group had prepared complexes of the type *trans*-$RuHCl(PPh_2\text{-}Q\text{-}NH_2)_2$ and $RuHCl(PPh_2\text{-}Q\text{-}NH_2)$(binap), where PPh_2-Q-NH_2 is an achiral or chiral bidentate ligand derived from the amino acids glycine, alanine, and proline.[17,18] These were found to be active precatalysts for the hydrogenation of ketones and imines to alcohols and amines, respectively, in the presence of an alkoxide base. However the enantioselectivity of the reactions when chiral complexes were employed was low. In this work, we investigate the use of the ligand (1*R,*2*R*)-PPh_2-$CHPhCHMeNH_2$ (L),[16] derived from (1*S,*2*R*)-norephedrine, to see if this more rigid bidentate ligand containing two chiral centers would be more effective than the amino acid derived ligands.

Scheme 1. Synthesis of the Complexes *trans*-$RuHClL_2$ and *trans*-$RuCl_2L_2$



Results and Discussion

Preparation of the Complexes The ligand L was prepared in three steps from the amino alcohol in 50% overall yield as an air-sensitive, white solid after chromatography under Ar.[16] The yellow, air-sensitive complex *trans*-$RuHClL_2$ was prepared in 65% yield by heating $RuHCl(PPh_3)_3$ with 2 equiv of L in toluene (Scheme 1). If benzene is used as the solvent for this

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10.1021/om049460h CCC: $27.50
Publication on Web 10/14/2004

Table 1. Selected Bond Lengths [Å] and Angles [deg][a]

	1		3	4	4[a]
Ru(1)−H(1RU)	1.67(4)	Ru(1)−H(1RU)	1.53(3)	1.8(1)	1.66(6)
Ru(1)−N(2)	2.168(4)	Ru(1)−N(1)	2.184(3)	2.185(5)	2.198(6)
Ru(1)−N(1)	2.184(4)	Ru(1)−P(2)	2.2738(8)	2.261(2)	2.264(2)
Ru(1)−P(2)	2.214(2)	Ru(1)−P(3)	2.3139(8)	2.322(2)	2.331(2)
Ru(1)−P(1)	2.216 (1)	Ru(1)−P(1)	2.3146(8)	2.331(2)	2.344(2)
Ru(1)−Cl(1)	2.590 (1)	Ru(1)−Cl(1)	2.5626(8)	2.576(2)	2.562(2)
H(1RU)−Ru(1)−N(2)	91(1)	H(1RU)−Ru(1)−N(1)	95(1)	89(3)	91(2)
H(1RU)−Ru(1)−N(1)	88(1)	H(1RU)−Ru(1)−P(2)	88(1)	90(3)	87(2)
N(2)−Ru(1)−N(1)	92.5 (1)	N(1)−Ru(1)−P(2)	177.22(8)	177.9(2)	177.7 (2)
H(1RU)−Ru(1)−P(1)	84(1)	H(1RU)−Ru(1)−P(3)	75(1)	73(3)	75(2)
N(2)−Ru(1)−P(1)	173.4 (1)	N(1)−Ru(1)−P(3)	90.78(7)	91.5(2)	91.6(2)
N(1)−Ru(1)−P(1)	83.6 (1)	P(2)−Ru(1)−P(3)	90.66(3)	89.84(7)	88.95(7)
H(1RU)−Ru(1)−P(2)	92(1)	H(1RU)−Ru(1)−P(1)	82(1)	89(3)	87(2)
N(2)−Ru(1)−P(2)	83.4(1)	N(1)−Ru(1)−P(1)	81.44(8)	80.4(2)	79.8(2)
N(1)−Ru(1)−P(2)	175.8 (1)	P(2)−Ru(1)−P(1)	98.19(3)	97.81(7)	99.02(7)
P(1)−Ru(1)−P(2)	100.52(5)	P(3)−Ru(1)−P(1)	154.90(3)	159.92(7)	160.07(8)
H(1RU)−Ru(1)−Cl(1)	164(1)	H(1RU)−Ru(1)−Cl(1)	173(1)	168(3)	172(2)
N(2)−Ru(1)−Cl(1)	78.4(1)	N(1)−Ru(1)−Cl(1)	78.56(8)	81.7(2)	82.2(2)
N(1)−Ru(1)−Cl(1)	81.3(1)	P(2)−Ru(1)−Cl(1)	98.83(3)	99.77(7)	99.93(7)
P(1)−Ru(1)−Cl(1)	106.26(5)	P(3)−Ru(1)−Cl(1)	101.21(3)	100.07(7)	99.54(7)
P(2)−Ru(1)−Cl(1)	97.17(5)	P(1)−Ru(1)−Cl(1)	100.57(3)	96.90(7)	97.04(7)

[a] The second column of data for **4** refers to a second molecule in the asymmetric unit with atom numbering: Ru(1) = Ru(2), N(1) = N(2), P(2) = P(5), P(3) = P(6), P(1) = P(4), H(1RU) = H(2RU).

reaction, the lower temperature of the reflux results in the incomplete displacement of the PPh_3. The complex *trans*-$RuHClL_2$ is obtained exclusively as the *trans* isomer with *cis* phosphorus atoms. This structure has no molecular symmetry elements. In solution this is revealed by the pattern of two doublets with a small J_{PP} coupling constant (29 Hz) in the ^{31}P NMR spectrum and a doublet of doublets in the hydride region of the ^1H NMR spectrum with J_{HP} values characteristic of *cis* H and P nuclei. In the solid state this is verified by the single-crystal X-ray diffraction structure (Figure 1, Table 1). The Ru−H bond is perpendicular to the RuP_2N_2 plane, while the Ru−Cl bond is tilted toward the NH groups. This is a geometry observed previously in other $RuP_2N_2(H)(Cl)$ structures.[13,14,18] The amino group containing N(1) has distinct axial and equatorial orientations of N−H with respect to the RuNCCP five-membered ring, while the other amino group has N−H orientations that are bisectional.[19] The axial N−H is parallel to the Ru−Cl bond with a short H···Cl contact.

Heating the ligand with the dichloride complex $[RuCl_2(p\text{-cymene})]_2$ results in the formation of the orange, air-stable complex *trans*-$RuCl_2L_2$ (Scheme 1) in good yield and as only one isomer. The complex is also prepared in good yield by heating the ligand with $RuCl_2(PPh_3)_3$. The $^{31}P\{^1H\}$ NMR spectrum has a single peak for this

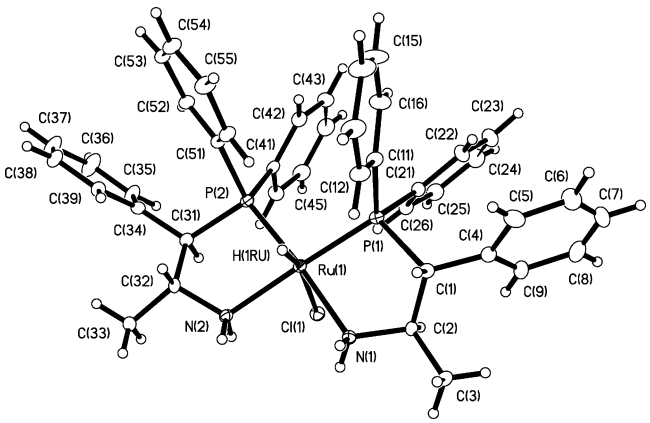
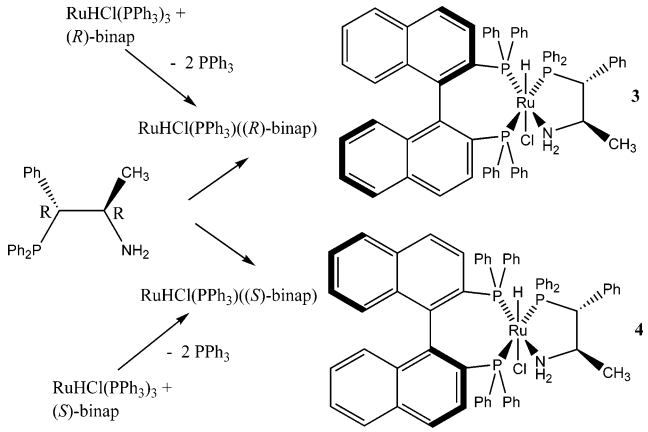


Figure 1. Molecular structure of *trans*-$RuHClL_2$, **1**.

Scheme 2. Preparation of the Complexes RuHCl(binap)L



complex at 78.1 ppm. The spectrum is similar to that of *trans*-$RuCl_2(PPh_2CH_2CH_2NH_2)_2$,[20] and the structure is thought to be similar as well.

The yellow complexes *trans*-RuHCl((*R*)-binap)(L) (**3**) and *trans*-RuHCl((*S*)-binap)(L) (**4**) were obtained in 55−60% yield by displacing PPh_3 from the appropriate precursor complexes (Scheme 2). The reaction solution is heated until one isomer is obtained as indicated by the ^{31}P and ^1H NMR spectra. The former shows an AMX pattern, while the latter shows only one doublet of pseudo-triplets in the hydride region of the ^1H NMR spectrum. The complexes can also be prepared in higher overall yield in a one-pot reaction starting from $RuHCl(PPh_3)_3$ by first reaction with binap and then reaction with L.

The X-ray structure of **3** is shown in Figure 2. The complex has a *trans* stereochemistry. The N−H bonds are bisectional[19] with respect to the RuPCCN ring.

The X-ray structure of **4** (Figure 3) is similar to that of **3** but in this case there is clearly an axial N−H

(19) Bisectional: between axial and equatorial. See: Luger; P.; Bülow, R. *J. Appl. Crystallogr.* **1983**, *19*16, 1431, for ring descriptor classifications.

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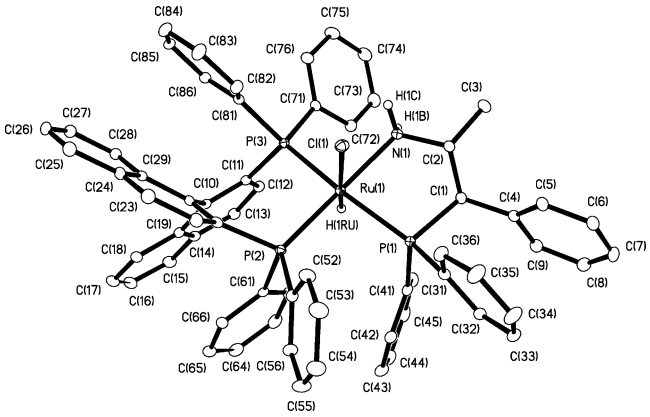


Figure 2. Structure of *trans*-RuHCl((*R*)-binap)(L), **3**.

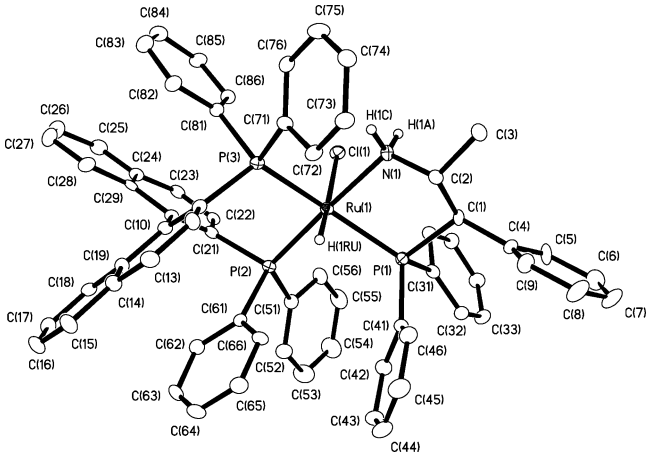


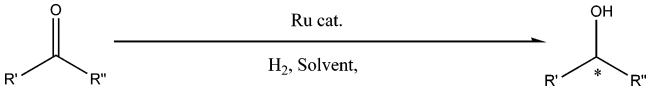
Figure 3. Structure of *trans*-RuHCl((*S*)-binap)(L), **4**.

parallel to the Ru−Cl bond. In **3**, **4**, and RuHCl((*R*)-binap)($PPh_2CH_2CH_2NH_2$),[18] the N atom is *trans* to the phosphorus that is attached to the naphthyl group on binap that is *syn* to the Ru−Cl bond. The bond distances around the ruthenium in **3** and **4** are very similar apart from those involving P(1) of the aminophosphine ligand (Table 1). The Ru−P(1) distance and the P(3)−Ru−P(1) angles are slightly greater in the two molecules of **4** than in **3**.

Asymmetric Hydrogenation of Ketones. In the presence of an alkoxide base in 2-propanol, *trans*-$RuHClL_2$ gives high reactivity and moderate enantioselectivity in the hydrogenation at 2−26 atm of simple ketones. For example the complete hydrogenation of acetophenone to (*R*)-1-phenylethanol in 47% ee occurs in less than 2 h at 5 °C and 2 atm, representing at least 5000 turnovers of the catalyst (Table 2, entry 3). The ee was greater at 5 °C than at 20 °C (32%, entry 1) but was not affected by a change in the H_2 pressure (entries 2 and 3). The use of the dichloride precatalysts **2** gave marginally higher ee (entries 4 and 5). Under similar conditions without H_2 there is negligible hydrogen transfer from the solvent to the ketone. These results encouraged us to modify the complex with the binap ligand to try to improve the enantioselectivity.

The complex *trans*-RuHCl((*R*)-binap)(L) (**3**) was also an excellent precatalyst under similar conditions and gave 1-phenylethanol enriched in the *S* enantiomer in ee up to 61% (entries 6−10). This is opposite of the enantioselectivity of precatalysts **1** and **2**. The ee increased at the lower temperature and was not affected by a change in pressure. The use of *trans*-RuHCl((*S*)-binap)(L) (**4**) improves the ee of the alcohol to 72% ee (entries 11−14). The product is enriched in the *S* isomer, similar to that from the use of **3**. Therefore (*S*)-binap instead of (*R*)-binap is better matched with L in the hydrogenation of acetophenone.

Table 2. Hydrogenation of Ketones with Ruthenium Complexes 1−4[a]



entry	substrate	cat.	P_{H2} (psi)	temp (°C)	time (h)[b]	conv %	ee %	conf
1	1	**1**	100	20	1	>99	32	*R*
2	1	**1**	400	5	1	>99	46	*R*
3[c]	1	**1**	30	5	2	>99	47	*R*
4[c]	1	**2**	400	20	1	>99	40	*R*
5[c]	1	**2**	30	5	4	>99	51	*R*
6	1	**3**	100	20	1	>99	60	*S*
7	1	**3**	400	20	1	>99	59	*S*
8[c]	1	**3**	400	20	1	>99	57	*S*
9	1	**3**	30	5	4	97	61	*S*
10	1	**3**	100	5	1	>99	55	*S*
11	1	**4**	100	20	1	>99	67	*S*
12	1	**4**	30	5	3	97	71	*S*
13	1	**4**	30	0	4	95	72	*S*
14[c]	1	**4**	30	5	4	>99	71	*S*
15	2	**1**	100	20	4	>99	29	
16	3	**1**	100	20	3	>99	40	*S*

[a] Reaction conditions: under H_2, the ketone, base, and 2-propanol were mixed first to give a total volume of 4 mL and stirred for 5 min; then the complex (5×10^{-3} mmol) was added. The molar ratio of substrate to base to catalyst was 2000:30:1. [b] 30 min before this time, the conversion was found to be incomplete. [c] The molar ratio of substrate to base to catalyst was 5000:50:1.

Complex **1** also catalyzes the hydrogenation of the less reactive ketones pivalophenone (entry 15) and pinacolone (entry 16) in ee's of 29% and 40%, respectively. The alcohol 3-methylbutan-2-ol derived from pinacolone is enriched in the *S* enantiomer, while the same catalyst gives 1-phenylethanol in the *R* configuration. Complex **2** can also be used with similar results. The activity of the catalysts, but not the enantioselectivity, compares favorably with the $RuCl_2$((*R*)-binap)((*R,R*)-dpen))[2] and $[RhCl(C_8H_{12})]_2$/Penphos[21] systems. The ruthenium complexes **3** and **4** have lower reactivity than **1** toward these ketones with bulky, electron-donating substituents.

Relationship between Structure and Enantioselectivity in the Hydrogenation of Acetophenone. The enantioselectivity of Noyori-type catalysts for the hydrogenation of prochiral ketones with a large substituent (e.g., Ph) and a small substituent (e.g., Me) has been explained in terms of the transition state for H^+/H^- transfer from a *trans*-dihydride to the prochiral ketone.[22] For example, for a model of the dihydride *trans*-RuH_2((*R*)-binap)((*R,R*)-dpen) [(*R,R*)-dpen = NH_2-$CHPhCHPhNH_2$] (Figure 4) reacting with acetophenone, the ketone orients its carbonyl oxygen above the axial NH and its carbonyl carbon above the ruthenium hydride.[23] The phenyl group is kept away from the binap naphthyl and phenyl groups that protrude above the

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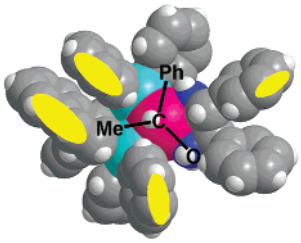

Figure 4. Model of acetophenone accepting an NH proton and RuH hydride from *trans*-RuH_2((*R*)-binap)((*R,R*)-dpen).

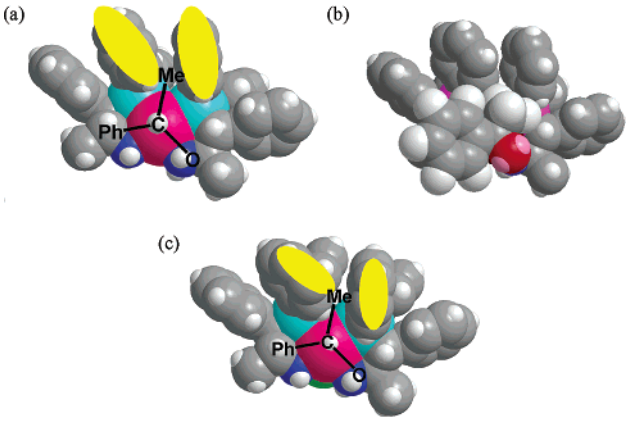

Figure 5. Proposed favorable orientation of acetophenone reacting with *trans*-RuH_2L_2 for H^+/H^- transfer that leads to the formation of (*R*)-1-phenylethanol. (a) The side of $RuHClL_2$ where the chloride has been replaced by a hydride to model *trans*-RuH_2L_2. This side clearly has an axial NH to align the carbonyl group with a hydrogen bond. (b) Space-filled (*R*)-1-phenylethanol oriented as in (a). (c) Hydride side of $RuHClL_2$ with the more axial NH involved in orienting the carbonyl group.

ruthenium complex, as indicated by the light ovals. This orientation results in the formation of (*S*)-1-phenylethanol, as is observed. This model was based on the known structure of the complex RuHCl((*R*)-binap)((*R,R*)-dpen),[13] where the chloride was replaced by a hydride.

This concept applies well for the hydrogenation of acetophenone catalyzed by complexes **1** and **4** on the basis of their structures as determined by single-crystal X-ray diffraction. It is suspected that the active catalysts generated from complexes **1**−**4** are *trans*-dihydride and amido-amine complexes on the basis of our previous work[14] even though these have not yet been identified. If the chloride ligand in **1** is replaced by a hydride ligand to model the proposed *trans*-dihydride catalyst for H^+/H^- transfer, then the resulting structure clearly interacts with acetophenone to produce the *R* alcohol, independent of the side of the molecule approached (Figure 5). Again the larger phenyl group is presumed to avoid the "mountainous regions" of the catalyst, as indicated by the light ovals. Figure 5b shows the relative sizes of the complex relative to the (*R*)-1-phenylethanol product, oriented like the acetophenone, shown schematically in Figure 5a. We assume that a high ee is not obtained for this catalyst because of the presence of the second NH group on the same face of the molecule that might also become axial because of the flexibility of the coordination environment and direct the H^+/H^- transfer to the opposite face of the ketone.

Similarly, if the chloride ligand is replaced by a hydride in the structure of **4**, the dihydride that results

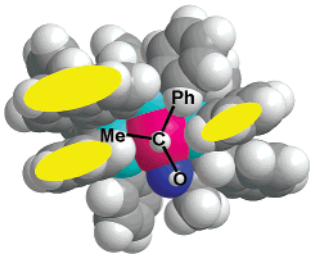

Figure 6. Proposed favorable orientation of acetophenone reacting with *trans*-RuH_2((*S*)-binap)L for H^+/H^- transfer that leads to the formation of (*S*)-1-phenylethanol. This structure is generated by replacing the chloride with a hydride in the structure of **4**.

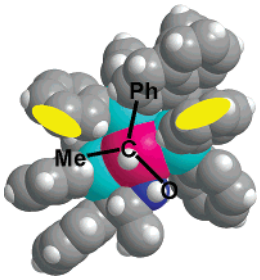

Figure 7. Orientation of acetophenone reacting with *trans*-RuH_2((*R*)-binap)L for H^+/H^- transfer that leads to the formation of (*S*)-1-phenylethanol. This structure is generated by replacing the chloride with a hydride in the structure of **3**.

is assumed to interact favorably with the ketone, as shown in Figure 6. This structure leads to the *S* alcohol, as is observed experimentally. The other side of **4** does not have an axial NH and is too congested to draw a reasonable transition state structure.

The topography of the chloride side of the structure of **3** is fairly flat (Figure 7). In the orientation draw, which is the one favored in the experiment, the discrimination may result from the binap phenyl that falls between the methyl and phenyl groups of the ketone and that leans to crowd the side where the methyl group falls.

Unfortunately this approach may be too simplistic since it does not work for pinacolone, at least for precatalyst **1**. This complex should give predominantly the *R* alcohol, while the *S* alcohol is actually observed (entry 16, Table 2).

Conclusions

The complexes *trans*-$RuHClL_2$ and *trans*-RuHCl(binap)L are precatalysts to active ketone hydrogenation catalysts. The enantioselectivity in the asymmetric hydrogenation of acetophenone was higher in the latter complexes containing the binap ligand. Noyori's group demonstrated that, for the hydrogenation of 1′-acetonaphthone, the use of the complex with the matched pair of ligands, *trans*-$RuCl_2$((*R*)-binap)((*R,R*)-dpen) leads to an alcohol in much higher ee (97% *S*) than the complex with mismatched ligands, *trans*-$RuCl_2$((*R*)-binap)((*S,S*)-dpen) (14% *S*).[2] We observe a different behavior: the *trans*-RuHCl((*S*)-binap)((*R,R*)-L) precatalyst leads to a higher ee than the *trans*-RuHCl((*R*)-binap)((*R,R*)-L) complex. The structures of *trans*-$RuHClL_2$, *trans*-RuHCl((*S*)-binap)L, and *trans*-RuHCl((*R*)-

Table 3. Crystallographic Data for Complexes 1, 3, and 4

	1	3	4
formula	$C_{42}H_{45}ClN_2P_2Ru{\cdot}C_4H_{10}O$	$C_{65}H_{55}ClNP_3Ru{\cdot}C_6H_6{\cdot}0.5C_5H_{12}$	$C_{65}H_{55}ClNP_3Ru{\cdot}2.25C_6H_6$
fw	850.38	1193.71	1255.28
temp, K	150(2)	150(2)	150(2)
wavelength, Å	0.71073	0.71073	0.71073
cryst syst	monoclinic	orthorhombic	monoclinic
space group	$P2_1$	$P2_12_12_1$	$P2_1$
a, Å	14.942(3)	15.1090(2)	17.667(4)
b, Å	9.686 (2)	18.86700(10)	11.113(2)
c, Å	16.344(3)	21.7860(2)	33.147(7)
α, deg	90	90	90
β, deg	114.46(3)	90	90.35(3)
γ, deg	90	90	90
volume, Å^3	2153.2(7)	6210.35(11)	6508(2)
Z	4	4	4
D_{calc}, g·cm^{-3}	1.312	1.277	1.281
μ, cm^{-1}	5.36	4.16	4.00
2θ max, deg	55.04	54.94	54.96
no. of reflns measd	19029	54076	43330
no. of reflns used	9115	14 022	25 483
no. of params	465	720	1385
final R indices [$I>2\sigma(I)$][a]	$R_1 = 0.0474$	$R_1 = 0.0380$	$R_1 = 0.0689$
	$wR_2 = 0.0984$	$wR_2 = 0.1075$	$wR_2 = 0.1589$
R indices (all data)[a]	$R_1 = 0.0732$	$R_1 = 0.0464$	$R_1 = 0.1272$
	$wR_2 = 0.1118$	$wR_2 = 0.1134$	$wR_2 = 0.1925$
goodness-of-fit on F^2	1.050	1.116	1.030

[a] $R_1 = \sum|F_o| - |F_c|/\sum|F_o|$. $wR_2 = [\sum w[(F_o^2 - F_c^2)^2]/\sum[w(F_o^2)^2]]^{1/2}$. $w = 1/[^2(F_o^2) + (0.075P)^2]$, where $P = [\max(F_o^2,0) + 2F_c^2]/3$.

binap)L can be used to explain the enantioselectivity observed in the hydrogenation of acetophenone but not pinacolone with the assumption that *trans*-dihydrides of analogous structure are responsible for the H^+/H^- transfer step.

Experimental Section

General Procedures. All manipulations were carried out under an inert atmosphere using standard Schlenk techniques. Solvents were dried and distilled prior to use. Other chemicals were purchased from Aldrich. The ketones were washed with saturated K_2CO_3 solution and dried with anhydrous Na_2SO_4, then distilled prior to use. The enantiomeric excess value of the products was determined with a Perkin-Elmer AutoSystem XL gas chromatograph system (column, Chirasil-DEX CB; 25 m × 0.25 mm, CHROMPACK, carrier gas, H_2). Varian Gemini 300, Unity 400, and Unity 500 spectrometers were used for NMR spectra. (1*R*,2*R*)-2-Amino-1-phenylpropyldiphenylphosphine (L),[16] $RuCl_2(PPh_3)_3$,[24] $RuHCl(PPh_3)_3$,[24] [Ru(cymene)$Cl_2]_2$,[25] and RuHCl(binap)(PPh_3)[13] were prepared according to the literature methods. Elemental analyses were done in our Chemistry Department.

***trans*-RuHCl((*R,R*)-PPh$_2$CHPhCHMeNH$_2$)$_2$ (1).** RuHCl($PPh_3)_3$ (462 mg, 0.5 mmol) and L (319 mg, 1.0 mmol) were put into a 50 mL Schlenk flask under argon. Toluene (5 mL) was added. The mixture was refluxed overnight. A yellow precipitate formed. The solution was cooled to 20 °C, and then the precipitate was collected by filtration under nitrogen, washed with benzene (3 mL) and hexanes (2 × 3 mL), and then dried in vacuo to give the yellow product (340 mg, 90%). The orange crystal suitable for the X-ray diffraction study was obtained from the slow evaporation of an ethanol/ether solution under Ar. ^{1}H NMR (300 MHz, CD_3CN): δ −17.53 (dd, J = 21.3, 27.0 Hz, 1H), 1.16 (d, J = 5.1 Hz, 3H), 1.21 (d, J = 6.0 Hz, 3H), 3.04 (m, 2H), 3.18 (m, 1H), 3.80 (m, 2H), 4.22 (m, 2H), 4.98 (m, 1H), 6.22−7.35 (m, 30H). ^{31}P{^{1}H} NMR (121.5 MHz, CD_3CN): δ 89.03 (d, J = 29.2 Hz), 97.22 (d, J = 29.2 Hz). Anal. Calcd for $C_{42}H_{45}ClN_2P_2Ru$: C, 64.98; H, 5.84; N, 3.61. Found: C, 65.14; H, 5.47; N, 3.47.

***trans*-RuCl$_2$((*R,R*)-PPh$_2$CHPhCHMeNH$_2$)$_2$ (2).** Method 1. The aminophosphine L (319 mg, 1.0 mmol) and [Ru(cymene)$Cl_2]_2$ (153 mg, 0.25 mmol) were placed in a 50 mL Schenk flask, and then 5 mL of EtOH/CH_2Cl_2 (1:1) was added. The resulting mixture was refluxed for 12 h under Ar, cooled to room temperature, and filtered through a Celite pad. The filtrate was evaporated under vacuum to give a yellow solid, which was washed with hexanes and dried in vacuo (354 mg, 90%). Method 2. $RuCl_2(PPh_3)_3$ (479 mg, 0.5 mmol) and L (319 mg, 1.0 mmol) were put in a 50 mL Schlenk flask under Ar, and then 10 mL of toluene was added. The mixture was refluxed for 48 h. The resulting orange solution was cooled to 20 °C and filtered through a pad of Celite. The solvent was removed, and the residue was washed with hexanes (3 × 15 mL) and dried in vacuo to produce a yellow solid (321 mg, yield 79.3%). ^{1}H NMR (300 MHz, C_6D_6): δ 1.19 (d, 6H), 3.86 (m, 4H), 4.12 (m, 2H), 4.68 (m, 2H), 6.6−7.78 (m, 30H). ^{1}H NMR ($CDCl_3$): δ 1.38 (d, J = 5.3 Hz, 6H), 3.77 (b, 4H), 3.96 (m, 2H), 4.23 (m, 2H), 6.50−7.80 (m, 30H). ^{31}P{^{1}H} (121.50 MHz, C_6D_6): δ 78.1 (s). ($CDCl_3$): 77.0 (s). Anal. Calcd for $C_{42}H_{44}Cl_2N_2P_2Ru$: C, 62.22; H, 5.47; N, 3.46. Found: C, 62.72; H, 5.57; N, 3.24.

***trans*-RuHCl((*R,R*)-PPh$_2$CHPhCHMeNH$_2$)((*R*)-binap) (3).** Method 1. RuHCl(PPh_3)((*R*)-binap) (204 mg, 0.2 mmol), aminophosphine L (64 mg, 0.2 mmol), and dry toluene (5 mL) were put into a 25 mL Schenk flask. The color of the solution changed from red to yellow immediately. The mixture was refluxed for 10 h. The solvent was removed under vacuum to 1 mL, and 8 mL of hexane was added to give a yellow precipitate. The yellow solid was filtered and washed with hexane several times and dried in vacuo (168 mg, yield 78%). Method 2. RuHCl($PPh_3)_3$ (462 mg, 0.5 mmol) and (*R*)-binap (311 mg, 0.5 mmol) were put in a Schlenk flask, and 10 mL toluene was added. The mixture was refluxed under argon overnight to produce a dark red solution. Then L (319 mg, 1.0 mmol) was added. The color of the solution changed to yellow immediately. The mixture was refluxed for another 24 h and then cooled to 20 °C. Suspended solids were filtered by use of a Celite pad, and the toluene was evaporated under vacuum to 1 mL. Hexanes (10 mL) was added to precipitate the product, which was filtered off, washed with hexanes (3 × 5

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mL) to remove PPh_3, and then dried in vacuo to produce yellow **3** (415 mg, 77%). ^{1}H NMR (400 MHz, C_6D_6): δ −17.15 (dt, J = 21.2 Hz, J = 29.2 Hz, 1H), 0.43 (d, J = 4.8 Hz, 3H), 3.44 (b, 2H), 3.62 (m, 1H), 4.43 (m, 1H), 6.27−8.67 (m, 47H). ^{31}P{^{1}H} NMR (121.5 MHz, C_6D_6): δ 35.07 (dd, J = 31.6 Hz, J = 289.2 Hz, 1P), 56.73 (dd, J = 26.7 Hz, J = 289.2 Hz, 1P), 66.63 (m, 1P). Anal. Calcd for $C_{65}H_{55}ClNP_3Ru$: C, 72.31; H, 5.14; N, 1.30. Found: C, 72.45; H, 5.37; N, 1.21.

***trans*-RuHCl((*R,R*)-PPh$_2$CHPhCHMeNH$_2$)((*S*)-binap) (4).** The procedure for the synthesis of complex **4** is similar to that of method 2 for complex **3**. The yield is about 75%. The orange crystals suitable for the X-ray diffraction study were obtained by recrystallization from benzene/hexanes. ^{1}H NMR (400 MHz, C_6D_6): δ −17.07 (dt, J = 20.0, 27.6 Hz, 1H), 0.44 (d, J = 4.8 Hz, 3H), 1.82 (br, 1H), 2.69 (m, 1H), 3.58 (dd, J = 5.2, 12.8 Hz, 1H), 4.25 (m, 1H), 6.33−8.32 (m, 47H). ^{31}P{H} NMR (121.5 MHz, C_6D_6): δ 41.48 (dd, J = 32.0, 286.7 Hz, 1P), 63.71 (m, 1P), 67.27 (dd, J = 27.9, 286.7 Hz, 1P). Anal. Calcd for $C_{65}H_{55}ClNP_3Ru$: C, 72.31; H, 5.14; N, 1.30. Found: C, 72.22; H, 5.07; N, 1.18.

Typical Procedure for the Ruthenium-Catalyzed Asymmetric Hydrogenation of Ketones. In a glovebox, the ruthenium complex (5.0×10^{-3} mmol) and ketone (10 mmol) were mixed and then KO^{t}Bu (17 mg, 0.15 mmol) was added. This mixture was diluted with 2-propanol to 4 mL and stirred under N_2 for 5 min. The mixture was injected into the thermostated autoclave against a flow of dihydrogen, and then the autoclave was pressurized with hydrogen. The reaction mixture was stirred at the desired temperature for the required time. The conversion and enantiomeric excess of the products were determined by NMR and chiral GC analysis, respectively. The absolute configuration of the product was determined by comparing the observed rotation with the reported value for 1-phenylethanol[26] or pinacolyl alcohol.[27]

X-ray Structure Analysis. Data were collected on a Nonius Kappa-CCD diffractometer using Mo Kα radiation (Table 3). The CCD data were integrated and scaled using the DENZO-SMN software package, and the structures were solved and refined using SHELXTL V6.0. Wherever reported, hydrides were located and refined with isotropic thermal parameters.

Acknowledgment. R.H.M. thanks NSERC for a discovery grant to support part of this research.

Supporting Information Available: The cif files of the crystallographic data for **1**, **3**, and **4**. This material is available free charge via the Internet at http://pubs.acs.org.

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